Latest Results from HiRes

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HiRes has made the first statistically significant observation of the Griessen-Zatsepin-Kuzmin suppression, by fitting the ultra high energy cosmic ray spectrum observed in monocular mode by the two HiRes detectors to a broken power law model. We find the break to be at an energy of 5.6×10^{19} eV, with a significance of 5.3σ. The significance is determined by Poisson statistics where we expect 43.2 events above the break point, but observe only 13. We have also looked for correlations between HiRes stereo events and active galactic nuclei. We observe no statistically significant correlation in a number of different tests. We have performed a search for upward going showers, which would be indicative of neutrinos propagating through the Earth and interacting just below the surface. Observing no such events, we set a limit on the electron neutrino flux. This limit is significantly lower in this topology than limits on the other types of neutrinos due to the LPM effect greatly increasing the available target mass for neutrino interactions. Finally we look forward to improving these and other results in our work in the Telescope Array.

The High Resoltuion Fly's Eye Experiment (HiRes) was operated for nine years, from June 1997 to April 2006, on Dugway Proving Grounds in Utah, USA. It was designed to observe ultra high energy cosmic rays (UHECR's) using the fluorescence technique, with two sets of telescopes placed on dessert hills separated by 12.6 km. Details of the fluorescence method and the analysis methods used by HiRes can be found elsewhere[1,2,3].

1 First Observation of the GZK Suppression

In 1966, Greisen [4], and Zatsepin and Kuzmin [5], proposed an upper energy limit to the cosmic-ray energy spectrum. Their predictions were based on the assumption of a proton dominated extra-galactic cosmic-ray flux which would interact with the photons in the cosmic microwave background (CMB) via photo-pion production. From the temperature of the CMB and the mass and width of the Δ^+ resonance, a "GZK" threshold of $\sim 6 \times 10^{19}$ eV was calculated, and a suppression in the cosmic-ray flux beyond this energy was predicted. This is a strong energy-loss mechanism that limits the range of cosmic protons above this threshold to less than ~ 50 Mpc. Forty years after its initial prediction, the HiRes experiment has observed the GZK cutoff. In this section we describe our measurement of the flux of cosmic rays, the resulting cosmic-ray spectrum, our analysis of this spectrum to infer the existence of the cutoff, and our estimate of systematic uncertainties.

HiRes data analysis is carried out in two ways. In monocular mode, events from each detector site are selected and reconstructed independently. The combined monocular dataset has the best statistical power and covers the widest energy range. The dataset consisting of events seen by both detectors, data analyzed in stereo mode, has the best resolution, but covers a narrower energy range and has less statistics. This section presents the monocular spectra from our two detectors.

The details of this anaysis have been now been published[6] and I will not repeat all the details here. The event reconstruction procedure begins with the determination of the shower axis. A shower-detector plane (SDP) is determined from the pointing direction of triggered PMTs. For the HiRes-II monocular dataset, the PMT times are then used to find the distance to the shower and the angle, ψ, of the shower within the SDP. This timing fit measures ψ to an accuracy of $\sim 5^\circ$.

The number of shower particles as a function of atmospheric depth (the amount of air traversed) is then determined. This calculation uses the fluorescence yield and corrects for atmospheric attenuation. We fit this shower profile to the Gaisser-Hillas function[7], after having subtracting scattered Čerenkov light. This profile fit yields both the energy of the shower and the depth at the shower maximum, $X_{\max}$.

The measurement of the cosmic-ray flux requires a reliable determination of the detector aperture. The aperture of the HiRes detectors has been calculated using a full Monte Carlo (MC) simulation. The MC includes simulation of shower development (using CORSIKA), fluorescence and Čerenkov light production, transmission of light through the atmosphere to the detector, collection of light by the mirrors, and the response of the PMTs, electronics and trigger systems. Simulated events are recorded in the same format as real data and processed in an identical fashion. To minimize biases from resolution effects, MC event sets are generated using the published measurements of the energy spectrum [8] and composition [9,10,11].

To ensure the reliability of the aperture calculation, the MC simulation is validated by comparing key distributions from the analysis of MC events to those from the actual data. Several of these comparisons were shown in reference[12]. Two comparisons are especially noteworthy. The data-MC comparison of the distances to showers shows that the simulation accurately models the coverage of the detector. The comparison of event brightness shows that the simulations of the optical characteristics of the detector, and of the trigger and atmospheric conditions, accurately reproduce the data collection environment. The excellent agreement between the observed and simulated distributions shown in these cases is typical of MC-data comparisons of other kinematic and physical quantities, and demonstrate that we have a reliable MC simulation program and aperture calculation. Figure 1 shows the result of the aperture calculation for both HiRes-I and HiRes-II in monocular mode.

Figure 2 shows the monocular energy spectra from the two HiRes detectors [13]. The data included in the figure were collected by HiRes-I from May, 1997 to June, 2005, and by HiRes-II from December, 1999 to August, 2004. Figure 2 shows the flux multiplied by E^3, which does not change the statistical interpretation of the results. Two prominent features seen in the figure are a softening of the spectrum at the expected energy of the GZK threshold of $10^{19.8}$ eV, and the dip at $10^{18.6}$ eV, known as the "ankle". Theoretical fits to the spectrum [14] show that the ankle is likely caused by e^+e^- pair production in the same interactions between CMB photons and cosmic-ray protons where pion production produces the GZK cutoff. The observation of both features is consistent with the published HiRes results of a predominantly light composition

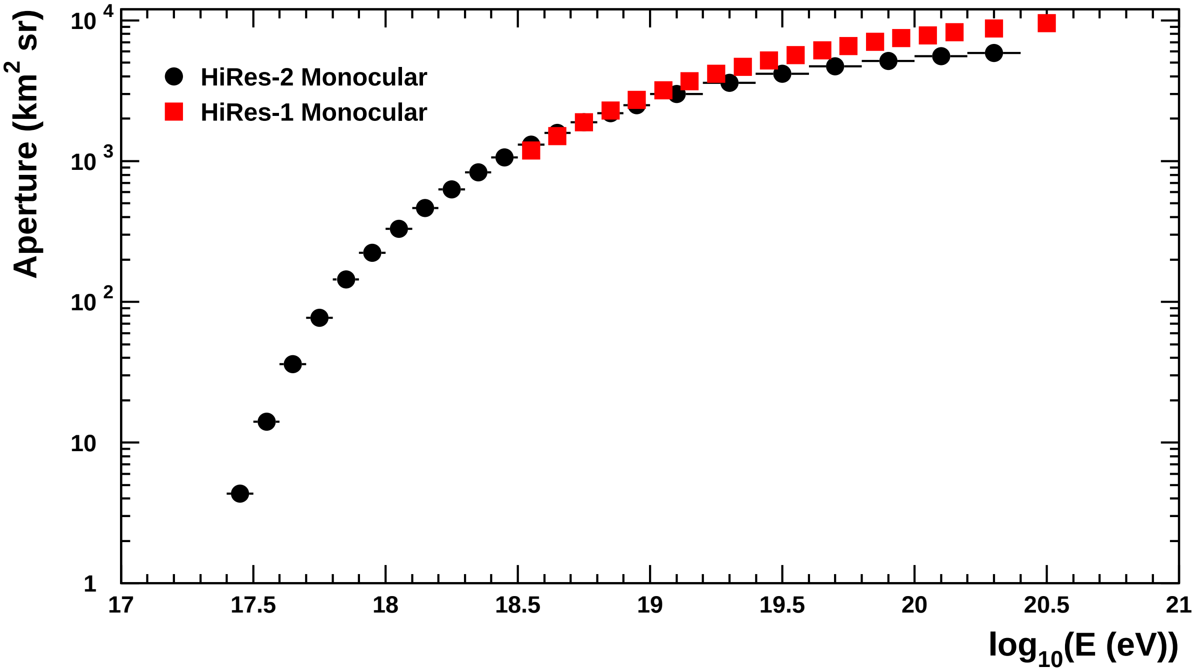

Figure 1: The apertures of the HiRes-I and HiRes-II detectors operating in monocular mode.

above 10^{18} eV [11].

At lower energies, the cosmic-ray spectrum is well fit by a piece-wise power law model. A similar fit also gives an excellent representation of the spectrum in Figure 2. The three straight line segments shown represent the result of a fit of the measured flux to a triple-power law. The model contains six free parameters: one normalization, the energies of two floating break points, and three power law indices.

We performed a binned maximum likelihood fit [15] to the data from the two detectors. The fits include two empty bins for each monocular dataset. We found the two breaks at $\log E$ (E in eV) of 19.75 ± 0.04, and 18.65 ± 0.05, corresponding to the GZK cutoff and the ankle, respectively. When the datasets were made statistically independent by removing events seen by both detectors from the HiRes-I dataset, we obtained a χ^2 of 35.1 in this fit for 35 degrees of freedom (DOF). In contrast, a fit to a model with only one break point, while able to locate the ankle, yielded a χ^2/DOF=63.0/37. The χ^2 difference of 27.9, while adding two DOF, implies that the two break point fit is preferred at a confidence level corresponding to 4.9σ.

Another measure of the significance of the break in the spectral index at $10^{19.8}$ eV is made by comparing the actual number of events observed above the break to the expected number for an unbroken spectrum. For the latter, we assume the power law of the middle segment to continue beyond the threshold. Folding the exposures with the overlap between the detectors removed, we expect 43.2 events above $10^{19.8}$ eV from the extrapolation, whereas 13 events were actually found in the data. The Poisson probability for the observed deficit is $\sim 7.2 \times 10^{-8}$, which corresponds to a significance of 5.3σ. Thus we conclude that there is a definite break in the UHE cosmic-ray energy spectrum at an energy of $(5.6 \pm 0.5) \times 10^{19}$ eV. Since the break occurs at the expected energy of the GZK cutoff, we conclude that it is the GZK cutoff.

A test of this interpretation is provided by the $E_{1/2}$ method suggested by Berezinsky and Grigorieva [16]. $E_{1/2}$ refers to the energy at which the integral spectrum falls to half of what would be expected in the absence of the GZK cutoff. Figure 3 shows the integral HiRes spectra

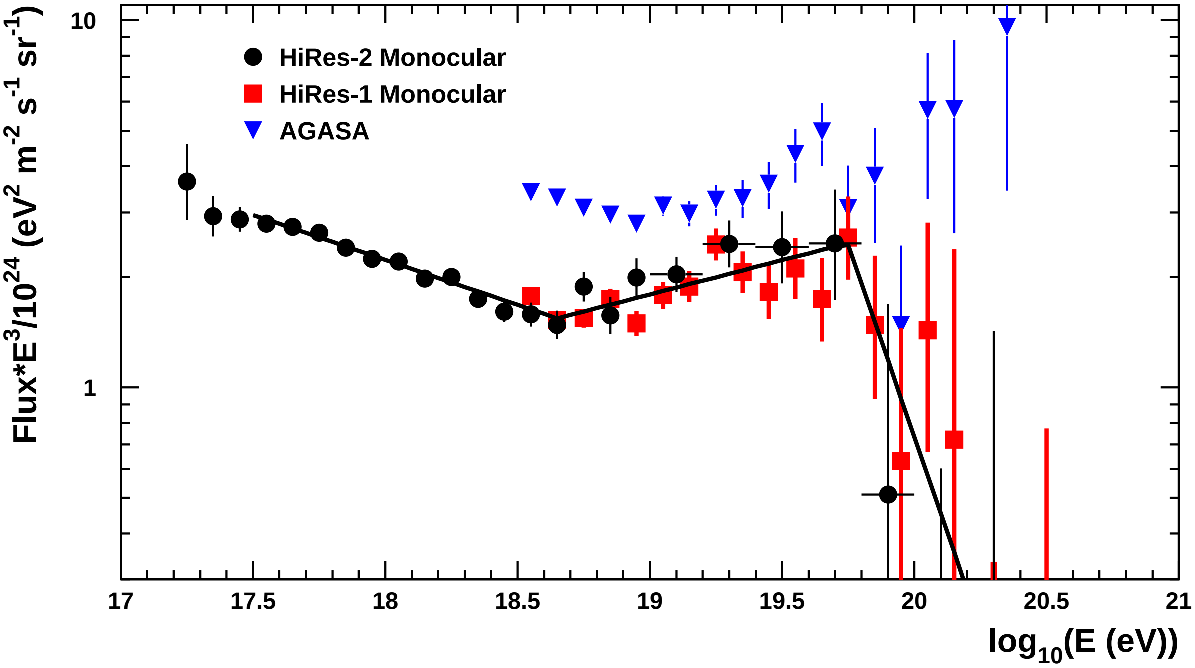

Figure 2: The cosmic-ray energy spectrum measured by the HiRes detectors operating in monocular mode. The spectrum of the HiRes-I and HiRes-II detectors are shown. The highest two energy bins for each detector are empty, with the 68% confidence level bounds shown. The spectrum of the AGASA experiment is also shown.

divided by the integral of the power law spectrum used above to estimate the number of expected events above the break. From this plot, we find $E_{1/2} = 10^{19.73 \pm 0.07}$. Berezinsky and Grigorieva predict a robust theoretical value for $E_{1/2}$ of $10^{19.72}$ eV for a wide range of spectral slopes [16]. These two values are clearly in excellent agreement, supporting our interpretation of the break as the GZK cutoff.

We measure the index of the power law between the ankle and the GZK cutoff to be 2.81 ± 0.03. Above the GZK cutoff the fall-off is very steep: we measure a power law index of 5.1 ± 0.7. This may have implications for the local density of extragalactic cosmic-ray sources [14].

For the monocular analyses, the main contributions to the systematic uncertainty in the energy scale and flux measurements are: PMT calibration (10%), fluorescence yield (6%), missing energy correction (5%), aerosol component of the atmospheric attenuation correction (5%), and mean energy loss rate (dE/dx) estimate (10%). These give a total energy scale uncertainty of 17%, and a systematic uncertainty in the flux of 30%.

The Pierre Auger Collaboration (Auger) has also recently released a measurement of the UHECR energy spectrum[17]. This is shown in comparison with the HiRes secptrum in Figure 4. While Auger confirms the existence of the Ankle and the GZK cutoff, there are still significant differences. The simplest is the over all flux level, which can be accomodated by an approximately 10% shift (at the GZK energy) in the energy scal of either experiment. More problematically, the spectral slopes at all energies are different. This is especially surprising as most previous experiments agreed is their spectral slope measurements[18].

2 Search for Correlations with AGN

The Auger Collaboration has recently released a sky map of their highest energy events[19]. They report that these events are strongly correlated with active galactic nucleii (AGN) when they

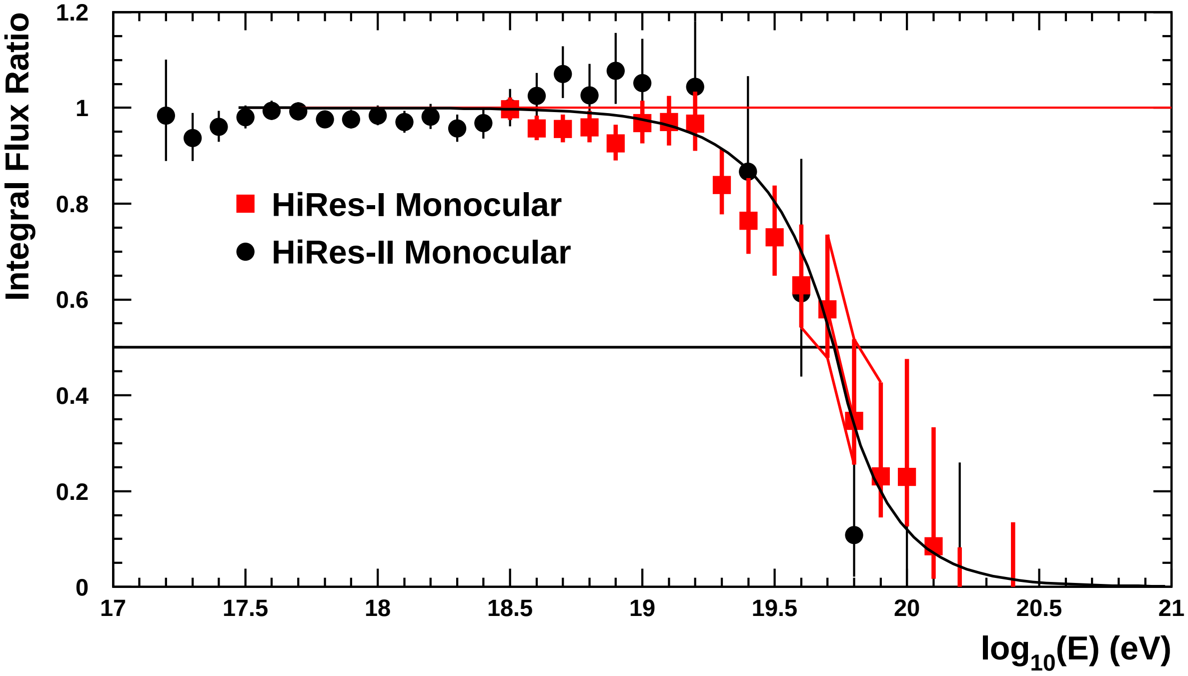

Figure 3: The HiRes monocular integral spectra, divided by the expectation from the fit in Figure 2 with no high energy break point. The integral spectrum from the actual fit is also displayed as the black line. Only HiRes-I values (in red) are used to make an estimate of $E_{1/2}$, interpolating between the central value and one standard deviation limits.

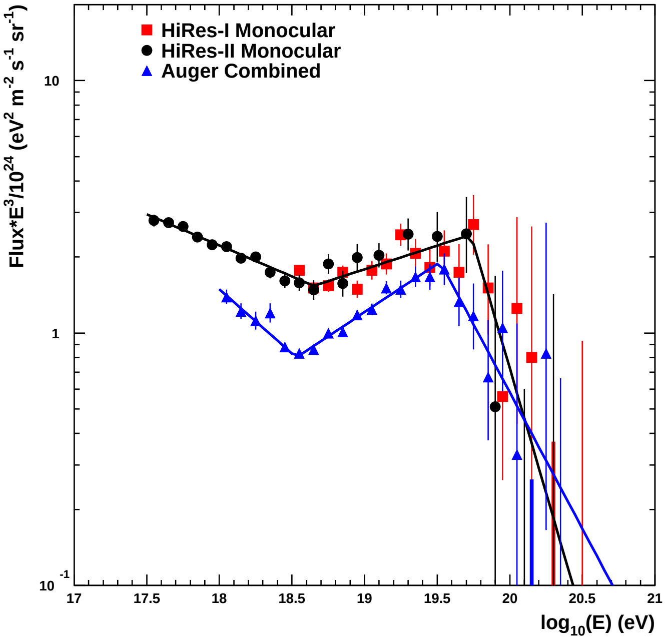

Figure 4: The HiRes and Auger spectra together for comparison.

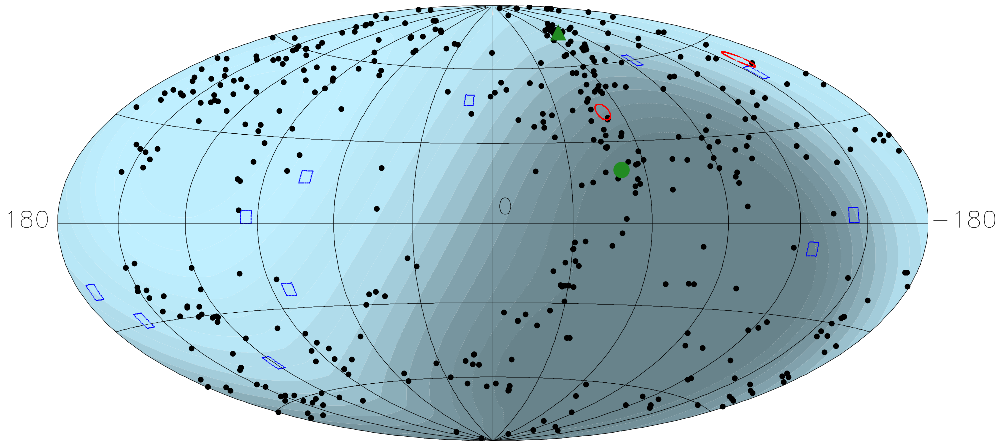

Figure 5: A sky map of HiRes events above 56 EeV (blue squares and red boxes) and AGN with $z < 0.018$ (black dots). Correlated HiRes events are shown as red circles of radius 3.1° while uncorrelated events are shown as blue squares. The HiRes relative exposure is shown by the shading with the lightest shades being fully exposed and the darkes shade having no exposure. There are 11 shading bands for no exposure and then each 10% of full exposure.

use the selection paramters $E > 56$ EeV, $\Delta\theta < 3.1^\circ$ and $z_{AGN} < 0.018$. The AGN are taken from the Veron catalog[20]. These selection parameters were found to give the largest correlation and were the result of a scan in the parameter space.

Since sources in the northern hemisphere may be different than in the south, and we also see a differently shaped energy spectrum, we tested this correlation with HiRes stereo data. Since the HiRes flux is larger than that seen in Auger, all HiRes energies were lowered by 10% (see above). These results have now been submitted for publication[21].

We first looked for correlations using the Aguer paramters. There are 13 events above 56 EeV (adjusted HiRes energy scale), but only 2 were correlated within 3.1° of AGN closer than $z = 0.018$. Given 13 events and the number of AGN, we expect 3.2 events to be corellated giving a random probability of 2 or more correlation of $P_{\text{rand}} = 0.83$. Thus, we don't confirm the Auger correlation with their exact parameters. The sky map of HiRes events above 56 EeV, and AGN used as sources ($z < 0.018$) along with the HiRes exposure is shown in Figure 5.

We also scanned the parameter space ourselves, to find the best correlation in our own data. The scan was done according to the Finley/Westerhoff method[22], so that we could correctly account for the scanning penalty and obtain an unbiased random probability for our best correlation. Our best fit was with the parameters $E > 16$ EeV, $\Delta\theta < 2.0^\circ$ and $z_{AGN} < 0.016$. We found 36 correlations among 198 events for $P_{\text{min}} = 0.0018$. However, when we look to see how often simulated isotropic data sets of the same size have a smaller P_{min}, we find that this happens in 24% of these data sets. Thus the probability of getting the observed correlation somewhere within our parameter space is an unconvincing 0.24. The sky map of HiRes events above 16 EeV, and AGN used as sources ($z < 0.016$) along with the HiRes exposure is shown in Figure 6.

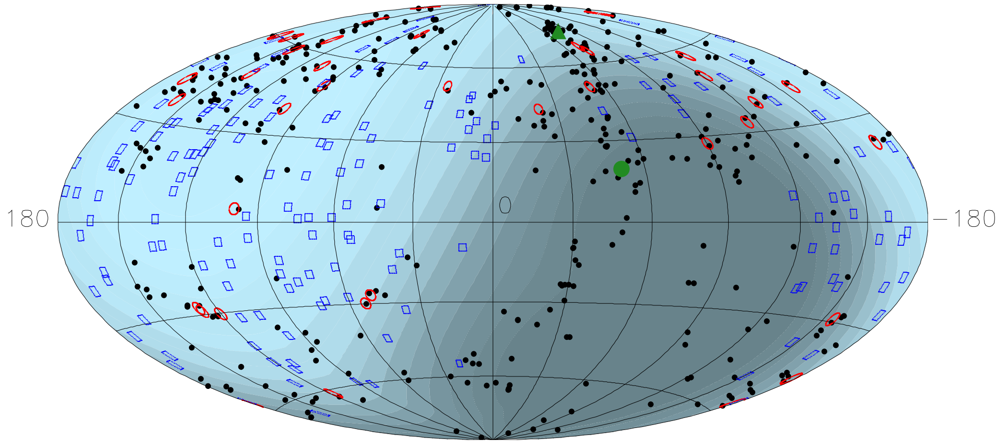

Figure 6: A sky map of HiRes events above 16 EeV (blue squares and red boxes) and AGN with $z < 0.016$ (black dots). Correlated HiRes events are shown as red circles of radius 2.0° while uncorrelated events are shown as blue squares. The HiRes relative exposure is shown by the shading with the lightest shades being fully exposed and the darkes shade having no exposure. There are 11 shading bands for no exposure and then each 10% of full exposure.

3 Electron Neutrino Flux Limit

By looking for upward going showers in a fluorescence detector, one can measure or limit the flux of neutrinos, since all other particles will be ranged out by the bulk of the Earth. In addition, because of the LPM effect[23,24], showers from electron neutrinos at high energies (above 10^{14} eV in rock) develop very slowly, and thus can emerge from the ground with significant particle numbers to be detectable starting from interaction points very deep in the rock. This gives a very large target mass for electron neurtinos compared to what's available in the atmosphere. The Earth is largely opaque to neutrinos at these energies, and the availale aperture come primarily from the limb of the Earth, which would be evident as showers emerging from the ground at large zenith angles.

A search was performed in the HiRes monocular data from the HiRes-II site. No such events were found, so a limit on the flux was set. This result has now been accepted for publication[25].

To estimate the aperture of the HiRes detector in this mode, electron neutrinos were thrown at random, and the probabilities of propagating through the Earth and then interacting within a volume where the shower would be visible to the detector were calculated. To then calculate the detector acceptance, showers were generated at rondom along the neutrino path within the interaction region and the fluorescence light propogated to the detector as for our spectrum aperture calculation. These simulated events were then subjected to the same cuts used to define our search. The calculated aperture resulting from this method is shown in Figure 7. Given the running time, and the fact that we saw no events, we can convert this into a limit on the electron neutrin flux. This limit is shown in Figure 8 along with (and combined with) a HiRes search for tau neutrinos. The current Auger[26] and older Fly's Eye[27] are also shown. References for the other shown limits and predictions can be found in the preprint[25] .

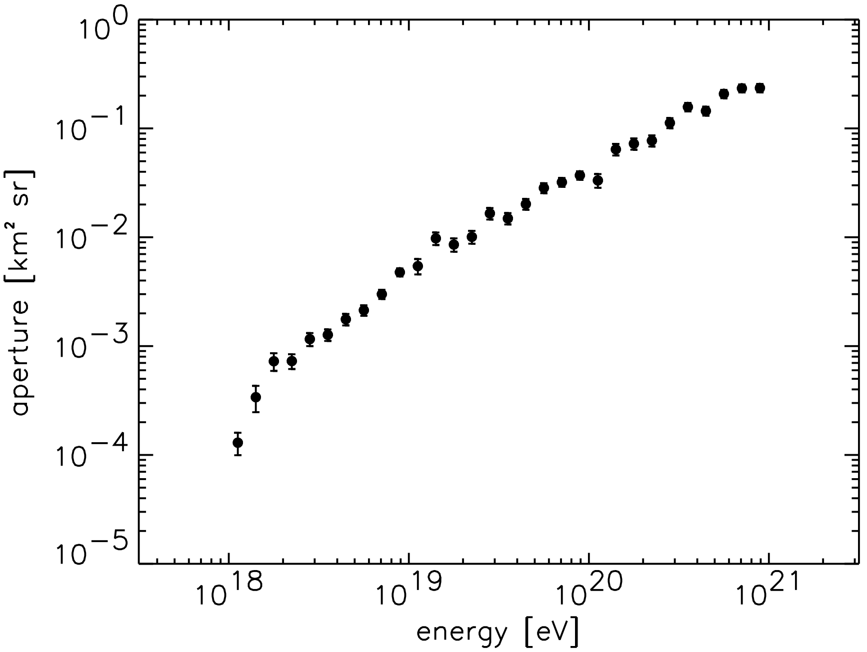

Figure 7: An estimate of the aperture for upward going showers produced by electron neutrinos. The aperture grows rapidly with energy due to the increase in available target mass due to the LPM effect.

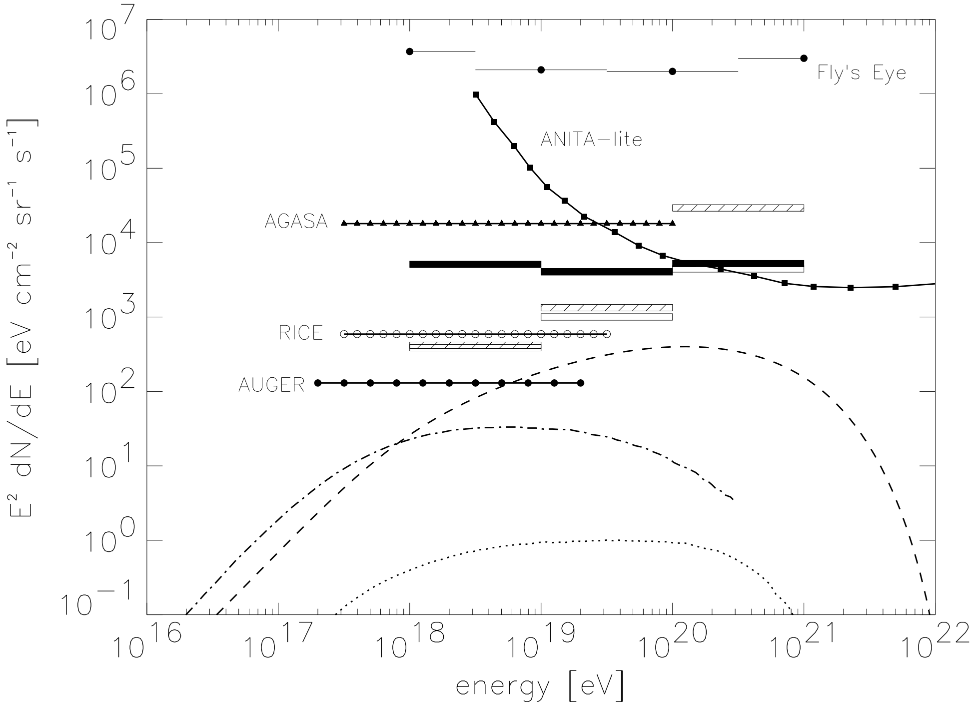

Figure 8: The flux limit for electron neutrinos, integrated over decade bins in energy, is shown as the solid horizontal bars. The HiRes tau-neutrino limit is shown as hatched bars, with the combination shown as open bars. The current Auger limit and the older Fly's Eye electron neutrino limit are also shown.

4 Future Plans: Telescope Array

Since neither the spectrum or the existence of source agree between HiRes and Auger, or one might say between northern and southern hemispheres, it is interesting to know what the future prospects are for determining the source of these discrepancies: are they detector related or due to viewing different parts of the universe. To this end the Auger collaboration hopes to build a detector in the North.

However, long before there is an Auger North detector, the Telescope Array[28] (TA) will answer many of these questions. TA is a hybrid detector (like Auger) combining the fluorescence detectors of HiRes (in some cases equipment take directly from the HiRes sites) with the scintillator based surface detectors of AGASA (though not using the actual AGASA units). It will have an aperture of 1400 km^2 sr, and will thus match the total HiRes exposure in about two years. Most importantly it is already deployed and is currently collecting data!

Acknowledgments

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