Recent Observations of Ultra High Energy Cosmic Rays

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The area of Ultra High Energy Cosmic Rays (UHECER) has been most recently studied by the Akeno Giant Air Shower Array, the High Resolution Fly's Eye, and the Pierre Auger Observatory. Datasets in the UHECR energy range of $10^{17.5}$eV-10^{21}eV are small, of order a few thousand to a few tens of events as energy increases. The three pillars of UHECR research are the energy spectrum, composition, and anisotropy in arrival directions. Due in large part to low statistics, all three pillars are under extensive debate. Motivation for UHECR studies and a discussion of experimental results is presented in this paper.

INTRODUCTION

Ultra High Energy Cosmic Rays (UHECR) are so named because they possess energies at the highest scale of the cosmic ray energy spectrum, of order $10^{17.5}$eV-10^{21}eV. These highly relativistic particles are interesting because they originate from the highest energy sources in the universe and because of a controversy surrounding the Greisen-Zatsepin-Kuzmin (GZK) effect.

The GZK effect is due to relativistic interactions with the Cosmic Microwave Background (CMB) radiation:

$$p^+ + \gamma \rightarrow \Delta^+ \rightarrow p^+ + \pi^0, n^0 + \pi^+. \qquad (1)$$

The GZK effect, also known as the pion production threshold, occurs at $10^{19.8}$eV, which is the energy required to interact with a CMB photon and produce a pion. Equation 1 shows the interaction with an incident proton, but similar interactions exist for a number of primaries: neutrons, nuclei, and photons, among others. Once a cosmic ray exceeds this threshold, the probability of interactions with the CMB dramatically increases, resulting in a short propagation distance in the universe. The farther a super-GZK cosmic ray travels, the more energy it is likely to lose in interactions.

The distance it takes for a super-GZK cosmic ray to become a sub-GZK cosmic ray is of order 10-100 Mpc, roughly the size of our local supercluster of galaxies, a short distance on an astrophysical scale. Thus, sources of cosmic rays possessing super-GZK energy when they arrive at earth must be nearby. The effect of limiting the distance of super-GZK sources results in a theoretically predicted sharp suppression of the energy spectrum of cosmic rays near $10^{19.8}$eV. However, as will be discussed below, experimental verification of the GZK effect is still controversial.

UHECR are also interesting due to their highly-energetic nature. UHECR are at energies far greater than anything producible on earth, making them an excellent testbed for high energy particle physics. As the most energetic particles in the universe, they give insight into the most energetic astrophysical processes in the universe. A number of acceleration mechanisms have been proposed, all of which have yet to be experimentally verified. Most acceleration mechanisms are electromagnetic, requiring the primary cosmic ray to have charge. The most popular acceleration mechanism is via many repeated electromagnetic shocks. The basic principle is that the cosmic rays 'surf' along multiple shocks, being electromagnetically accelerated as each shock front passes. This requires an astrophysical source that produces many highly energetic electromagnet shocks, the most popular of which are active galactic nuclei, or AGN. AGN are super-massive black holes in the centers of galaxies, consuming so much nearby matter that they produce jets of energy streaming from their poles. While the mechanism is poorly understood, it is thought the jets are highly electromagnetic and are prone to shocks as different pieces of matter are consumed. BL-Lacertae objects, a variety of AGN, are particularly interesting as they have highly variable energy output. A wide variety of electromagnetic shock sources are shown in Figure 1. The Hillas plot considers different energies and the resulting confinement radius vs. the magnetic field strength. It shows the possible astrophysical sources that are both large enough and have strong enough magnetic field to accelerate to UHECR energies.

The GZK effect and the need for highly energetic sources make UHECR events rare, occurring at the rate of $1/\text{km}^2$/year-$1/\text{km}^2$/century as energy increases. UHECR detectors thus require a large area of coverage and a substantial period of operation, requiring experiments with large statistics to be built on the ground. The three most recent experiments, also the experiments with the largest datasets, are the Akeno Giant Air Shower Array (AGASA: 1991-2004), the High Resolution Fly's Eye (HiRes: 1994-2006), and the Pierre Auger Observatory (Auger: 2005-present). Despite the large area and time coverage of all three experiments, their datasets range in size from a few thousand to a few tens of events as energy increases. These low statistics make experimental studies a challenge, indeed, there is considerable disagreement between their results.

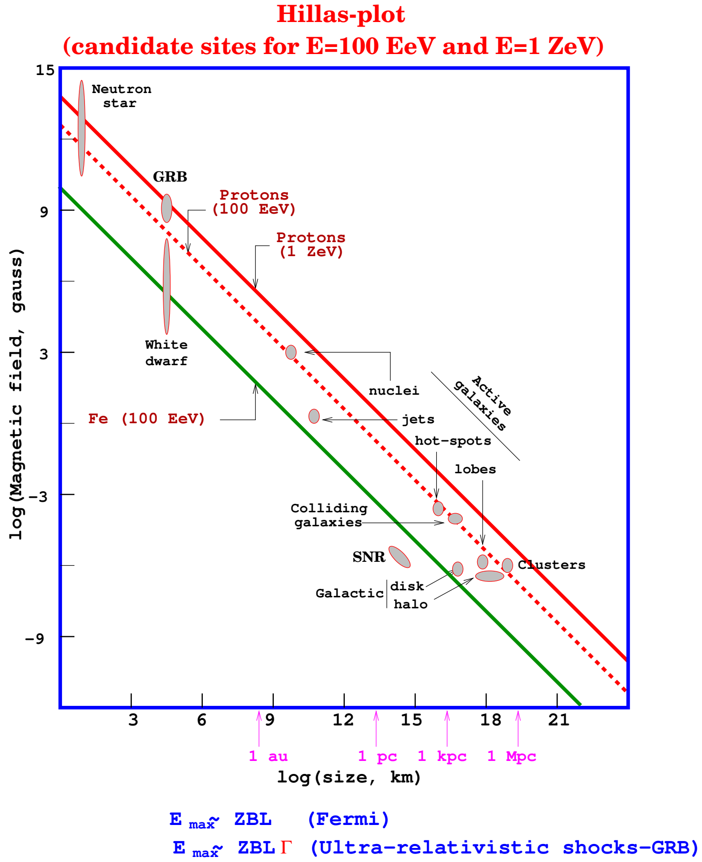

FIG. 1: Potential sources of UHECR. By considering the confinement radius for particles of varying energy and the requisite magnetic fields, different candidates can be considered. The green line shows the required minimum size and magnetic fields to accelerate an iron nucleus to 10^{20}eV, the dashed red for a proton of $10^{20}eV$, and the solid red for a proton of 10^{21}eV. Sources are typically compact and highly magnetic or large and moderately magnetic. GRB stands for gamma-ray bursts, SNR for supernova remnants.

THE THREE EXPERIMENTS

The primary differences between the three experiments are their detection methods. When a UHECR interacts in our atmosphere, it creates a cascade of secondary particles, producing quite lengthy and sizable showers, of order 10km deep by a few tens of km^2 cross-section by the time they reach the ground. The two detection methods for UHECR showers are directly via their footprint or indirectly via the fluorescence of nitrogen excited by the particles in the shower.

AGASA utilized a ground array of scintillator plates, essentially a plastic that emits light when struck by an energetic particle. The light is measured via a photomultiplier tube and is a function of the energy of the particle. A large array of scintillator plates are arranged to detect the piece of the shower which intersect the Earth's surface, the footprint. The plates do not cover the entire area, but can instead be thought of as sampling points, which yield the energy in the footprint when considering the area spanned by the shower footprint and the fractional coverage by the scintillator plates. Additionally, showers which arrive at any angle other than perpendicular to the Earth's surface will trigger the scintillator plates at different times. In other words, as the shower propagates at a fixed velocity in a cone-like shape, different edges of the cone will arrive at the Earth's surface at different times. The footprint geometry and time of arrival of different edges of the shower allow reconstruction of the direction the shower points, presumed to be the initial velocity vector of the UHECR. The shower arrival direction and the energy of the footprint then allow reconstruction of the net energy of the shower using shower development models.

HiRes utilized a ring of photomultiplier tubes, arranged on a hill to look out at the horizon, observing the shower as it develops indirectly through nitrogen fluorescence. Therefore, HiRes, able to observe the shower directly, has better pointing-accuracy than AGASA. However, the relationship between the energy emitted by nitrogen fluorescence and light propagation through the atmosphere is heavily dependent on the weather and shower development models, making HiRes generally less accurate in energy. HiRes must also run on moonless nights, significantly reducing its aperture, although HiRes does have a significantly larger dataset than AGASA. HiRes observation of the shower as it develops also allows HiRes to calculate the shower penetration depth, an important value for composition studies, as will be discussed later.

Because of the many disparities between the experimental results of AGASA and HiRes, Auger was constructed as the first hybrid detector, employing Cherenkov water tanks as a ground array and fluorescence detectors at the same time. Cherenkov water tanks operate on the same principle as scintillator plates except the detection method relies on the particles entering the water tanks and producing light through Cherenkov radiation instead of excitation of the scintillator plastic. Cherenkov radiation, colloquially referred to as a "light-boom," is produced whenever a particle travels faster than the speed of light in that medium - a common occurrence for particles inside UHECR showers once the particles go into water.

THE THREE PILLARS

The three pillars of UHECR research are studies of the energy spectrum, composition, and anisotropies in arrival direction. The energy spectrum has historically received the greatest attention. AGASA claims non-detection of the GZK feature, while HiRes claims detection. Preliminary Auger results indicate detection of the GZK feature.

Composition studies require a large dataset over a large

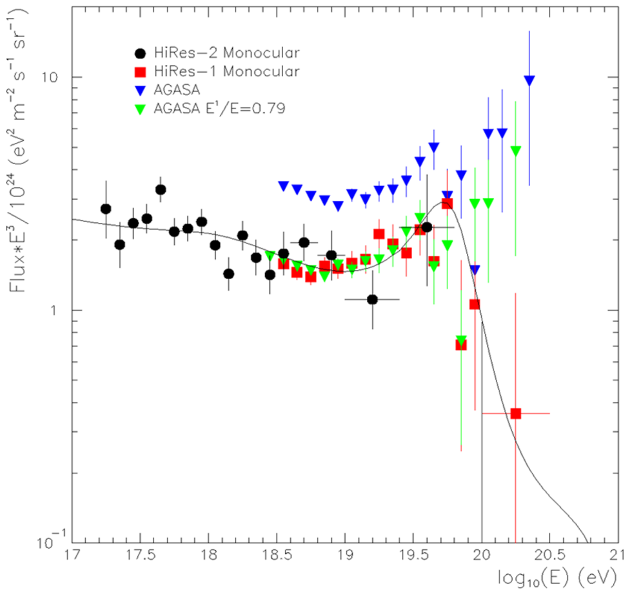

FIG. 2: The UHECR energy spectrum as observed by AGASA and HiRes. Black and red data points are for two HiRes datasets, blue for the published AGASA spectrum, and green for the AGASA spectrum shifted in energy by a factor of roughly 80%. AGASA clearly does not detect the GZK suppression effect, while HiRes clearly does.

range of energy so are rarely performed. HiRes studies indicate a possible composition change from heavy to light, probably from iron nuclei to protons since the acceleration mechanisms for neutral or weakly interacting particles are fairly exotic. The Telescope Array (TA), a detector currently under construction, aims to substantially increase statistics over a tremendous energy range and has the greatest potential to perform composition studies.

Currently, the studies enjoying the most attention are searches for anisotropy. AGASA claims detection of point sources and a galactic dipole, while both Auger and HiRes detect neither.

SPECTRUM

An energy spectrum is a plot of the flux of particles vs. their energy. Naturally, since high energy cosmic rays require high energy sources, they are less common than low energy cosmic rays. However, the energy spectrum of UHECR is particularly interesting due to the GZK effect. Numerous experiments in the mid and late twentieth century detected a flux of super-GZK particles that was apparently too large, resulting in speculation that the GZK effect may not be occurring. In fact, the first experiment with meaningful statistics, AGASA, did not detect the GZK effect [1], as shown in Figure 2.

However, HiRes detected the GZK effect [2, 3], leading to a many year debate. Preliminary studies of the spectrum by Auger [4] also indicate observation of the GZK effect. Auger, among others, has presented evidence that the large disparity in the AGASA and HiRes experimental results is due to a poor shower development model, which had always been the major source of error. Previous shower development models had been extracted from the lower energy interactions of particle cascades in calorimeters. These models could not provide good parameterizations on the effects of much higher energies and weather, both important factors in shower development.

In addition to the GZK effect near $10^{19.8}$eV, there are several other features of note in Figure 2. Just prior to the GZK suppression, a ‘build-up’ of events can be seen, due to super-GZK particles from distant sources interacting with the CMB until reaching sub-GZK levels. The “ankle,” near $10^{18.6}$eV, is due to a phenomenon nearly identical to the GZK feature, except the ankle is from electron pair production instead of pion production. Finally, a feature near $10^{17.8}$eV, known as the “second knee,” has been weakly observed by several experiments. There is no accepted explanation for this feature although there are numerous theories attempting to explain it.

COMPOSITION

Composition is determined via the combination of two effects: (1) higher energy particles penetrate further into the atmosphere before they interact and (2) lower mass particles penetrate further into the atmosphere before they interact. A plot of penetration depth vs. energy will have positive slope due to the first effect. The second effect results in a high mass particle appearing to have low energy because it does not penetrate very far into the atmosphere; iron, with 56 nucleons, produces showers that develop much like a proton with 56 times less energy. Therefore, a high mass particle effectively ‘compresses’ the x-axis (energy), increasing the slope. However, the exact slopes for a light particle, such as a proton, and a heavy particle, such as an iron nuclei, are difficult to calculate without extensive assumptions about the shower development model. Therefore, experimentalists look for a change in the slope to indicate a composition change. A change from a steep (large) slope to a shallow (small) slope would indicate a change from heavy to light particles and vice versa.

Ground detectors are almost completely incapable of measuring penetration depth, requiring observation of the shower as it develops by a fluorescence detector. Since composition studies need data over a large energy range, they are rarely done, but HiRes conducted a study [5] in combination with experimental data from several other detectors, shown in Figure 3.

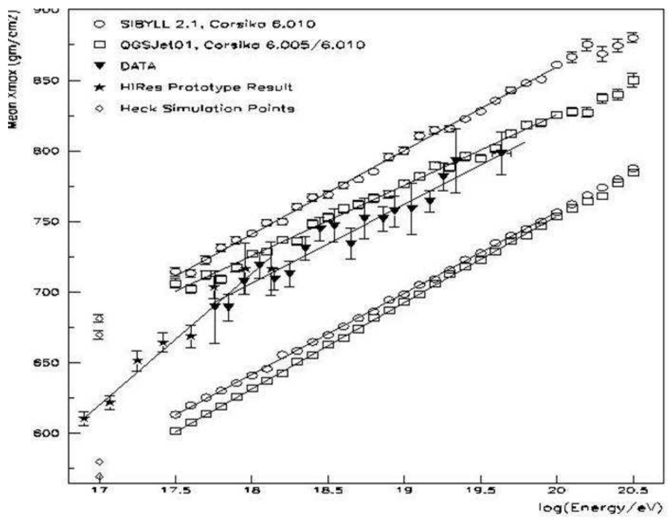

FIG. 3: Penetration depth vs. energy. The always-positive slope is because higher energy particles penetrate further before they interact. The slope change near 10^{18}eV may indicate a composition change from heavy to light particles.

Figure 3 shows the expected positive slopes from higher energy particles penetrating further into the atmosphere. The slope change near 10^{18}eV indicates a possible composition change from heavy to light particles, probably iron nuclei to protons because they have charge and are prevalent in the universe. However, the slope change is over data from completely different experiments, reducing the significance of the result. Extremely preliminary Auger results (probably to be presented at the 2007 International Cosmic Ray Conference) indicate weak agreement with a heavy to light composition change.

ANISOTROPY SEARCHES

Anisotropy searches are a direct attempt to pinpoint the origin of UHECR; unfortunately, a potential source is yet to be confirmed. Anisotropy searches are typically divided into two classes: (1) point source searches and (2) dipole searches. Point source searches are a search for very close clustering of events in the data. Unfortunately, theoretical motivation for point-like clusters is weak because the galactic magnetic field is strong enough to significantly bend the trajectories of all but the highest energy UHECR. Some theories have promoted neutral particles or gaps in the galactic magnetic field, but the primary reason point source searches are performed is because AGASA claimed observation of a point source in their data [6].

While magnetic fields motivate dipole-type searches, the only anisotropy search in this category with a positive result was a search by AGASA for a galactic dipole moment [7]. While a galactic dipole moment is not completely unreasonable – if UHECR come from the galactic center, magnetic bending should cause a surplus in the direction of the galactic center and a deficit opposite the galactic center – the AGN thought to be in the center of our galaxy has jets pointing away from Earth. A galactic source of UHECR would therefore require objects such as neutron stars, which naturally cluster in the direction of the galactic center but are not as favored as AGN as potential sources of UHECR.

Point Source Searches

AGASA claimed observation of five "doublets" and one "triplet" – clustering of events within 2.5° – in events with energy greater than 4×10^{19}eV [6], shown in Figure 4. Monte Carlo simulations predicted 1.7 doublets and when they treat the triplet as three doublets, they calculated a chance probability $< 10^{-4}$, i.e., they claim there is less than .01% probability that the doublets are due to normal statistical fluctuation from isotropy. The .01% false-positive probability is calculated by performing Monte Carlo simulations, generating UHECR datasets with the same exposure and characteristics as the AGASA dataset, but with the arrival directions randomly chosen in a manner which reflects AGASA's exposure. They then count the fraction of Monte Carlo data sets which also had eight doublets (counting triplets as three doublets) and found eight doublets or more in .01% of the Monte Carlo data.

However, independent criticism of the AGASA result [8, 9] claim that AGASA's choice of angular separation and energy, chosen to maximize the signal, results in a statistical penalty, reducing the significance of the AGASA clusters. The critics claim that AGASA should have performed a scan for eight doublets in the Monte Carlo data by varying the criteria for a doublet – just as they varied it for the real data – considering all the possible combinations of angular separation and energy. Statistically speaking, the 'harder' you look for something, the more likely you are to find it from sheer random chance alone; AGASA's claim of .01% false-positive probability does not take into account their implicit scan over many possible combinations of angular separation and energy.

HiRes also looked for point-like clusters in their data [10], using Monte Carlo simulated point-like sources to determine the selection criteria. Figure 5 shows F, calculated for each bin, which is the fraction of neighboring bins within 2.5° with value ξ greater than 4, where ξ is given by

$$\xi = \frac{N_{DATA} - \langle N_{MC} \rangle}{\sigma_{MC}}. \tag{2}$$

N_{DATA} is the density of real events in the bin, $\langle N_{MC} \rangle$ the

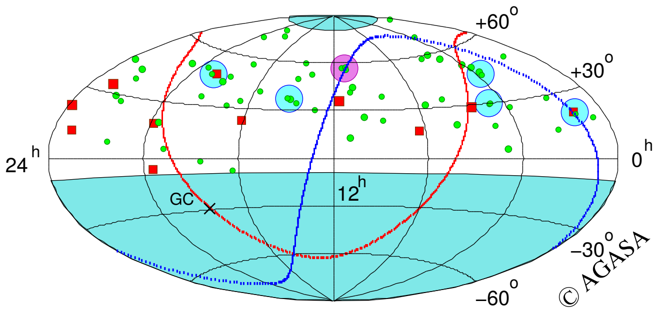

FIG. 4: AGASA events with energy greater than 4×10^{19}eV. The triplet is marked in pink, the five doublets in blue. The galactic plane is shown as the red line, the supergalactic plane in blue.

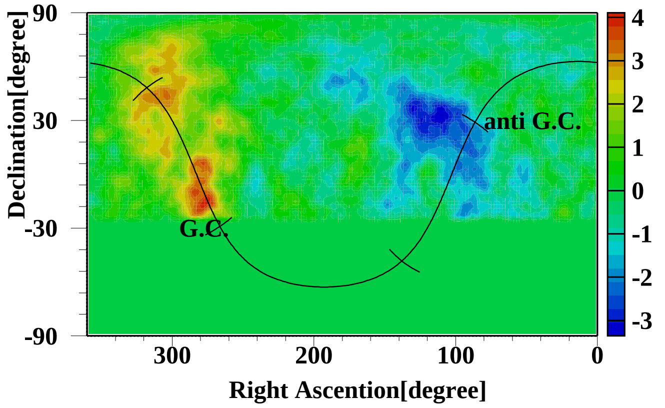

FIG. 6: A significance map of AGASA events. The galactic plane is shown with tick marks 20° from the galactic center and anti-galactic center.

average event density in the bin predicted by Monte Carlo simulation, and σ_{MC} the standard deviation of the event density in the bin predicted by Monte Carlo simulation. The radius of 2.5°, and the ξ minimum value of 4 were tuned on simulated sources, eliminating the statistical penalty of choosing these values to maximize the signal in the real data. The most significant excess in Figure 5 corresponds to an 87% probability of having an equal or larger signal in the Monte Carlo data, making HiRes data consistent with the null hypothesis for point sources.

A preliminary Auger point source study shows data consistent with an isotropic background [11].

Galactic Dipole Searches

AGASA performed a galactic dipole search in their events with energy greater than 10^{18}eV, shown in Figure 6, which clearly shows an excess in the direction of the galactic center and deficit opposite the galactic center. AGASA claimed a signal of approximately 20° radius with chance probability of 0.21% [7].

HiRes also performed a galactic dipole search by calculating the angular separation between the galactic center

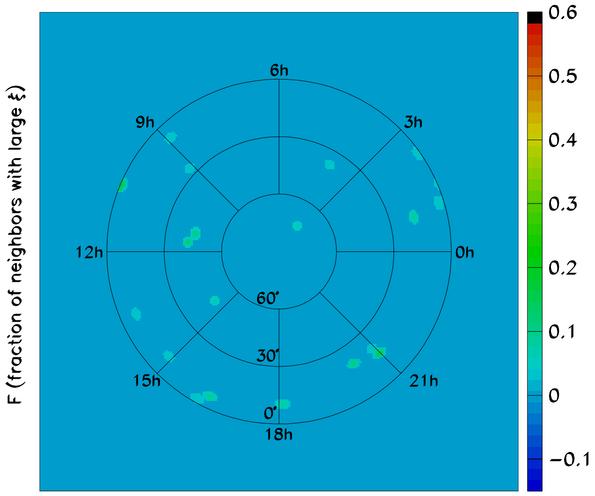

FIG. 5: The distribution of F as a function of position. F is the fraction of bins within 2.5° with value ξ greater than 4.

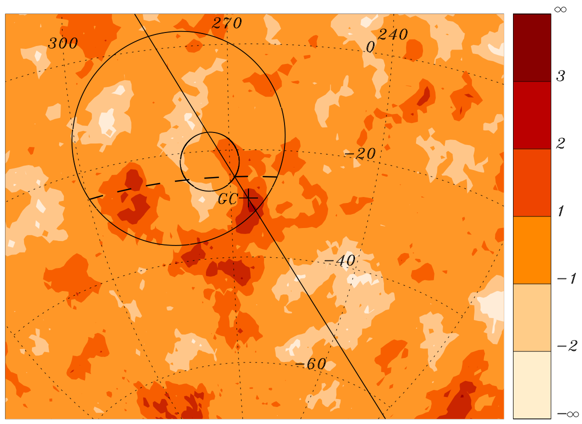

FIG. 7: Auger significance map in the region of the galactic center, marked as a +. The galactic plane is drawn as a line and the excess region measured by AGASA is shown as the larger circle. Another smaller excess, measured by a different experiment, is also shown. The Auger significance map is consistent with isotropy.

and all HiRes events [12]. After correcting for isotropy as predicted by Monte Carlo simulation (HiRes does not have uniform exposure across the sky), a galactic dipole would manifest as a deficit in the distribution near $cos\ \theta = -1$ and a surplus in the distribution near $cos\ \theta = 1$, where θ is the angular separation. No such deficit or surplus was found in the direction of the galactic or anti-galactic centers.

Auger calculated a significance map in the region of the galactic center, shown in Figure 7. While the galactic center does show a slight excess, Auger calculated the same significance map for Monte Carlo data and found the distribution in Figure 7 was consistent with isotropy [13].

SUMMARY

It is clear that a great deal of controversy still surrounds all three pillars of UHECR research. AGASA did not detect the GZK effect, while HiRes and Auger did. However, Auger results point to shower development models and the two different forms of shower detection as the culprit. HiRes weakly observes a transition from heavy to light UHECR, probably from iron nuclei to protons. Further composition studies will require more data over a wide range of energy, which will hopefully be achieved by TA. Finally, isotropy studies by AGASA show a tight clustering of events and a galactic dipole, while HiRes and Auger do not. Future Auger data will significantly help in the effort to find sources of UHECR, particularly at the highest energies.

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