Status of extensive air shower studies at the Pierre Auger Observatory

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Abstract

The construction of the Southern site of the Pierre Auger Observatory is now essentially finished. While the total acceptance accumulated so far only amounts to about one year of the completed detector, i.e. ~ 7000 km^2 sr yr, a number of valuable results could be reached about the highest energy cosmic ray spectrum (above a few 10^{18} eV), the evolution of composition indicators as a function of energy, photon and neutrino flux limits, and the arrival directions of the ultra-high-energy cosmic rays (UHECRs). In particular, the first experimental evidence of their anisotropic distribution above ~ 60 EeV was obtained. These results strongly suggest an extragalactic and bottom-up origin of the UHECRs, but do not yet allow us to determine either their mass distribution (nuclear type), or their sources. While these results are very encouraging for charged particle astronomy and individual source studies, significantly larger statistics will be needed to complete such an ambitious program.

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1. Introduction

The story of cosmic ray physics has been elegantly weaved into that of fundamental physics and astrophysics for almost a century. In the first half of the XXth century, cosmic rays have revealed a whole new world with unexpected content and properties, and effectively lead to the founding of particle physics, with major discoveries including antimatter, muons, pions and strange particles. On the side of astrophysics, the discovery of these high-energy particles coming from the cosmos was accompanied by the development of non-visible astronomy, revealing the ubiquity of non-thermal distributions of particles and powerful acceleration processes throughout the Galaxy and the whole universe. Then came the discovery that cosmic rays (CRs) play a central role in what may be called *the Galactic ecology*, as they control the ionization and heating of the interstellar medium, help building turbulent magnetic fields at various scales, influence important astrochemical processes, produce the bulk of the light elements and even influence star formation. Among the major discoveries related to CRs is the existence of particles with energies larger than 10^{20} eV, which is a challenge for standard astrophysical acceleration models.

On the other hand, particles of such high energies are a source of hope for astrophysicists trying to identify the sources of cosmic rays, since the process of isotropization related to the interaction of charged particles with the ambient magnetic fields should not be efficient at such high rigidities, at least not on the scale of the Galaxy (for magnetic fields of a few microgauss) nor on the scale of a few hundreds of Mpc (for magnetic fields in the nanogauss range). Now, unless well known physics is at fault at Lorentz factors above a few 10^{10} (which is by itself an interesting matter of investigation), the ultra-high-energy cosmic rays (UHECRs) are guaranteed to originate from sources closer than such isotropization scales, because they would lose the bulk of their energy by producing pions or being photodisintegrated through interactions with the CMB photons

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if they travelled larger distances accross the universe. This is the well-known *GZK effect*, exposed by Greisen and Zatsepin & Kuzmin immediately after the discovery of the CMB[1].

By focusing on the highest energy CRs, one may thus relate to some extent their arrival directions with the source directions, which the isotropization process makes impossible at lower energy. This should obviously help in identifying the sources, and if one were able to isolate the contributions from individual sources on the sky, one would be able to better constrain their source spectrum and cosmic-ray injection power – quite valuable information with which to refine the modeling of the corresponding astrophysical sources, together with multi-wavelength astronomy data and hopefully other messengers as well.

The main problem of UHECR astronomy, however, is the flux: of the order of a few cosmic-rays per century and per km^2 over the whole sky! For this reason, the Auger Collaboration set out to build the biggest possible detector of UHECRs, with a full sky coverage and a hybrid detection technique to reconstruct the extensive air showers induced by the CRs in the Earth atmosphere, both from the fluorescence light emitted in the wake of the shower and from the sampling of the shower particles reaching the ground and producing light coherently and coincidentally through water Cherenkov detectors[2]. The Southern site, in Malargue, Argentina, is now essentially completed, with $\sim$ 1600 water tanks deployed over 3000 km^2 and 24 fluorescence telescopes overlooking the site up to 30 degrees above the horizon. The Northern site, in Colorado, US, is in its R&D phase and its deployment over a significantly larger area will start as soon as funding becomes available.

Here, we update the current status of the Auger detector and report on a selection of the first results obtained by Auger from the analysis of the data collected during the installation phase, with a total acceptance of $\sim$ 7000 km^2 sr yr from January 1st, 2004, to August 31st, 2007, i.e. roughly 1 year of operation of the full Auger detector.

2. Reconstruction of CR-induced atmospheric showers in Auger

2.1. *Hybrid detector layout*

The Pierre Auger Observatory is the first large aperture UHECR detector making extensive use of both a surface detector (SD) and a fluorescence detector (FD). The SD consists of an array of 1600 water tanks deployed on a hexagonal grid with a spacing of 1.5 km. These tanks detect the Cherenkov light produced by shower particles crossing their (1.2 m)×(10 m^2) water volume, thanks to three 9-inch photo-multipliers (PMT). The geometry of a given cosmic-ray shower can be reconstructed from the arrival time of the shower front on the triggered stations and from the respective intensity of the detected signals. Given the Auger SD configuration, the interpolated signal 1000 m away from the shower axis can be inferred with satisfactory precision ($\sim$ 4%) for any shower energetic enough to trigger 3 or more stations. This so-called S_{1000} signal can then be related to the energy of the incoming cosmic ray either by comparing to Monte-Carlo simulations of EAS development (relying on the extrapolation of hadronic models constrained at lower energy by accelerator physics) or by calibrating this signal with the fluorescence signal measured simultaneously by the FD in the case when the shower is seen by both detectors, which is referred to as a *hybrid event.*

The FD consists of four ensembles of six telescopes, each of which has a field of view of 30° vertically and 30° horizontally (i.e. 180° for each FD site). The telescopes are based on Schmidt optics and provide images of any (powerful enough) shower developing in the atmosphere above the SD array. Each telescope consists of: i) a filter at the entrance window, with very high efficiency in the 300–400 nm range, hosting the main molecular lines of Nitrogen, ii) an optimized circular aperture, iii) a corrector ring reducing spherical aberrations and keeping the spot size on the camera within 15 mm (which corresponds to an angular resolution of 5°, i.e. one third of the field of view of a single pixel-PMT), iv) a segmented $3.6 \times 3.6\,\mathrm{m}^2$ mirror (with a radius of curvature of 3.4 m), and v) a camera made of 440 1.5-inch PMTs arranged in a 22×20 matrix.

The FD gives access to two important parameters of an extensive air shower: the "shower maximum", $X_{\max}$, at a given energy, which depends on the mass of the incoming high-energy nucleus, and the total ionization power, which is directly related to its energy. This relation involves three important steps: i) the generation of the fluorescence itself, which depends on the *fluorescence yield* in the atmosphere, ii) the transmission of light through the atmosphere (involving both absorption and diffusion), which is experimentally determined thanks to intense atmospheric monitoring, and iii) the response of the cameras, which are calibrated in a relative manner at least twice a night and in an absolute manner less frequently, using a calibrated LED with known spectrum, intensity and directionality.

As of May 2008, all four FD buildings are operational and all 24 fluorescence telescopes are taking data, while more than the nominal 1600 tanks are sending data (some of which lie outside the regular Auger grid, for technical quality studies), with an overall up time larger than 98%. The deployment of the last regular SD stations is expected in the coming weeks.

2.2. *Shower reconstruction*

The key problem in high-energy cosmic ray experiments is the reconstruction of the shower energy. Identifying showers themselves is usually straightforward, as there is essentially no "background" for the detectors, at least above their energy threshold. In the case of Auger, the threshold for the SD is around 0.5 EeV, below which less than 10% of the showers can trigger three tanks or more, as required. However, full detection efficiency (i.e. 100%, or "saturated acceptance") is achieved only around 3 EeV for showers with zenith angles lower than 60°, and lower energy showers are usually discarded to avoid any complication caused by the energy dependence of both the detection efficiency and the energy resolution. For the FD, showers with energies as low as 0.1 EeV can be observed. However, the corresponding acceptance is relatively low, since the total intensity of the fluorescence light does not allow detection from a large distance, and the shower maximum is then usually above the field of view of the telescopes, which prevents accurate reconstruction. Like for any fluorescence detector, the Auger FD acceptance increases with energy (as bigger showers can be seen from larger distances) and depends on the atmospheric conditions. However, a precise determination of the FD acceptance is not crucial for Auger, thanks to its hybrid nature, since the energy differential flux (or "spectrum") is not obtained from the FD, but from the SD whose absolute acceptance is essentially geometrical above saturation (~ 3 EeV) and is thus controlled within a few percent at most.

The axis of development of the showers (indicating the arrival direction of the cosmic rays) is reconstructed with the SD by triangulation, using a GPS time tagging of the shower front arrival in the triggered tanks. With the FD, a fit of the track observed on the pixelized camera gives the plane containing the shower axis and the telescope, within which the axis itself is obtained thanks to the time information of each pixel, with improved precision when a signal from an SD tank is also available, i.e. for hybrid events. The resulting angular resolution for the SD alone (i.e. for most of the events) is better than 2° in the worse case of vertical showers with only three tanks triggered, and significantly improves for higher multiplicities, down to less than 1° for 6-fold (or more) events, i.e. above ~ 10 EeV[3]. This is less than the expected deflection of the CR trajectories in the Galactic magnetic field alone (except for photons and neutrinos, of course), even at the highest energies, and angular accuracy is thus not perceived as a limiting factor in Auger, at least for the current analyses.

The energy reconstruction is more delicate, since the CR spectrum is a steeply decreasing function of energy and a misunderstanding of i) the link between the measured quantities (i.e. secondary observables) and the actual incoming energy and/or ii) the underlying energy resolution (especially its dependence with energy) can have an impact on the reconstructed spectrum. The hybrid design of the Pierre Auger Observatory is very useful in this respect. On the one hand, the FD measurements can provide a calorimetric estimate of the energy of cosmic-ray showers, while the traditional method to reconstruct the shower energy from the SD data involves a comparison with Monte-Carlo simulations based on extrapolations of the hadronic models beyond the energy range investigated in particle accelerators on Earth. On the other hand, the SD can be used to gather large statistics with a well-controlled (geometrical) acceptance, while the FD detector is limited by its 10% duty cycle (since it can only work at night, with no or little moon) and an energy-dependent acceptance and energy resolution.

Taking advantage of both aspects of the detector, the Auger Collaboration developed a cross-calibration technique enabling one to use the SD statistics with the FD energy scale measurement. As mentioned above, the intensity of the signal measured in a tank located 1000 meters away from the shower axis, denoted S_{1000}, is directly related to the energy E of the incoming CR. It can thus be used as an energy estimator, independently of shower simulations, provided one can experimentally establish a quantitative relation between E and S_{1000}. This is done by systematically comparing the value of S_{1000} and the energy $E_{\rm FD}$ reconstructed by the FD

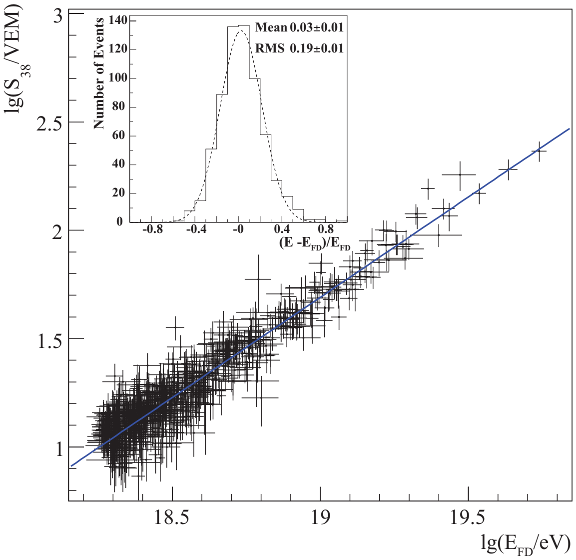

Fig. 1. Correlation between the SD energy estimator S_{38} (see text), and the reconstructed FD energy of Auger hybrid showers. The fractional dispersion of the SD/FD energy correlation is shown in the inset (from ref.[5]). The signal unit is the VEM (vertical equivalent muon), which is the integrated signal produced by a muon crossing an SD tank vertically.

whenever it is available, i.e. for all hybrid events passing the appropriate quality cuts. The result is shown in Fig. 1, exhibiting an excellent correlation, and the corresponding dispersion of the values is also displayed (inset). The small relative dispersion (which includes uncertainties in the determination of both the FD energy and the SD signal) demonstrates that S_{1000} is intrinsically a very good energy estimator, to provide reliable energy measurements once properly calibrated.

More precisely, the quantity that is plotted against E_{FD} in Fig. 1 is not S_{1000}, but a modified quantity, $S_{1000}(38°)$ (or S_{38} for short), representing the S_{1000} signal that would have been measured, had the shower developed at a zenith angle $\theta = 38°$ (which happens to be the median of the Auger data set). The reason for using this modified quantity is that showers with the same energy developing at different zenith angles produce different S_{1000} signals *at ground level*, because the corresponding grammage of atmosphere along the shower axis (and thus the shower development stage, or "age") is different. Fortunately, it is in principle easy to relate $S_{1000}(\theta)$ to $S_{1000}(38°)$, using the approximate isotropy of the observed CR flux: the value of $S_{1000}(\theta)$ (i.e. S_{1000} for a shower observed at zenith angle θ) that corresponds to the same energy as a given value, S_{38}, measured for a shower at zenith angle $\theta = 38°$, is the very value that gives the same integral flux of more-energetic CRs detected in the respective angular bin: $\int_{S_{1000}(\theta)}^{\infty} \Phi_{\mathrm{CR}}(S_{1000}(\theta))\mathrm{d}(S_{1000}(\theta)) = \int_{S_{1000}(38°)}^{\infty} \Phi_{\mathrm{CR}}(S_{1000}(38°))\mathrm{d}(S_{1000}(38°))$, as determined experimentally by mere event counting[4].

3. A few chosen results

The cosmic rays are characterized experimentally by their energy spectrum (differential flux), their mass spectrum (composition), and their angular spectrum (arrival directions). We briefly present here a few results related to these three observables and refer the reader to the recent Auger publications for further details and additional results [5–8].

3.1. *Energy spectrum*

The above-mentioned method was used to build the energy spectrum of cosmic rays above 3 EeV, with the full statistical power and controlled acceptance of the SD and the energy scale derived from the FD measurements. The result is shown in Fig. 2 (top), where the number of events in each energy bin is indicated. The plot uses all the data gathered from January 1^{st}, 2004, to August 31^{st}, 2007, corresponding to an integrated exposure of $\sim 7000\,\mathrm{km}^2$ sr yr. In Fig. 2 (bottom), we show the fractional difference between the Auger spectrum and a power-law in $E^{-2.69}$, which roughly corresponds to the measured spectrum between $10^{18.6}$ eV and $10^{19.5}$ eV (the data from the HiRes experiment[9] are also shown for comparison). A break is clearly visible around $4\,10^{19}$ eV: under the assumption of a continued power-law, one would expect 167 ± 3 events and 35 ± 1 events above $10^{19.6}$ eV and 10^{20} eV, respectively, while only 69 events and 1 event are observed. The hypothesis of a pure power-law can thus be rejected with a significance better than 6 standard deviations.

The interpretation of this flux suppression is not straightforward, however. The coincidence between the measured UHECR spectrum and the spectral shape typically expected as a result of the GZK effect under standard assumptions suggests that the so-called GZK cutoff has been observed. However, one might also be observing the end of the injection spectrum, rather independently of propagation effects, if the astrophysical accelerators turned out to be unable to produce cosmic-rays above a few tens

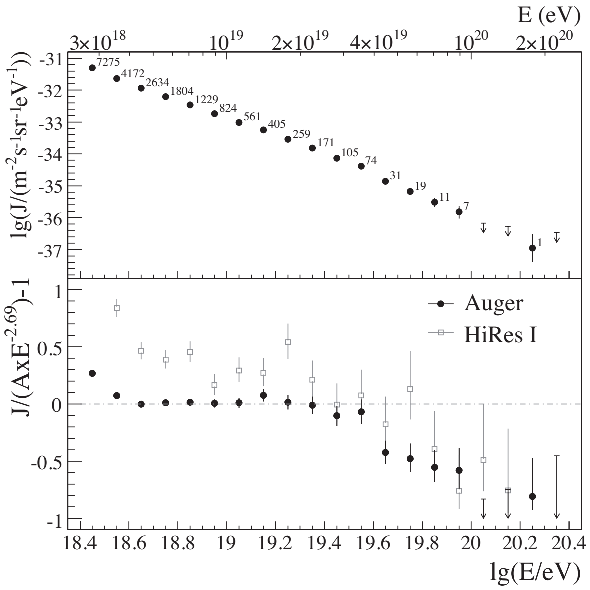

Fig. 2. Top: Auger energy spectrum, with statistical error bars only (the number of events in each bin is indicated). Bottom: fractional difference between the Auger spectrum and an assumed CR flux in $E^{-2.6}$, as a function of energy.

of EeV. Even if the observed suppression is due to the interaction of UHECRs with the ambient photon fields, it is not clear whether the dominant effect is the photo-production of pions induced by UHE protons or the photo-dissociation of UHE nuclei, or a combination of both effects. This essentially depends on the composition of the UHECRs at their sources, which remains unknown.

As shown in [10], at the present level of statistics the spectral shape itself cannot be used to constrain the UHECR composition, since a large choice of source compositions can be used to fit the data with similarly good accuracy, from pure protons to pure Fe or a mixture of nuclei. In each case, however, the injection spectrum and/or source evolution profile has to be quite different, with power-law spectral indices ranging from 2.1 to 2.7. A direct measurement of the overall UHECR composition is thus very important to constrain the models and understand particle acceleration at the highest energies.

3.2. *Composition*

While the mass of each incoming cosmic-ray is not accessible, because of the large stochastic fluctuations in the shower development which can easily make a given proton-induced shower look like a Fe-induced shower, the analysis of the whole set of showers detected at a given energy can give an indication about the overall CR composition. For instance, in a first approximation a Fe-induced shower behaves roughly like 56 proton-induced showers developing in parallel, which means that on average Fe-induced showers develop quicker (i.e. higher in the atmosphere) and with smaller intrinsic fluctuations than proton-induced showers of the same energy.

The most commonly used indicator of the primary CR mass is the depth in the atmosphere at which the shower reaches its maximum development. This is measured by the cumulated grammage, $X_{\max}$ (in g/cm^2), from above the atmosphere to that maximum. This grammage is an increasing function of energy and a decreasing function of mass. Unfortunately, the direct comparison of the measured quantities with theoretical predictions is somewhat uncertain, as it involves Monte-Carlo simulations of the shower development, which in turn involve some knowledge about the high-energy hadronic interactions that can only be extrapolated from low-energy measurements through some phenomenological models. Different models result in somewhat different values for the mean $X_{\max}$ at a given energy. Therefore, it can be argued that the comparison of the global shape of the average $\langle X_{\max}\rangle$ evolution with energy with model predictions may have more discriminating power than the comparison of absolute values themselves[11].

The evolution of $\langle X_{\max}\rangle$ with energy is shown in Fig. 3, where the upper and lower lines correspond to the expectations for the evolution of $\langle X_{\max}\rangle$ for pure protons (upper lines) and pure Fe nuclei (lower lines), under different assumptions for the modeling of high-energy hadronic interactions. The results are obtained with a subset of the Auger hybrid data, satisfying appropriate quality and uniformity cuts, which guarantee an $X_{\max}$ resolution at the level of 20 g/cm^2[12].

Some inflection might be seen around 3 EeV, i.e. in the so-called ankle region, while the highest energy points might indicate that the composition gets somewhat heavier at high-energy, although a firm conclusion would require larger statistics and an extension of the data at higher energy. This will eventually be accessible to Auger. Note also that other composition-sensitive indicators, such as the fluctuation of $X_{\max}$ as a function of energy, the muon content of the showers, the radius of curvature of the shower front or the signal rise time (from 10% to 50% of the total) in the SD stations (accessible with the full statistics of the SD detector) can also be used in

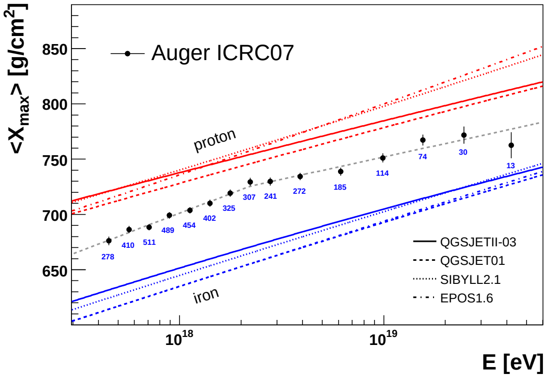

Fig. 3. Evolution with energy of the average atmospheric grammage at shower maximum, $\langle X_{\max}\rangle$. The number of hybrid events used in each energy bin is indicated, and the expectations for pure proton and pure Fe UHECRs from different hadronic interaction models are shown for reference.

principle to constrain the propagated UHECR composition. The corresponding studies are underway.

This composition result is potentially interesting, because the presence of nuclei at the highest energy would have important implications for the acceleration models, for the global phenomenology of the CRs, including the transition from the Galactic to the extragalactic component at lower energy[13], and for the high-energy neutrino production associated with UHECR propagation (both at the sources and in the intergalactic space)[10]. On the other hand, some features in the energy evolution of $\langle X_{\max}\rangle$ may also occur as a consequence of unanticipated hadronic properties, even without a change in composition. High-energy physics issues are thus very important for Auger as well, both for the interpretation of the data and as a way to provide complementary constraints, related to the interaction cross sections and multiplicities in an energy range as yet unaccessible in terrestrial accelerators. On this matter again, larger statistics are needed to provide significant information.

It is easier to distinguish primary photons from nuclei than to distinguish between different nuclear species, because the reactions involved in the development of photon-induced showers have a much smaller multiplicity than in hadronic showers. The photon showers therefore develop more slowly and penetrate more deeply into the atmosphere (and even more so above 30 EeV, where the suppression of the Bethe-Heitler pair production due to the LPM effect becomes important). The result is a much larger $X_{\max}$, which provides an efficient discrimination tool for hybrid events. In addition, the larger $X_{\max}$ results in a larger rise time of the signals in SD tanks, and in a smaller radius of curvature of the shower front. These two parameters can be measured for all SD events and combined into a single SD observable through the principal component analysis to maximize the discrimination power (see [7]). No photon candidate has been identified, and the resulting upper limits on the fraction of photons among high-energy CRs are shown in Fig. 4. Many top-down and exotic models of CR sources are thus excluded or disfavored, as shown on the figure.

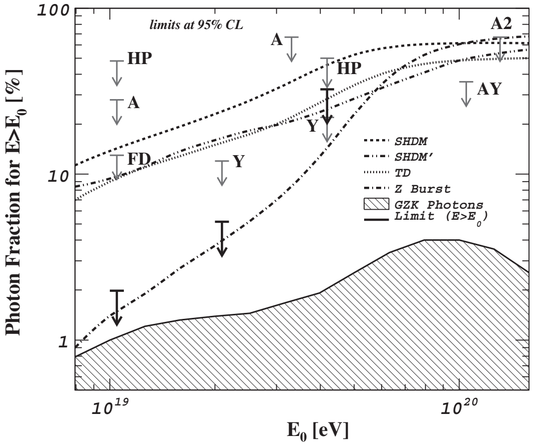

Fig. 4. Upper limits with a confidence level of 95% on the fraction of photons in the integral cosmic-ray flux derived from SD events (black arrows) along with previous experimental limits (HP: Haverah Park; A1, A2: AGASA; AY: AGASA-Yakutsk; Y: Yakutsk; FD: Auger hybrid limit). Also shown are predictions from top-down models and for the GZK photon fraction. See [7] and references therein.

Finally, Auger is also a high-energy neutrino detector, as neutrino-induced showers can be unambiguously identified when they develop deep in the atmosphere and almost horizontally, or when they arise from Earth-skimming tau neutrinos leading to upward going tau decay showers. The elongated pattern of the shower expected on the ground, the apparent velocity of theshower front propagation ($v \simeq c \pm 3.3\%$) and its dispersion when calculated between any pair of tanks involved in the event ($\sigma < 0.08$ m/ns) were used together to construct a neutrino selection criterion with an efficiency of 80%. No neutrino candidate has been identified so far, and the resulting upper limit on the diffuse tau neutrino flux is shown in Fig. 5. For a spectrum in E^{-2}, it reads $E_\nu^2 \mathrm{d}N_{\nu_\tau}/\mathrm{d}E_\nu < 1.3\times10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ in the energy range 2×10^{17} eV $< E_\nu < 2\times10^{19}$ eV, which is the most stringent limit so far and will be

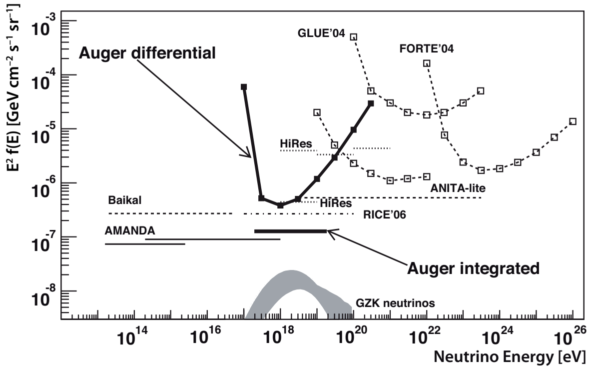

Fig. 5. Tau neutrino flux limits at 90% confidence level. Limits from other experiments are converted to a single flavor assuming a 1:1:1 ratio of the 3 neutrino flavors. The shaded curve shows a typical range of expected fluxes of GZK neutrinos. See [8] and references therein.

improved by an order of magnitude in the future. See [8] for details and references.

3.3. *Angular distribution*

Concerning the CR arrival directions, none of the previously reported departures from isotropy has been confirmed by Auger. In particular, an upper limit on the first harmonic (dipole) amplitude was set to 0.7% in the 1–3 EeV energy range, while no significant excess emission from the direction of BL Lac type galaxies (known VHE gamma ray emitters) nor from the Galactic center was observed [14].

On the other hand, the first observational evidence that UHECRs are indeed anisotropic above ~ 60 EeV was unambiguously obtained with a 99% confidence level on a virgin data set, confirming the hopes that CR astronomy is indeed possible in the GZK range. This remarkable result has been obtained thanks to a correlation between the UHECR arrival directions and the direction of nearby active galactic nuclei (AGNs) in the 12th edition of the Veron-Cetty & Veron catalog (VCV)[15]. Specifically, searches of the Auger data collected before mid-2006 found a very strong excess (with respect to the expectations from a purely isotropic sky) of coincidences within 3.2° between VCV objects closer than redshift 0.018 ($\sim$ 75 Mpc) and the arrival direction of UHECRs above 57 EeV (with the current Auger energy scale). This excess, however, could not be assigned any reliable significance, because the data set had been scanned and searched in many ways by many independent groups. Therefore, a *prescription* was set up to see if the same anisotropy signal, with correlation parameters prescribed beforehand, could be seen in an independent data set, namely the set of future events. Details of the procedure and associated significance calculations can be found in [15]. A map showing the arrival direction of the 27 highest energy events together with the 472 AGNs with redshift lower than 0.018 is plotted in Fig. 6.

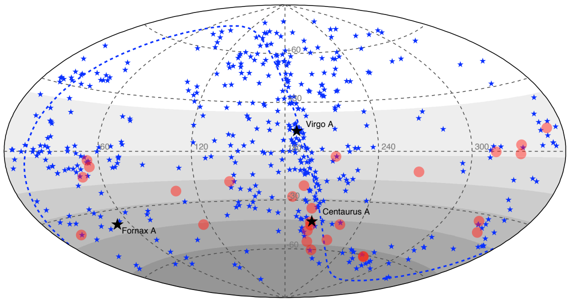

Fig. 6. Sky map in equatorial coordinates. Colored circles with radius 3.1 degrees are centered at the arrival directions of the Auger 27 highest energy CRs. The positions of the 472 AGN with redshift $z < 0.018$ from the 12th VCV catalog are indicated by the blue stars. Darker grey shading indicates larger relative exposure. Centaurus A, Fornax A, and Virgo A, three of the closest AGN, are marked with black stars. The super-galactic plane is shown as a dashed blue line.

As indicated, the result demonstrates that the UHECRs are anisotropic above $\sim$ 60 EeV, with 99% confidence level. It is important to realize that this is the only explicit claim that is directly related to this result. The quoted significance does not involve any identification of the correlating AGNs as UHECR sources, nor any measurement of the actual deflection of the UHECRs on their way from their sources to the Earth. Some AGNs may be the sources of some UHECRs, but this possibility was known before the Auger data, and other sources are possible as well. In this respect, the current Auger data do not have the statistical power to modify the landscape of theoretical or phenomenological reflexions about the origin of UHECRs.

It is worth noting that the energy above which a significant departure from isotropy could be detected corresponds to the energy where the cosmic-ray flux drops to 50% of the high-energy extrapolation of the lower-energy power law fit. This gives support to the idea that the observed flux suppression is related to the GZK effect by which the UHECR horizon is sharply reduced in this energy range, because of the energy losses suffered by the particles (either protons or heavier nuclei) in the intergalactic photon background. In this picture, the anisotropy would indeed show up when the number of contributing sources and the source distance become both small enough to form an anisotropic image on the sky, probably related to the matter distribution in the nearby universe.

4. Summary

The deployment of the Southern site of the Pierre Auger Observatory is now essentially over. A hybrid analysis procedure has been developed to take advantage of the intrinsic accuracy of the energy measurement of the fluorescence detector, together with the large acceptance of the surface detector.

With an accumulated data set corresponding to roughly one year of operation of the full Auger detector, a number of interesting results could be obtained: a significant suppression of the spectrum at the highest energies, reminiscent of the expected GZK effect; a composition apparently getting heavier at high energy; a constraining upper limit on the UHE photon flux, disfavoring top-down models; the most stringent upper limit on the background neutrino flux in the relevant energy range; and of course the first evidence of the underlying anisotropic distribution of UHECRs.

These results point towards an astrophysical (bottom-up) and extragalactic origin of the UHECRs. The sources, however, remain unknown. The fact that the anisotropy result was established through a correlation with an AGN catalog cannot be used to favor a scenario in which UHECRs would be accelerated in active galaxies. The prescribed test mentioned above was only designed to discriminate against a purely isotropic distribution of cosmic rays at their arrival on Earth, not to test other specific scenarios. To do so, a model of the CR deflections – and thus of the intervening magnetic field – would be needed, in addition to the source positions, intrinsic luminosity, injection spectrum and composition. In turn, high-statistics UHECR studies can help us to understand the intensity and topology of both Galactic and extragalactic magnetic fields, which is important for astrophysical and cosmological scenarios.

The Auger anisotropy result marks the long-awaited opening of CR astronomy, and allows one to hope for the detection, identification and study of individual CR sources. This represents a major step for cosmic-ray physics, but also for high-energy astrophysics in general, since the question of particle acceleration in various astrophysical environments remains one of the most challenging in the field.

To make the most of this new era opening in high-energy cosmic ray physics, and take advantage of the multi-wavelength and multi-messenger study of the most powerful sources in the universe, much larger statistics will be necessary. To this effect, the Auger Collaboration is now seeking to develop the Northern site of its planned full sky coverage Observatory, in Colorado, USA, with a significantly larger detection surface on the ground, up to 8000 square miles, i.e. ~ 7 times that of Auger South, focusing on the highest energy cosmic rays. In the meantime, the lower end of the Auger energy range will receive increased attention, thanks to specific enhancements of the Southern site[16], to collect precious information about the CR composition and the structure of the Galactic/Extragalactic transition, and thus about low-energy CRs as well.

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