COSMIC RAYS AT THE HIGHEST ENERGIES: RESULTS FROM THE PIERRE AUGER OBSERVATORY

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Abstract

The Pierre Auger Observatory has been designed to measure the most energetic particles in nature. It is located on a plateau in the Province of Mendoza, Argentina, and covers an area of 3000 km^2. The construction is nearing completion and almost 1600 water Cherenkov detectors positioned on a 1.5 km hexagonal grid combined with 24 large area fluorescence telescopes erected at the perimeter of the array continuously take data. After briefly sketching the design of the observatory, we shall discuss selected first results covering (i) the energy spectrum of cosmic rays with the observation of a flux suppression starting at the GZK energy-threshold, (ii) upper limits of the photon and neutrino flux, and (iii) studies of anisotropies in the arrival direction of cosmic rays including the observation of directional correlations to nearby AGNs.

1 Introduction

Understanding the origin of the highest energy cosmic rays is one of the most pressing questions of astroparticle physics. Cosmic rays (CR) with energies exceeding 10^{20} eV have been observed for more than 40 years (see e.g. [1]) but due to their low flux only some ten events of such high energies could be detected up to recently. There are no generally accepted source candidates known to be able to produce particles of such extreme energies. An excellent review, published by Michael Hillas more than 20 years ago, presented the basic requirements for particle acceleration to energies $\geq 10^{19}$ eV by astrophysical objects [3]. The requirements are not easily met, which has stimulated the production of a large number of creative papers. Moreover, there should be a steeping in the energy spectrum near 10^{20} eV due to the interaction of cosmic rays with the microwave background radiation (CMB). This Greisen-Zatsepin-Kuzmin (GZK) effect [2] severely limits the horizon from which particles in excess of $\sim 6 \cdot 10^{19}$ eV can be observed. For example, the sources of protons observed with $E \geq 10^{20}$ eV need to be within a distance of less than 50 Mpc [4]. The non-observation of the GZK-effect in the data of the AGASA experiment [5] has motivated an enormous number of theoretical and phenomenological models trying to explain the absence of the GZK-effect and has stimulated the field as a whole.

Besides astrophysics, there is also a particle physics interest in studying this energy regime. This is because CRs give access to elementary interactions at energies much higher than man-made accelerators can reach in foreseeable future. This opens opportunities to both measuring particle interactions (e.g. proton-nucleus, nucleus-nucleus, γ-nucleus, and ν-nucleus interactions) at extreme energies as well as to probe fundamental physics, such as the smoothness of space or the validity of Lorentz invariance in yet unexplored domains.

After decades of very slow progress because of lack of high statistics and high quality data, the situation has changed considerably during the last year. This is mostly due to the advent of the hybrid data from the Pierre Auger Observatory (PAO). Both, the HiRes and the Pierre Auger experiments have reported a flux suppression as expected from the GZK-effect [6, 7]. The very recent breaking news about the observation of directional correlations of the most energetic Pierre Auger events with the positions of nearby AGN [8] complements the observation of the GZK effect very nicely and provides evidence for an astrophysical origin of the most energetic cosmic rays. Another key observable allowing one to discriminate different models about the origin of high-energy cosmic rays is given by the mass composition of CRs. Unfortunately, the interpretation of such data is much more difficult due to the strong dependence on hadronic interaction models. Only primary photons and neutrinos can be discriminated safely from protons and nuclei and recent upper limits to their fluxes largely rule out top-down models, originally invented to explain the apparent absence of the GZK-effect in AGASA data.

2 The Pierre Auger Observatory

The two most important design criteria for the Pierre Auger Observatory were to achieve a sufficiently large aperture at $E \gtrsim 10^{19}\,\mathrm{eV}$ so that the answer about the existence of the GZK-effect could already be given within the first years of operation, and to measure CR induced air showers simultaneously by two independent observation techniques in order to better control systematic uncertainties in the event reconstruction. This is called the *hybrid* approach. Another important objective was to achieve a uniform full sky-coverage to allow studying global anisotropies of CRs and correlations with matter concentrations in the nearby Universe. This is planned to be realized by one observatory each on the southern and northern hemisphere. Because of funding constraints, the Pierre Auger Collaboration decided to start constructing the southern site first with the northern one to follow as soon as possible.

The first of the two design criteria asked for a detector area of $\gtrsim 3000\,\mathrm{km}^2$ in order to collect about one event per week and site above 10^{20} eV, depending on the extrapolation of the flux above the GZK threshold. The most cost-effective hybrid approach was found to be a combination of an array of surface detectors (SD) of water Cherenkov tanks, operating 24 hours a day and a set of air fluorescence detectors (FD) observing the light emission of extensive air showers above the array in clear moonless nights.

The ground array at the southern site comprises 1600 cylindrical water Cherenkov tanks of 10 m^2 surface area and 1.2 m height working autonomously by solar power and communicating the fully digitized data by radio links. The tanks are arranged on a hexagonal grid with a spacing of 1.5 km yielding full efficiency for extensive air shower (EAS) detection above $\sim 5{\cdot}10^{18}$ eV. Presently (May 2008), about 1580 tanks are in operation and taking data.

Charged particles propagating through the atmosphere excite nitrogen molecules causing the emission of (mostly) ultraviolet light. The fluorescence yield is very low, approx. four photons per meter of electron track (see e.g. [9]), but can be measured with large area imaging telescopes during clear new- to half-moon nights (duty cycle of $\approx$ 10-15 %). The fluorescence detector of the southern site comprises 24 telescopes arranged into four 'eyes' located at the perimeter of the ground array. Each eye houses six Schmidt telescopes with a $30^\circ \times 30^\circ$ field of view (f.o.v.). Thus, the 6 telescopes of an eye provide a 180° view towards the array center and they look upwards from 1° to 31° above the horizon. All 24 telescopes are in operation and taking data.

The layout of the southern site and its current status is depicted in Fig. 1.

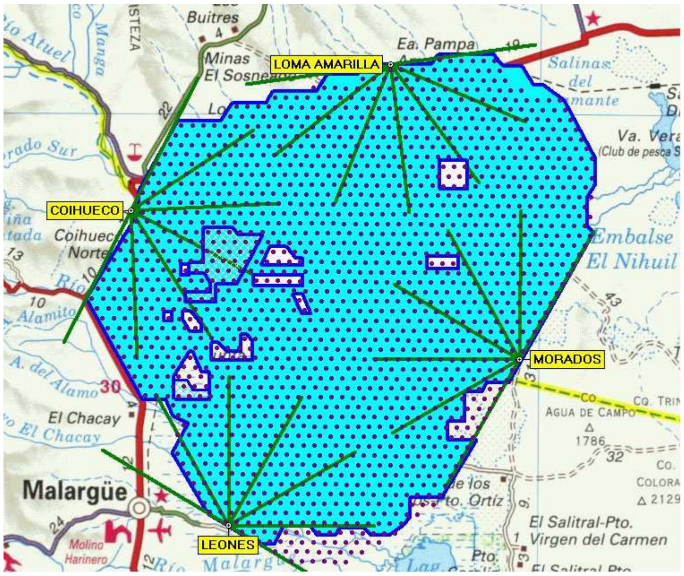

Figure 1: *Layout of the southern site with the locations of the surface detector tanks indicated. Also shown are the locations of the flourescence-eyes with the f.o.v. of their telescopes. The blue region indicates the part of the ground array currently in operation (May 2008). Furthermore, all 24 telescopes distributed over the four sites Los Leones, Coihueco, and Loma Amarilla and Los Morados are in operation.*

It shows the locations of the four eyes and of the water tanks already in operation. Further details about the experiment and its performance can be found in Refs. [10, 11]. Nearing completion of the southern site, the collaboration has selected southeast Colorado to site the northern detector and started to perform related R&D work.

3 The Energy Spectrum

A very important step towards unveiling the origin of the sources of UHECR is provided by measurements of the CR energy spectrum. The *ankle* observed at $E \simeq 4 \cdot 10^{18}$ eV is believed to be either due to the onset of an extragalactic CR component or due to energy losses of extragalactic protons by e^+e^- pair production in the CMB [12]. At energies $E \simeq 6 \cdot 10^{19}$ eV the the GZK-effect [2] is expected due to photo-pion production of extragalactic protons in the CMB.

Recent measurements of the CR energy spectrum by AGASA and HiRes

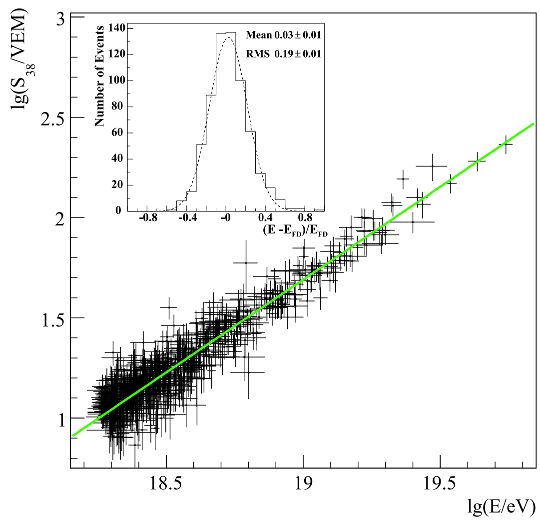

Figure 2: *Correlation between lg* S_{38° *and lg* E_{FD} *for hybrid events. The full line is the best fit to the data. The fractional difference between the FD and SD energies is shown in the inset* [7].

have yielded results which differ in their shape and overall flux [13]. This may be explained by the fact that the energy determination of CR particles by ground arrays like AGASA relies entirely on EAS simulations with their uncertainties originating from the limiting knowledge of hadronic interactions at the highest energies (total inelastic cross sections, particle multiplicities, inelasticities, etc.). SENECA simulations [14] have shown that the muon density at ground predicted by different hadronic interaction models differ by up to 30 %. Fluorescence telescopes, such as operated by HiRes and the PAO, observe the (almost) full longitudinal shower development in the atmosphere. In this way, the atmosphere is employed as a homogenous calorimeter with an absorber thickness of 30 radiation lengths or 11 hadronic interaction lengths. Corrections for (model dependent) energy 'leakage' into ground - mostly by muons and neutrinos - are below 10 % and their uncertainties are only a few percent. As a consequence, fluorescence detectors provide an energy measurement which is basically independent from hadronic interaction models. Uncertainties in the energy scale arise most dominantly from the fluorescence yield in the atmosphere. Several measurements have been performed in the past, e.g. the Auger Collaboration uses the fluorescence yield by Nagano et al. [15] and HiRes by Kakimoto et al. [9]. Major efforts have been started to remeasure the fluorescence yield as

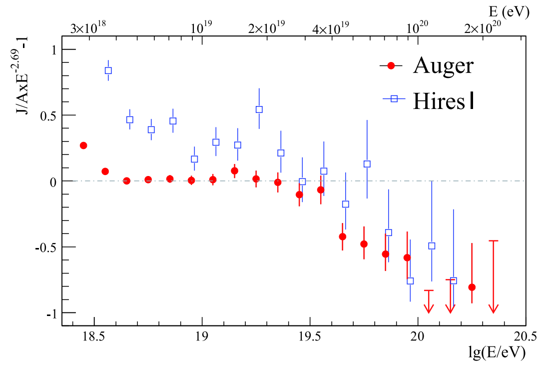

Figure 3: *Fractional difference between the derived energy spectrum and an assumed flux* $\propto E^{-2.69}$ *as a function of energy* [7].

a function of temperature, pressure and humidity with high precision [16] in order to reduce this source of uncertainty.

Taking benefit of the Auger hybrid detector, the Auger Collaboration has used a clean set of hybrid data, in which EAS have been detected simultaneously by at least one florescence eye and the ground array, to calibrate the observatory. This is shown in Fig. 2, where the shower size parameter $S(1000)$ extracted from lateral particle density distribution of EAS at a distance of 1000 m (and normalized to zenith angles of 38°) is plotted versus the CR energy determined from the fluorescence telescopes. The straight line represents the fitted calibration relation which is applied to the much larger data set of the ground array. The 19 % rms value shown in the inset of the figure is found to be in good agreement to the quadratic sum of the S_{38° and E_{FD} uncertainties.

The resulting energy spectrum based on $\sim 20\,000$ events is displayed in Fig. 3. To enhance the visibility of the spectral shape, the fractional difference of the measured flux with respect to an assumed flux $\propto E^{-2.69}$ is shown. The suppression of the flux above $\sim 5 \cdot 10^{19}$ eV and the ankle at $E \simeq 4 \cdot 10^{18}$ eV are evident. Data from HiRes-I [6] are also shown. In the region where our index is measured as -2.69, the HiRes data indicate a softer spectrum.

Using different statistical approaches, a significance for flux suppression at a level of more than 6 standard deviations can be derived from the Auger data [7]. The observation of the GZK-effect 40 years after its prediction provides for the first time evidence for an extragalactic origin of EHECRs. Of course, this interpretation is challenged if the sources would happen to run out of acceleration power just at the value of the GZK threshold. However, this would be a strange coincidence and in fact is not supported by Pierre Auger

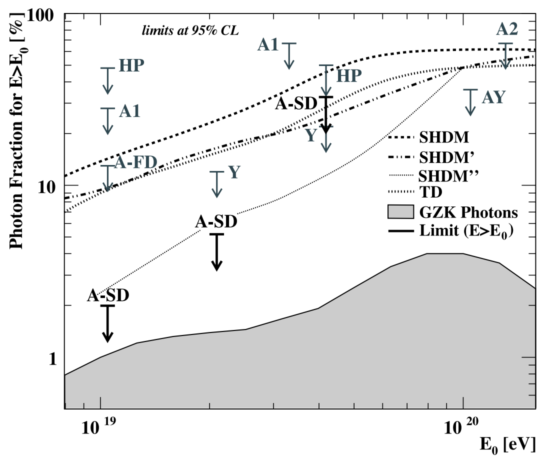

Figure 4: Upper limits on the fraction of photons in the integral CR flux compared to predictions. The lower curve is for a subdominant SHDM contribution [17]. For other references see [18].

data (see Sect. 5).

4 Photon and Neutrino Limits

Primary photons can experimentally be well separated from primary hadrons as they penetrate deeper into the atmosphere, particularly at energies above 10^{18} eV. Their EAS development is also much less affected by uncertainties of hadronic interaction models due to the dominant electromagnetic shower component. They are of interest for several reasons: top-down models, invented to explain the apparent absence of the GZK-effect in AGASA data, predict a substantial photon flux at high energies [19]. In the presence of a GZK effect, UHE photons can also act as tracers of the GZK process and provide relevant information about the sources and propagation. Moreover, they can be used to obtain input to fundamental physics and UHE photons could be used to perform EHE astronomy.

Experimentally, photon showers can be identified by their longitudinal shower profile, most importantly by their deep X_{max} position and low muon numbers. Up to now, only upper limits could be derived from various experiments, either expressed in terms of the photon fraction or the photon flux. Figure 4 presents a compilation of present results on the photon fraction. The most stringent limits are provided by the Auger surface detector [18]. Current top-down models appear to be ruled out by the current bounds. This result can be considered an independent confirmation of the GZK-effect seen in the energy spectrum. The lowest model curve in figure 4 represents most recent SHDM calculations [17] which are still compatible with the Auger energy spectrum and current photon limits. However, the contribution would have to be subdominant and the decaying mass $M_X > 10^{23}$ eV. In future measurements and after several years of data taking it will be very exciting to possibly touch the flux levels expected for GZK-photons ($p + \gamma_{CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma$).

The detection of UHE cosmic neutrinos is another long standing experimental challenge. All models of UHECR origin predict neutrinos from the decay of pions and kaons produced in hadronic interactions either at the sources or during propagation in background fields. Similarly to GZK-photons one also expects GZK-neutrinos, generally called 'cosmogenic neutrinos'. Moreover, top-down models predict dominantly neutrinos at UHE energies. Even though neutrino flavors are produced at different abundances, e.g. a 1:2 ratio of ν_e:ν_μ results from pion decay, neutrino oscillations during propagation will lead to equal numbers of ν_e, ν_μ, and ν_τ at Earth. At energies above 10^{15} eV, neutrinos are absorbed within the Earth so that upgoing neutrino induced showers cannot be detected anymore. Only tau neutrinos entering the Earth just below the horizon (Earth-skimming) can undergo charged-current interactions to produce τ leptons which then can travel several tens of kilometers in the Earth and emerge into the atmosphere to eventually decay in flight producing a nearly horizontal air shower above the detector. Such showers can be searched for in ground arrays and fluorescence detectors. The absence of any candidates observed in the detectors has been used to place upper limits on diffuse neutrino fluxes. As can be seen from Fig. 5, AMANDA and the PAO provide at present the best upper limits up to energies of about 10^{19} eV and, similarly to the photons discussed above, they already constrain top-down models and are expected to reach the level of cosmogenic neutrinos after several years of data taking.

5 Arrival Directions and Correlations with AGN

Recently, the Pierre Auger Collaboration reported the observation of a correlation between the arrival directions of the highest energy CRs and the positions of nearby AGN from the Véron-Cetty - Véron catalogue at a confidence level of more than 99 % [8, 22]. Since several claims about seeing clustering of EHECRs were already made in the past with none of them being confirmed by independent data sets, the Auger group has performed an 'exploratory' scan of parameters using an initial data-set and applied these parameters to a new independent data-set for confirmation. With the parameters specified *a priori* the analysis avoids the application of penalty factors which otherwise would need to be applied for in *a posteriori* searches. The correlation has maximum

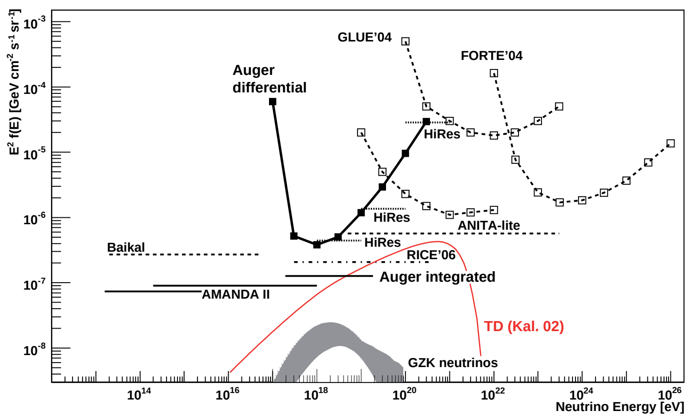

Figure 5: Limits at the 90 % C.L. for a diffuse flux of ν_τ assuming a 1:1:1 ratio of the 3 neutrino flavors ([20] and references therein) and predictions for a top-down model [21] (Taken from [13]).

significance for CRs with energies greater than $5.7 \cdot 10^{19}$ eV and AGN at a distance less than ~ 71 Mpc. At this energy threshold, 20 of the 27 events in the full data set correlate within 3.2° with positions of nearby AGNs.

Observing such kind of anisotropy can be considered the first evidence for an extragalactic origin of the most energetic CRs because none of any models of galactic origin even when including a very large halo would result in an anisotropy such as observed in the data. Besides this, the correlation parameters itself are highly interesting as the energy threshold at which the correlation becomes maximized matches the energy at which the energy spectrum shows the GZK feature (~ 50 % flux suppression), i.e. CRs observed above this threshold - irrespective of their masses - need to originate from within the GZK-horizon of $\sim$ 100-200 Mpc. This number again matches (within a factor of two) the maximum distance for which the correlation is observed. Thus, the set of the two parameters suggests that the suppression in the energy spectrum is indeed due to the GZK-effect, rather than to a limited energy of the accelerators. Thereby, the GZK-effect acts as an effective filter to nearby sources and minimizes effects from extragalactic magnetic field deflections. On top of this, it is also the large magnetic rigidity which helps to open up the window for performing charged particle astronomy.

The correlation may tell us also about the strength of galactic and extragalactic magnetic fields. The galactic fields are reasonably well known and one expects strong deflections for particles arriving from nearby the galactic plane even at energies of 60 EeV. And in fact, 5 of the 7 events that do not

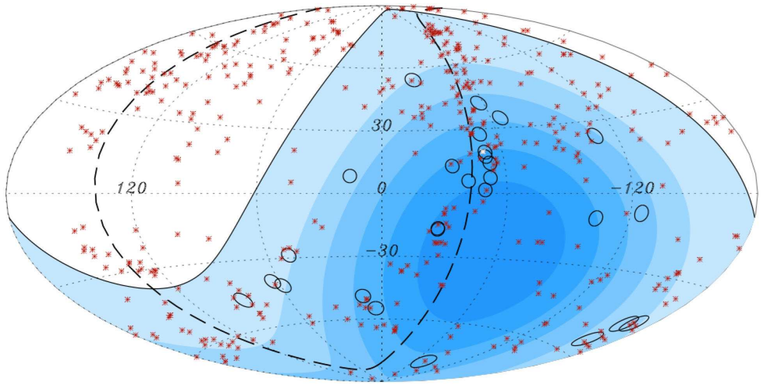

Figure 6: Aitoff projection of the celestial sphere in galactic coordinates. The positions of the AGN within $D < 71\,\mathrm{Mpc}$ (stars) and of the events with $E > 57\,\mathrm{EeV}$ (circles) are marked. The colors indicate equal exposure [8, 22].

correlate with positions of nearby AGN arrive with galactic latitudes $|b| < 12°$. The angular scale of the observed correlation also implies that the intergalactic magnetic fields do not deflect the CRs by more than a few degrees and one can constrain models of turbulent magnetic fields to $B_{\mathrm{rms}}\sqrt{L_c} \leq 10^{-9}\ \mathrm{G}\sqrt{\mathrm{Mpc}}$ within the GZK horizon assuming protons as primary particles [22].

The results have stimulated a large number of papers discussing the correlation results and their interpretation and/or applying the Auger correlation parameters to other data-sets, part of which will be discussed below.

6 Discussion and Concluding Remarks

Remarkable progress has been made in cosmic ray physics at the highest energies, particularly by the start-up of the (still incomplete) Pierre Auger Observatory. The event statistics above 10^{19} eV available by now allows detailed comparisons between experiments and indicates relative shifts of their energy scales by $\pm 25\,\%$. Given the experimental and theoretical difficulties in measuring and simulating extensive air showers at these extreme energies, this may be considered a great success. On the other hand, knowing about overall mismatches of the energy scales between experiments may tell us something. Clearly, in case of fluorescence detectors better measurements of the spectral and absolute fluorescence yields and their dependence on atmospheric parameters are needed and will hopefully become available in the very near future [16]. This should furnish all fluorescence experiments with a common set of data. Differences in the calibration between surface detectors and fluorescence telescopes, best probed by hybrid experiments like Auger and the Telescope Array [23], may then be used to test the modelling of EAS. The muon component at ground, known to be very sensitive to hadronic interactions at high energies [14], could in this way serve to improve hadronic interaction models in an energy range not accessible at man-made accelerators. In fact, several studies (e.g. [24]) indicate a deficit of muons by 30 % or more in interaction models like QGSJET.

The energy scale is of great importance also for the AGN correlation discussed in the previous section. As shown in [22], the correlation sets in abruptly at an threshold energy of about 57 EeV. The distance parameter of the correlation of 71 Mpc may indicate a mismatch of the energy scale: For protons above 57 EeV the GZK horizon would be 200 Mpc [4] but already for 20 % higher energy it would shrink by more than a factor of two to become consistent to the correlation parameter. Another puzzling feature is the observed small deflection of particles which suggests dominantly protons as primaries. Note that 90 % of the events (20/22) off the galactic plane are correlated to within $\sim 3^\circ$ which AGN positions which is very unlikely for heavy nuclei. On the other hand, the elongation curves seen by Auger [25] suggests an admixture of heavy nuclei by more than 10 %. This may be related again to imperfections of the hadronic interaction models used for comparison in the elongation curves.

Irrespective from the details in the energy calibration, the observation of the highest energy events from different directions in the sky and from distances larger than the scale of the solar system has been used to derive the best present limits about the smoothness of classical spacetime [26]. This conclusion is based on the apparent absence of vacuum Cherenkov radiation which would degrade the CR energy already on very short distance scales. Another conjecture is that the fundamental length scale of quantum spacetime may be different from the Planck length [26].

Another test of fundamental physics based on the upper limits of photons is discussed in Ref. [27]. In presence of the GZK effect, one expects high energy photons from the π^0-decay resulting from $p + \gamma_{CMB} \rightarrow p + \pi^0$ interactions. The photons then rapidly cascade down to low energies by pair production. However, in many models of Lorentz-Invariance Violation (LIV), the dispersion relation is modified to $\omega^2 = k^2 + m^2 + \xi_n k^2 \left(k/M_{Pl}\right)^n$ so that the cascading of photons would be suppressed dependent on the LIV parameters ξ_n resulting in high γ/hadron-ratios. Again, the limits on LIV based on the Auger photon data are better by orders of magnitude compared to previous limits. All of these results come for free, just making use of the enormous energies of CRs.

All of this tells us that the near future will be highly exciting: The question of the energy scales will soon be settled and more detailed comparisons between experiments will become possible. The shape of the energy spectrum in the GZK region will tell us about the source evolution, the composition in the ankle region will answer the question about the galactic-extragalactic transition, observations of cosmogenic photons and neutrinos are in reach and in case of neutrinos will probe the GZK effect over larger volumes, the correlations will be done with better statistics, with improved search techniques and with more appropriate source catalogues and source selection parameters to tell us about source densities, and finally about the true sources of EHECRs. Very important to note is that different pieces of information start to mesh and are being accessed from different observational techniques and can be cross-checked.

Given the scientific importance of this, it would be a mistake to have only one observatory taking data - even when operated as a hybrid detector. Auger-North will be imperative and needs immediate vigorous support. The next generation experiment JEM EUSO to be mounted at the Exposed Facility of Japanese Experiment Module JEM EF will potentially reach much larger exposures but still faces many experimental challenges to be addressed.

Acknowledgement

I would like to thank the organizers of the La Thuile conference for arranging an interesting meeting at the interface of particle and astrophysics. Also, it's a pleasure to thank many of my colleagues for stimulating discussions. The German Ministry for Research and Education (BMBF) is gratefully acknowledged for financial support.

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