# The Highest Energies in the Universe

H. Rebel

Forschungszentrum Karlsruhe, Institut für Kernphysik, POB. 3640, D-76021 Karlsruhe,
Germany

**Abstract.** There are not many issues of fundamental importance which have induced so many problems for astrophysicists like the question of the origin of cosmic rays. This radiation from the outer space has an energy density comparable with that of the visible starlight or of the microwave background radiation. It is an important feature of our environment with many interesting aspects. A most conspicuous feature is that the energy spectrum of cosmic rays seems to have no natural end, though resonant photopion production with the cosmic microwave background predicts a suppression of extragalactic protons above the so-called Greisen-Zatsepin-Kuz'min cutoff at about $E_{\rm GZK} = 5 \times 10^{19}$ eV. In fact the highest particle energies ever observed on the Earth, stem from observations of Ultrahigh Energy Cosmic Rays ($E > 3 \times 10^{19}$ eV).

But the present observations by the AGASA and HiRes Collaborations, partly a matter of debate, are origin of a number of puzzling questions, where these particles are coming from, by which gigantic acceleration mechanism they could gain such tremendous energies and how they have been able to propagate to our Earth. These questions imply serious problems of the understanding of our Universe. There are several approaches to clarify the mysteries of the highest energies and to base the observations on larger statistical accuracy.

The Pierre Auger Observatory, being in installation in the Pampa Amarilla in the Province Mendoza in Argentina, is a hybrid detector, combining a large array of water Cerenkov detectors (registering charged particles generated in giant extended air showers) with measurements of the fluorescence light produced during the air shower development.

This contribution will illustrate the astrophysical motivation and the current status of the experimental efforts, and sketch the ideas about the origin of these particles.

## 1 Introduction

The rather featureless energy spectrum of primary cosmic rays (CR) comprises more than 12 orders of magnitude in the energy scale (Figure 1). The all-particle spectrum follows an overall power-law $\propto E^{-2.7}$ with a distinct change of the index to $\propto E^{-3}$ around $3 \times 10^{15}$ eV, called the "knee". This feature and other discontinuities are more distinctly displayed, when the flux is multiplied with the power dependence of the flux. The observation is still not consistently explained, though discovered 40 years ago by German Kulikov and George Khristiansen from the Moscow State University [1] with studies of the intensity spectrum of Extensive Air Showers (EAS), of the so-called shower size, which roughly reflects the primary energy. Distinct progress in explaining the knee has been made in the last years by the KASCADE experiment in Karlsruhe [2,3].

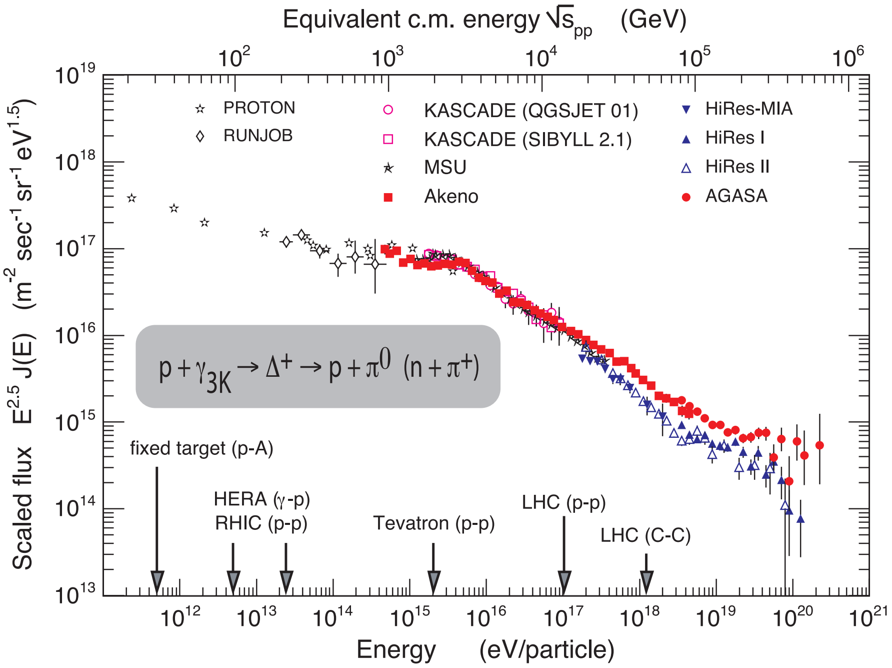

Figure **1.** The all particle energy spectrum of primary cosmic rays determined by different experiments. The difference of the data from the AGASA [6] surface detector array and that from HiRes air fluorescence detectors [7–10] at the highest energies is just a subject of actual experimental interest.

A great deal of interest and current efforts concern the shape of the spectrum in the EeV-region, above $10^{18}$ eV, where the spectrum seems to flatten ("ankle"), especially around $5 \times 10^{19}$ eV. In the mid-1960s Greisen [4] and Zatzepin and Kuz'min [5] realized that the space filling molasses of photons constituting the cosmic wave background (CMB) are limiting the observation of high energy charged particles originating from astrophysical sources. Above $E_{\mathrm{GZK}} \approx 6 \times 10^{19}$ eV the protons experience the CMB photons as $\gamma$-rays of about 300 MeV and photoproduction of pions starts: $p + \gamma_{3K} \rightarrow \Delta \rightarrow p + \pi^0(n + \pi^+)$. Thus the attenuation length of protons drops below 50 Mpc. In case of heavier nuclei photo-disintegration with CMB photons predicts a similar or even stronger attenuation. Hence the apparent horizon of ultrahigh energy (UHE) charged cosmic rays has an extent comparable with our local supercluster and the more distant universe gets relatively opaque for cosmic rays. Accordingly extragalactic charged particles measured on Earth are expected to show the GZK cutoff.

Table 1. Formulation of an enigma.

| |
|---|
| *On one hand they are coming most likely from outside our galaxy as there is no acceleration mechanism known which could produce them. They approach from all directions though a galactic magnetic field is insufficient to bend them.*<br>*On the other hand their source can not be more than 100 million light years away, because the particles otherwise lose energy by the interaction with the universal microwave background, left from the birth of the cosmos in the big bang.*<br>(James W. Cronin) |

In particular, the AGASA experiment in Akeno (Japan) [6], but also other detector installations, seem to indicate that this limit does not exist within the statistical accuracy of the observation.

However the present accuracy of AGASA [6] and HiRes [7–10] observations do not unambiguously confirm or exclude that the GZK suppression exists. This question is an issue of extreme astrophysical interest and exciting cosmological relevance. Something seems to be hurling incredibly energetic particles around the universe. Simultaneously the interaction with CMB photons limits the distances of the sources to some tens of Mpc, to a region where we do hardly find adequate astronomical objects (– may be with few speculative exceptions –) able to accelerate charged particles to such high energies.

This contribution to the 25th International workshop in the Rila Mountains 2006 is particularly focussed to UHE cosmic rays and will sketch some experimental efforts to establish or disprove the indicated features.

## 2 Observations

The research of UHECR has started with John Linsley's observation of an event exceeding the symbolic energy limit of $10^{20}$ eV [11]. The first generation of data around the ankle and above have been provided by a few large-aperture ground based detector arrays (see Table 2) with two types of techniques. Alternatively to particle detector arrays, registering the charge particle components of Extended Air Showers, the observation of the nitrogen fluorescence is applied.

The air fluorescence technique relies on the fact that an ionising particle can excite $N_2$ molecules in the atmosphere, Such excited molecules emit fluorescence photons (typically within 10 ns to 50 ns after excitation: rigorously speaking it is "luminescence"). The optical fluorescence comes from various bands of molecular nitrogen of the molecular nitrogen ion, with light emitted between 3000 Å and 4000 Å, which happens to be the wave band for which the atmosphere is quite transparent. An EAS of $10^{17}$ eV has more than 100 million electrons in the shower maximum, so that there are many fluorescence photons, even with 0.5 % fluorescence efficiency.

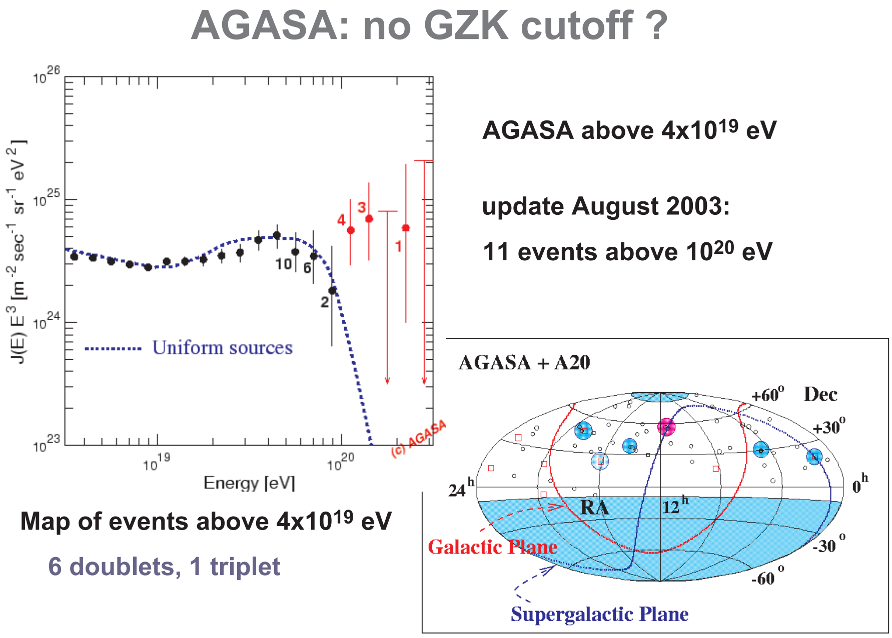

Figure **2.** The quasi-vertical flux of UHECR by AGASA [6]. The spectrum is multiplied by $E^3$. For searching possible sources and assuming that the UHE particles get no more noticeably deflected by the interstellar and intergalactic magnetic fields (within distances defined by the GKZ cutoff) the lower part displays the distribution in the supergalactic plane, missing any tendency within the present statistical accuracy.

The fluorescence light is isotropically emitted and can be detected at large distances from the shower axis. Thus it can be distinguished from air-Cerenkov light which is induced by the fast electrons and is emitted in forward direction, confined to near distances from the shower axis. The problem is to identify the weak light traces quasi from a 100-Watt light bulb, flying some microseconds through the atmosphere in some kilometres distance.

The effective area for recording showers is very large as compared with conventional detector arrays and compensates the low duty cycle resulting from observations only on clear dark moonless nights. There are special techniques used for discrimination against night sky background and terrestial sources of light noise (air planes, lightnings). The fluorescence light (– a flash of a few microseconds of duration –) is collected using a lens or a mirror and imagined to a camera, located in the focal plane. Essentially the camera is an assembly of a large number of photo multipliers, each looking to a certain region of the sky. The camera pixelizes the image and records the time interval of the light arrival in each pixel element.

The detector (Figure 4) comprises a large area spherical mirror telescope of 11 m$^2$ collecting area of aluminium segments, assembled with a correcting lens (Schmidt-optics), covering a field of 30° × 30°.

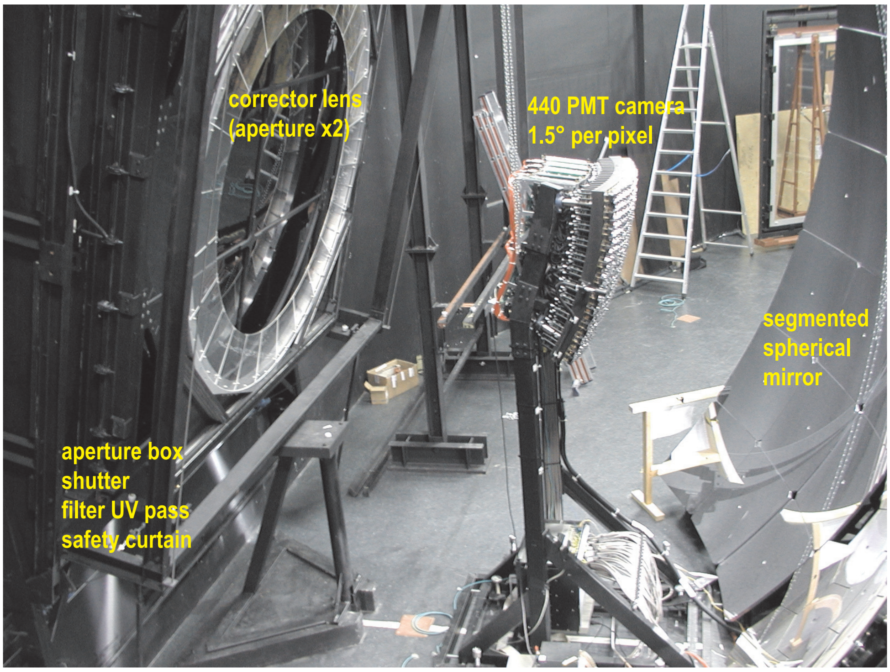

Figure **3.** Fluorescence detector telescope setups in the Forschungszentrum Karlsruhe and installed at the Pierre Auger Observatory (PAO) in Argentina for studying CR of the highest energies.

The camera is an assembly of 20 × 22 photomultipliers in the focus. The light trace is stored by a digital film in 100 ns time distances. From such traces together with the timing information or more accurately by a stereoscopic procedure using

Table **2.** Compilation of some detector arrays for the first generation of UHECR data. For more details about such an array and observation techniques see [12].

| ARRAY | LOCATION | AREA | DETECTORS |
|---|---|---|---|
| Haverah Park | England | 11 km$^2$ | Water Cerenkov tanks |
| Yakutsk | Russia | 10 km$^2$ | Scintillation counters<br>Atmospheric Cerenkov det.<br>Muon detectors |
| SUGAR | Australia | 60 km$^2$ | Muon detectors |
| AGASA | Japan | 100 km$^2$ | Scintillation counters<br>Muon detectors |
| Volcano Ranch | New Mexico | 8 km$^2$ | Scintillation counters |
| Fly‘s Eye | Utah (USA) | | Air fluorescence detector |
| HiRes | Utah (USA) | | Air fluorescence detector |

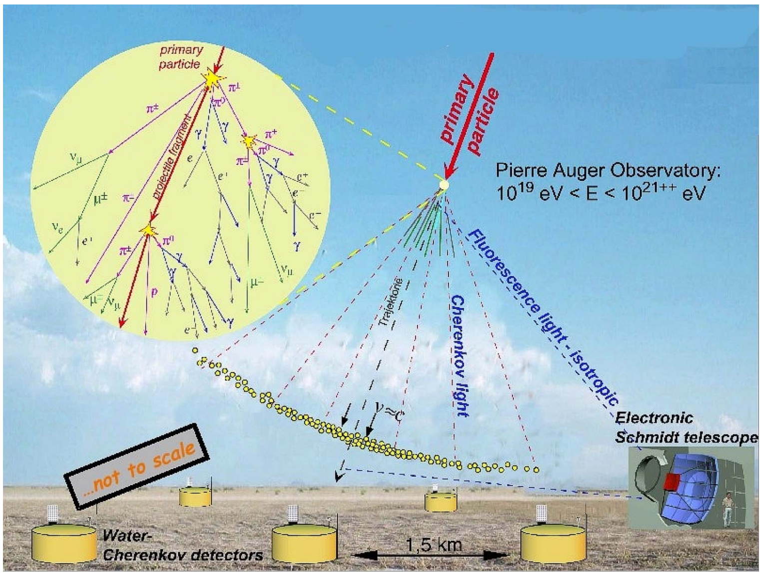

Figure **4.** Schematic layout of a hybrid detector installation, combining a surface detector array (water Cerenkov detectors) with air fluorescence telescopes, built up for the Pierre Auger observatory [13].

two telescopes, the longitudinal development of the extended air shower in the atmosphere can be well reconstructed.

This fluorescence observation technique has been developed and efficiently used by the Fly's Eye detectors [7] installed in Dugway, Utah, 160 km from Salt Lake City, US. The modernised version of the Fly's Eye are the HiRes detectors for studying CR of the highest energies.

The UHECR flux estimates derived from the AGASA [6] and HiRes [8–10] show qualitative differences. While AGASA reports an excess of eleven trans-GZK events, the reanalysed HiREs data tend to support the existence of the GZK cutoff. However, the significance of the differences is small due to lack of statistical accuracy and large systematic errors in the energy calibration. In addition the chemical composition of the UHECR is not clarified. This is one of the goals of the next generation of detectors (PAO [13], in particular).

## 3 The Next and Over-Next Generation of Detectors

The next detector is the Pierre Auger observatory [13] with $14.000\ \text{km}^2$ sr aperture over two sites (30 times the size of Paris), one in each hemisphere. The installation of the southern observatory has started in 2000 with a prototype array of $55\ \text{km}^2$ and an air fluorescence telescope, near the small town of Malargüe in the province of Mendoza, Argentina. In fine the site will be equipped with 1600 detector stations

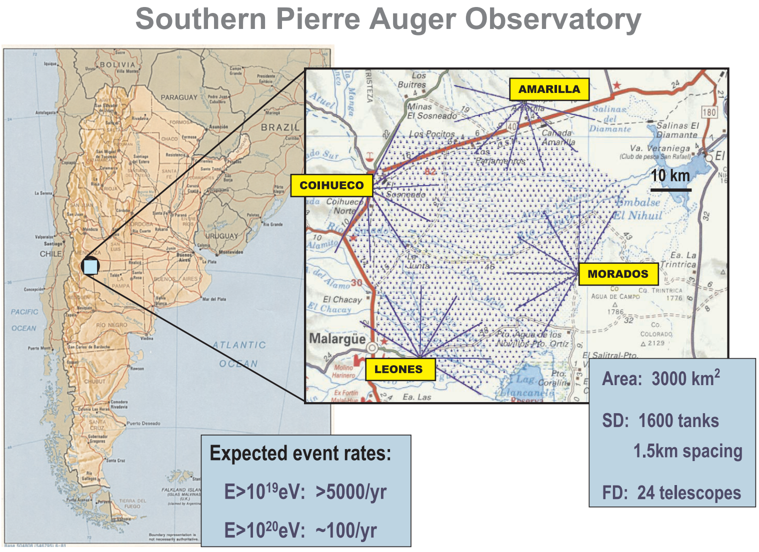

Figure **5.** Scheme of the southern observatory.

(12 m$^3$ tanks filled with water detecting Cerenkov light produced by secondary particles), distributed in a grid with 1.5 km spacing.

Table **3.** Actual questions of interest of current UHECR investigations.

| WHAT ARE THE FOCAL POINTS OF CURRENT STUDIES OF EXTREME ENERGY COSMIC RAYS? |
|---|
| The change of the spectral index at the "ankle".<br>Change of the production mechanism?<br>Change in elemental composition?<br>Change of the interaction processes? |
| Evidence for the existence of CRs with energies $>$ 100 EeV. |
| What is the maximum CR energy, if there is any limit at all? |

Four "eyes" composed of 24 air fluorescence telescopes will view 3000 km$^2$ of the site and measure during clear moonless nights i.e. with a duty cycle of 10 % the giant showers through the fluorescence generated in air. The hybrid detection techniques provides unique advantages. A subsample of 10 % of the total number of events simultaneously observed with both techniques, enables a cross calibration and yield an unprecetended quality for shower identification.

The Pierre Auger Observatory had just started by a collaboration of 19 contributing countries, and the community looks already forward to the next generation of detectors. There is less doubt that this will be an air-borne detector observing the giant shower development in the atmosphere with a huge aperture quasi "from above". This is envisaged e.g. with the EUSO project [14]: fluorescence detectors installed on the International Space Station.

## 4 Some Remarks about Speculations and Models for the Origin of UHECR

The UHECR events (if finally confirmed) constitute a mystery, when we put the question: Where are the sites and what are the acceleration mechanisms being capable to impart energies of macroscopic orders (in the most energetic case of $3 \times 10^{20}$ eV: 50 joules) to a microscopic particle. For that many scenarios have been proposed, where in an astrophysical plasma of large scale macroscopic motion is transferred to individual particles, for example in a turbulence and by shock waves. These constitute the traditional bottom-up models. The crucial role plays the size of the acceleration region and the magnetic field embedded in the plasma and keeping the gyroradius of the particle in the acceleration region. That depends from the velocity $\beta$ of the motion. Along this idea different astronomical objects may be ordered along their capability to accelerate charged particles to a certain energy (Hillas-Plot [15]). In this zero-order sketch synchotron losses or the interaction with the microwave background are neglected.

Table **4.** Some theoretical scenarios for the origin of UHECR.

| THEORETICAL SCENARIOS: |
|---|
| I. Traditional Astrophysics: Bottom - up. The magnetic field must be strong enough to keep the particles within the region of the acceleration: $R_{\text{acc}} \geq R_{\text{gyro}} \approx E/(ZeB) \rightarrow$ Hillas Plot. |
| II. Top-down Models: Decay of X-particles from topological defects. |
| III. Scenarios beyond the Standard Model: Z-bursts – Strongly interacting neutrinos – Stable neutral particles. |
| IV. Lorentz invariance violation. |

However if all parameters related to the question are taken into account, one has fairly to admit that none of the proposed scenarios seems to be fully convincing. In addition that the sources should be situated nearby in cosmological scales. Within the present statistical accuracy the data do also not show a distinct correlation with nearby point sources. There are only few acceleration sites inside the GZK radius for charged hadrons. As potential candidate the radio galaxy M87 in the Virgo cluster (about 20 Mpc away) e.g. has been reported [16].

On the other side if future studies would exclude “conventional” astrophysical acceleration mechanisms, one would need to consider another class of theories proposed as possible explanation, so-called “top-down” processes. Most of those scenarios study the possibility that UHECR arise from decay of some super-heavy X particle whose mass is in the Grand Unification range ($10^{25}$ eV) produced during a phase transition period of the early Universe. Thus hypothetical objects can be thought, in a sense, as infinitesimal pockets preserving bits of the universe as it existed in some fractional instants after big bang. When these pockets collapse, supermasive X-particles are created, decaying afterwards in the highest energy cosmic rays. Models of this type differ mainly, how to produce the density of X-particles to fit the actual UHECR observations and in their survival in some $10^{-35}$ s after Big Bang. Additionally there are a number of different scenarios which are based on physics beyond the standard model: Z-bursts and strongly interacting neutrinos.

An appealing possibility is the so-called Z-burst scenario [17], in which a large fraction of these cosmic rays are decay products of Z bosons produced in the scattering of ultrahigh energy neutrinos (having a finite mass) on cosmological relic neutrinos. The comparison between the observed and predicted spectra constrains the mass of the heaviest neutrino. The required neutrino mass is fairly robust against variations of the presently unknown quantities, such as the amount of relic neutrino clustering, the universal photon radio background and the extragalactic magnetic field. The most plausible case that the ordinary cosmic rays are of extragalactic origin and the universal radio background is strong enough to suppress high energy photons, the required neutrino mass is $0.08$ eV$< m_\nu < 0.40$ eV. The required ultrahigh energy neutrino flux should be measured in the near future by several current experiments. The problem of energy loss of CR during propagation would not arise if the trans-GZK primaries were neutrinos, interacting strongly at very high energies and inducing proton-like showers. In this case the cosmogenic neutrino flux( secondaries from photopion production of extremely high energy protons from far distant sources) could account for the trans-GZK events [18]. Details depend on energetic set in of the strong interaction of the neutrinos.

A most general proposal is to assume that Lorentz invariance is violated at sufficiently high energies. This idea is in fact not new and would evidently relax some problems of the existence of trans-GZK cosmic ray, also of another paradox: that 20 TeV gamma rays from Mk 501 e.g. reach the Earth (in spite of absorption due to interaction with the extragalactic infrared background). The most popular scenario [19] invokes a scheme which assigns Lorentz invariance violation by different maximal speeds to different particles species, none of them or some of them being equal to what is known to be the speed of light in vacuo. In other words: modifying the energy-momentum relation. In this way, the rate of pair production by photons or the threshold and rate of photo production of pions can be suppressed by a rather small amount of Lorentz invariance violation. Actually a violation of Lorentz invariance as an explanation of the trans-GZK events cannot be ruled out presently.

## 5 Concluding Remarks

The different models and speculations about the origin of the UHECRs show specific features and possible experimental signatures by the predicted shape of the energy spectrum and by the mass composition.

The lesson of the advanced studies [3] of the knee region at lower energies is, that the investigation of the far-reaching astrophysical aspects by EAS observations has to be accompanied by a serious and quantitative understanding of the hadronic interactions of these particles in the atmosphere of the Earth in the studied energy range. That is the other side of the medal of all necessary efforts! Without that, even the energy determination of EAS and the scale of the spectrum may remain finally under debate! As indicated, such a debate got some impact when the HiRes collaboration had presented a new calibration inducing doubts on the non-existence of GZK-cutoff. In the moment the current status of PAO is shown by a result (Figure 6) shown at the last International Conference on Cosmic Rays [20]. Though it tends to support the recalibrated HiRes results for the moment, any conclusion needs improved statistical accuracy!

We may characterize the actual general status by the statement: The most remarkable feature of the cosmic radiation is that the investigators have not yet found

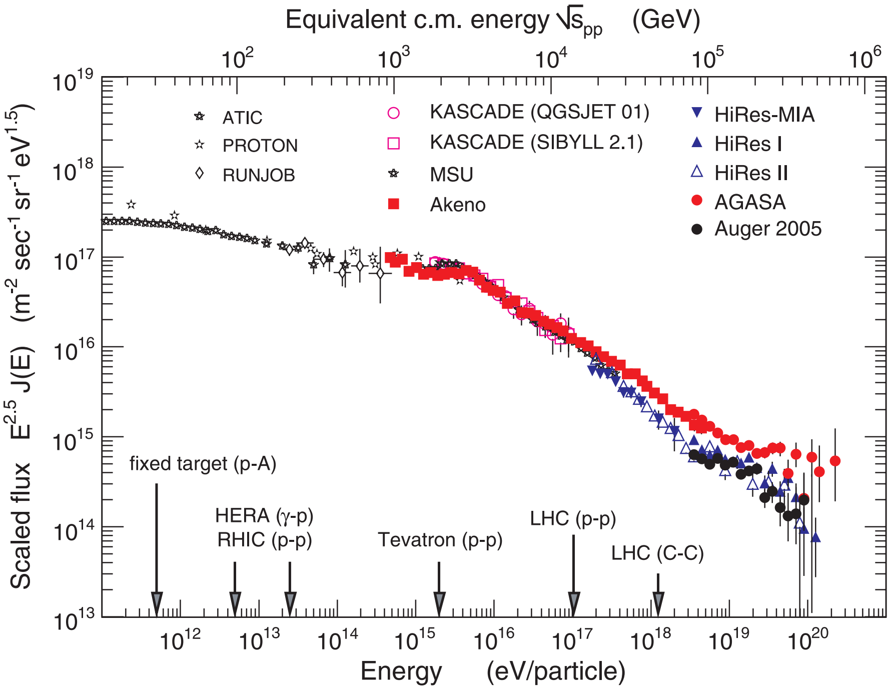

Figure **6.** Energy spectrum of primary cosmic rays including the preliminary results [20] of the Pierre-Auger Observatory.

a natural end of the energy spectrum, albeit with decreasing intensity. We do not know the cosmic source of such a radiation, and the features of origin establish a mystery of great cosmological relevance at the frontier of natural science.

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