

# Recent results from the Pierre Auger Observatory

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**Abstract.** The main results from the Auger Observatory are described. A steepening of the spectrum is observed at the highest energies, supporting the expectation that above  $4 \times 10^{19}$  eV the cosmic ray energies are significantly degraded by interactions with the CMB photons (the GZK effect). This is further supported by the correlations observed above  $6 \times 10^{19}$  eV with the distribution of nearby active galaxies, which also show the potential of Auger to start the era of charged particle astronomy. The lack of observation of photons or neutrinos strongly disfavors top-down models, and these searches may approach in the long term the sensitivity required to test the fluxes expected from the secondaries of the very same GZK process. Bounds on the anisotropies at EeV energies contradict hints from previous experiments that suggested a large excess from regions near the Galactic centre or the presence of a dipolar type modulation of the cosmic ray flux.

**Introduction:** After having been studied for almost a century, cosmic rays (CRs) still offer many puzzling results, particularly at the highest energies which are now being explored at the Pierre Auger Observatory. From  $10^9$  eV up to about  $10^{20}$  eV the spectrum of cosmic particles is essentially a power law  $dN/dE \sim E^{-\alpha}$ , with  $\alpha \simeq 3$ , with some small but relevant breaks at the so-called knee (at about  $5 \times 10^{15}$  eV), the second knee (slightly above  $10^{17}$  eV) and the ankle (at about  $3 \times 10^{18}$  eV). The steeply falling nature of the CR spectrum implies that although the fluxes are large at low energies, i.e. of order 1 particle per  $\text{cm}^2$  per second in the GeV range, they become extremely small in the highest energy end, e.g. of about 1 particle per  $\text{km}^2$  per century above  $6 \times 10^{19}$  eV. This implies that huge detectors are required to gather sizeable statistics in this last regime.

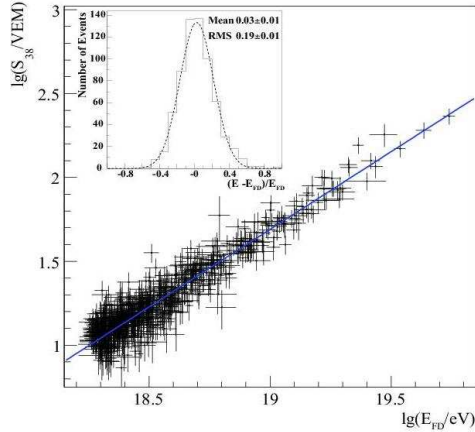
The non-thermal nature of CRs is what led Fermi to speculate that their acceleration was the result of stochastic processes involving charged particles in the presence of astrophysical magnetic fields, what later evolved into the scenario of diffusive acceleration in shock waves. In particular, the bulk of the CRs of low energies may be produced in this way in galactic supernova explosions. But the highest energies are so extreme that only a few sites are large enough and have sufficiently strong magnetic fields to be (marginally) able to produce them, with possible candidates being active galactic nuclei and gamma-ray bursts. If indeed the highest energy cosmic rays are extragalactic, as is also suggested by the lack of observed anisotropies associated with the galactic plane, a further issue is that inelastic collisions with CMB photons are expected to degrade the CR energies as they propagate. If CRs are protons this takes place by photopion production, while if they are heavier nuclei the dominant process is photodisintegration. In both cases losses become important above a certain energy threshold, which coincidentally is  $\sim 5 \times 10^{19}$  eV for both protons and Fe nuclei, and is somewhat smaller for lighter nuclei. As a consequence of this, the spectrum is expected to steepen above this so-called GZK threshold even if the sources continue to be powerful. Until very recently the existence, or otherwise,

of this suppression was strongly debated, with results from the AGASA instrument (detecting air showers at ground level with scintillators) not observing any signs of it, while the HiRes experiment (looking to the fluorescence emitted in the air by nitrogen molecules excited by the passage of the shower) found indications in favor of it.

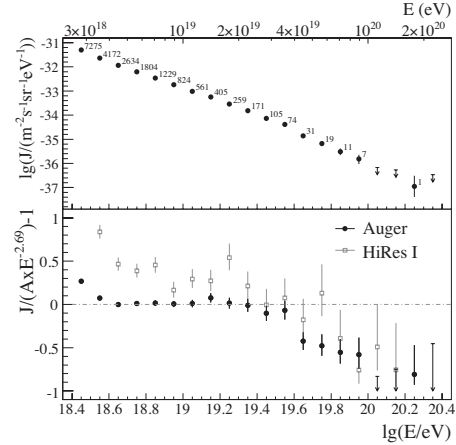
This situation led in the past to the proposal of many exotic scenarios to overcome the limitations of the bottom-up acceleration in known astrophysical sources, in which CRs were produced instead in a top-down way, e.g. from decays of topological defects or superheavy relics from the early universe, from ‘Z-burst’ models, etc. One of the main distinguishing features of the top-down scenarios is that a large fraction of photons and neutrinos should be present at the highest energies. Also exotic physics, such as Lorentz invariance violation, was sometimes invoked to avoid the prediction of a GZK suppression. Anyway, the AGASA and HiRes results were based on small number of events and, using different techniques, were affected by different systematics. To overcome these difficulties the Auger Observatory was conceived as a hybrid detector combining the two detection methods and covering an area 30 times bigger than that of AGASA. As is discussed below, even during the Auger construction phase which is now almost finished, it proved possible to obtain measurements of the CR spectrum, composition and arrival directions which already contributed significantly to the progress in this field.

**The Observatory and recent results:** The Auger Observatory is located near the town of Malargüe, Argentina, at  $35.2^\circ$  S latitude and 1400 m a.s.l. It is an international collaboration of about 400 scientists from 17 countries. The Observatory has a hybrid design, with the surface detector (SD) consisting of a grid of 1600 water Cherenkov stations with 1.5 km spacing, covering a total of  $3000 \text{ km}^2$ , and the fluorescence detector (FD) consisting of 4 buildings on the outskirts of the SD array, each one with 6 telescopes that overlook the array covering  $30^\circ$  in elevation and  $180^\circ$  in azimuth. The surface detectors are tanks with 12 tonnes of pure water in which Cherenkov light is produced by both the electromagnetic and the muonic component of the air showers. This light, after reflection by the diffuse liner, is detected by three 9” phototubes. Three or more nearby triggered stations are required to detect a shower, and while the relative timing (with a 25 ns sampling) gives the information on the arrival direction, the size of the signal contains information on the shower energy  $E$ . A fit is indeed performed to timing and signal data to reconstruct the location of the shower core and the lateral distribution of the shower. From this the expected signal size at 1000 m from the core,  $S(1000)$ , is obtained, and this is used as an estimator of the shower energy. Actually, for a given CR energy the showers with different zenith angles  $\theta$  are being sampled at ground level in different stages of their development, so that the relationship between  $S(1000)$  and  $E$  is  $\theta$  dependent. A direct way to obtain this attenuation effect without relying on shower simulations is to use the fact that the CR flux is essentially isotropic, so that above a given energy one expects a uniform number of events in bins of equal exposure (i.e. in bins of  $\cos^2\theta$  once the detector is fully efficient, which is the case for  $E > 3 \times 10^{18} \text{ eV}$ ). Hence, looking in each bin of  $\cos^2\theta$  for the value of the signal above which there is a certain fixed given number of events, the  $\theta$  dependence of the relation between  $S(1000)$  and energy is obtained. This allows a quantity  $S_{38}$  to be assigned for each value of  $S(1000)$  and  $\theta$ , which is the signal that would have been observed had the shower arrived with  $\theta = 38^\circ$  (the median zenith for the showers with  $\theta < 60^\circ$ , which is the range in which most analyses rely). To calibrate the energies one can use the showers measured with both SD and FD during clear moonless nights. For these hybrid showers the energy can be measured almost calorimetrically with FD by fitting the longitudinal development of the shower, integrating it to include the tails and accounting also for the unobserved particles in the shower (neutrinos and muons). However, since what is observed by the FD telescopes is the light emitted by the air molecules, not directly the energy deposited by the shower particles, the inferred energy depends sensitively on the value adopted for the fluorescence yield, which is unfortunately still subject to significant systematic errors (for instance Auger and HiRes use determinations that differ by

about  $\sim 10\%$ ). It is expected that the determination of the fluorescence yields will improve soon, allowing a major source of systematic uncertainty in the determination of the shower energies to be eliminated. With this set of hybrid events a relation of the form  $E_{FD} = A S_{38}^B$  can be fitted to the data, as is shown in fig. 1, and this can then be used to obtain the energies of all the SD events (only about 15% of the showers are hybrid). From the inset in the figure it is seen that a 19% dispersion remains in this relation, associated mainly to the reconstruction procedure and to shower-to-shower fluctuations. The systematic uncertainty in the energy assignment is 22%.



**Figure 1.** Correlation between the SD energy estimator  $S_{38}$  and the FD energy for good quality hybrid events. The inset shows the dispersion in  $E_{SD}/E_{FD}$ .

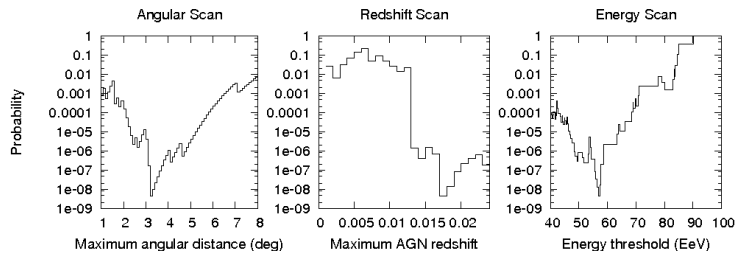


**Figure 2.** Auger differential energy spectrum with statistical error bars. Lower panel shows fractional differences of Hires I and Auger data with respect to a power law with index 2.69.

The energy spectrum obtained [1] from the events collected up to August 2007 (about 20000 events above  $2.5 \times 10^{18}$  eV, with about four times the exposure of AGASA and twice that of HiRes) is shown in fig. 2. To better appreciate the suppression at the highest energies it is also shown in the lower panel normalized to the power law  $E^{-2.69}$  which fits the spectrum below  $4 \times 10^{19}$  eV. The numbers of events expected if this power law were to hold above  $4 \times 10^{19}$  eV or  $10^{20}$  eV, would be  $167 \pm 3$  and  $35 \pm 1$ , while 69 events and 1 event are observed, clearly showing the strong suppression present and rejecting the simple power law extrapolation at more than  $6\sigma$  level. For comparison also the latest HiRes [2] results are shown, with the two experiments being in agreement, except for a possible systematic energy mismatch that is necessary to account for the different flux normalizations obtained.

If the suppression in the CR spectrum is indeed due to the interactions with the CMB photons (and not just due to an unfortunate coincidence with the maximum attainable energies at the sources) a further crucial point is that when looking at energies above the GZK threshold the only CRs that can reach us are those produced in relatively nearby sources (for instance, above  $6 \times 10^{19}$  eV 90% of the protons should come from less than  $\sim 200$  Mpc, while 50% should come from less than 90 Mpc). Hence, the arrival directions of the highest energy CRs are expected to be correlated with the nearby matter distribution, which is quite inhomogeneous. Observing this kind of correlations can be a first step towards doing actual CR astronomy. Note that a major difficulty for charged particle astronomy is the fact that deflections in the galactic and extragalactic magnetic fields may well be large, of order  $10^\circ Z(10^{19} \text{ eV}/E)$ , with  $Z$  the CR charge. On the other hand, the angular resolution of Auger above  $10^{19}$  eV is better than one degree.

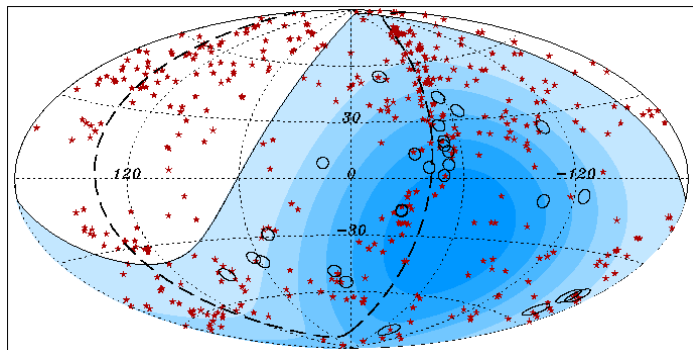
To test for possible correlations with extragalactic sources the Auger collaboration analyzed



**Figure 3.** Probability for the null hypothesis (isotropy) vs.  $\psi$ ,  $z_{max}$  and  $E_{th}$ . In each case the other two parameters are kept fixed at the values leading to the minimum probability (  $\psi = 3.2^\circ$ ,  $z_{max} = 0.017$ ,  $E_{th} = 57$  EeV).

the arrival directions of the events above  $4 \times 10^{19}$  eV to look for coincidences with the positions of the known nearby (less than 100 Mpc) active galactic nuclei [3, 4]. Given the unknown magnetic deflections, the possible systematic uncertainties in energy as well as the unknown CR composition (what would also affect the GZK horizon distance), a scan over the angle  $\psi$  between the events and the AGNs, the maximum AGN redshift considered  $z_{max}$  and the threshold energy  $E_{th}$  is performed to search for the most significant correlation. The results of this scan are shown in fig. 3, showing a deep minimum in the probability  $P$  of observing a similar or larger number of correlations arising from isotropic simulated data. This minimum is obtained for  $\psi = 3.2^\circ$ ,  $z_{max} = 0.017$  (or maximum AGN distance of 71 Mpc) and  $E_{th} = 57$  EeV (corresponding to the 27 highest energy events), where  $1 \text{ EeV} \equiv 10^{18} \text{ eV}$ . Only  $\sim 10^{-5}$  of the isotropic simulations have a deeper minimum under a similar scan. In particular, for these 27 events 20 are at less than  $3.2^\circ$  from an AGN closer than 71 Mpc, while only 6 were expected to be found by chance from an isotropic distribution of arrival directions. A correlation was first observed in the data obtained before the end of May 2006, with a very similar set of parameters, and fixing that set of parameters a priori the subsequent data up to August 2007 were studied, confirming the original correlation with more than 99% CL significance in the additional data set alone.

The map of the arrival directions and of the AGN positions is shown in fig. 4. A remarkable alignment of several events with the supergalactic plane (dashed line) is observed, and it is also worth noting that two events fall within  $3.2^\circ$  from Centaurus A, the closest active galaxy. A further interesting fact is that the energy maximizing the correlation with AGNs coincides with that maximizing the autocorrelation of the events themselves [5] and is also that for which the spectrum falls to half of the power law extrapolation from smaller energies (fig. 2).

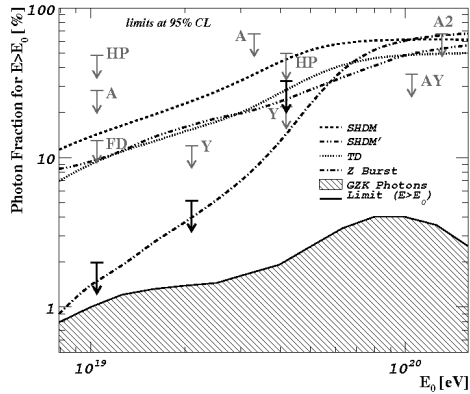


**Figure 4.** Map in galactic coordinates with the positions of the AGNs within 71 Mpc (stars) and the 27 events with  $E > 57$  EeV (circles of  $3.2^\circ$  radius). Shading indicates regions of equal exposure.

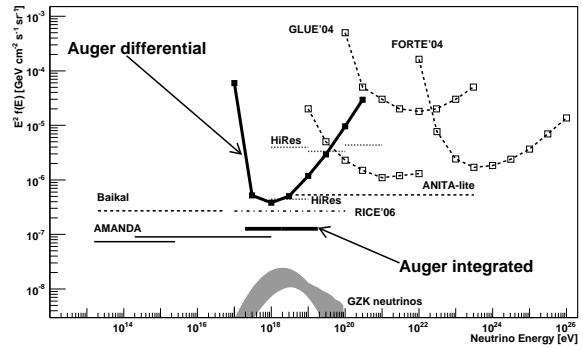
Let us also mention that a search for correlations with BL Lacs gave negative results [6].

Another important search performed by Auger was to look for the presence of photons in the highest energy CRs. One possible signature of photon showers is their comparatively larger values of  $X_{max}$ , the column depth of air at which the longitudinal development reaches a maximum. This is due to the slower development of purely electromagnetic showers with respect to hadronic ones. A first limit was set using this technique in [7] using the FD measurements.

A more sensitive search for photons was done using the full statistical power of the SD detector and looking at the risetime of the SD signals (which are slower in muon poor showers) and the curvature radius of the front of the showers (which is smaller in late developing showers). This led to the bounds [8] displayed in fig. 5, which show in particular that above  $10^{19}$  eV only less than 2% of the CRs may be photons. This excludes most of the top-down model predictions (also shown in the figure). The amount of photons expected (dashed region) from the decays of neutral pions produced in the GZK process, if CRs at the highest energies are proton dominated, is somewhat below present sensitivities, but may be within the reach of future searches.



**Figure 5.** Upper limits on the fraction of photons in the integral CR flux compared to bounds from previous experiments. Lines indicate predictions in different top-down models. Shaded region is for GZK photons.

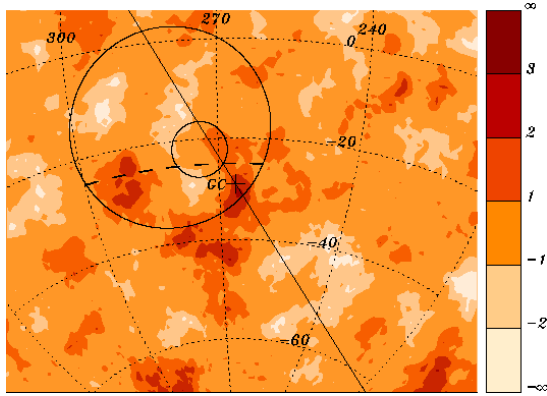


**Figure 6.** 90% CL bounds on diffuse flux of  $\nu_\tau$  from Auger. Bounds from other experiments apply assuming equal proportions of the three  $\nu$  flavors (horizontal lines assume  $E^{-2}$  spectrum). Shaded region indicates possible expectations from GZK neutrinos.

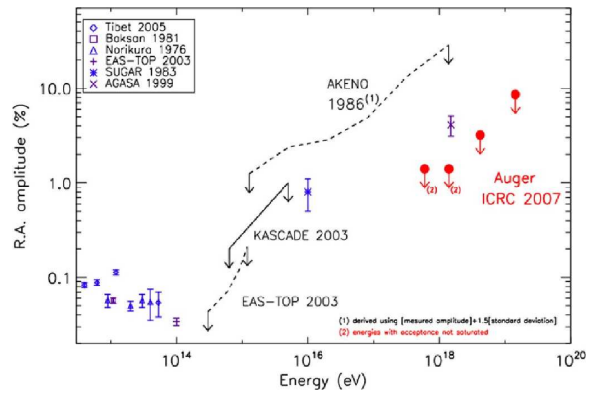
Also neutrinos have been searched with Auger trying to identify horizontal showers with a significant electromagnetic component (i.e. young showers produced by deeply penetrating particles). The background from horizontal showers of hadronic origin would have their electromagnetic component attenuated well before reaching ground, being then dominated by the muonic component that just produces narrow pulses in the SD detectors. Searching then for elongated footprints on the ground consistent with the horizontal propagation of the shower front at close to the speed of light and requiring that a large fraction of the triggered detectors have broad ‘electromagnetic rich’ pulses allows then to identify the neutrino induced showers. No candidates of this kind were found up to now. Although electron or tau neutrinos from slightly above the horizon may produce this type of signals, the most sensitive search is that for tau neutrinos from slightly below the horizon, since they can interact in the rock and the tau leptons so produced can travel several tens of km before decaying, and hence can be efficiently observed when the decays happen just above the detector. Note that even if the sources produce only muon and electron neutrinos by charged pion decays, due to neutrino oscillations an equal admixture of electron, muon and tau neutrinos would be expected upon arrival on Earth. The bounds obtained for the tau neutrinos should hence apply to all neutrino flavors. The present bounds are shown in fig. 6 [9] and the best sensitivity to  $E^2 f(E)$  is around  $10^{18}$  eV, just where the GZK neutrinos produced in the photopion interactions of the CR protons are expected (grey region in the plot). The sensitivity of the Auger instrument will steadily approach the relevant level of fluxes (although if CRs are mostly heavy, that prediction moves down significantly).

Finally there have also been some relevant anisotropy studies at lower energies, around the EeV. Being in the southern hemisphere, the Auger Observatory has a privileged view towards the galactic centre (GC), which passes at just  $6^\circ$  from the zenith at the site. This allowed to test

claims from previous work indicating possible excess fluxes from directions near it. In particular, the AGASA collaboration found a  $4.5\sigma$  excess ( $observed/expected = 506/413.6$ ) in a  $20^\circ$  radius region for the energy range  $10^{18}$ – $10^{18.4}$  eV, while for the same region and energies Auger data led to  $obs/exp = 2116/2159.6$  [10], a result inconsistent with a large excess. Similarly, an excess reported by the SUGAR collaboration in a  $5^\circ$  region slightly displaced from the GC was not confirmed by Auger. A map of overdensity significances on  $5^\circ$  radius windows in the region around the GC is shown in fig. 7, together with the regions where the AGASA and SUGAR excesses were reported. The excesses present in this map are consistent with the expectations from fluctuations of an isotropic distribution.



**Figure 7.** Map in equatorial coordinates around the GC (cross) showing the significance of the overdensities in  $5^\circ$  radius windows, for  $10^{17.9}$  eV  $< E < 10^{18.5}$  eV.



**Figure 8.** Summary of Auger 95% CL upper bounds on the amplitude of a dipolar modulation in right ascension and results from previous experiments.

Another result from the AGASA collaboration indicated the presence of a modulation in the right ascension distribution of the events, with 4% amplitude at EeV energies. The search for a dipolar amplitude of this kind in data from the Auger Observatory gave negative results, allowing to set an upper bound on the amplitude of 1.4% at 95% CL [11], contradicting the previous finding. This kind of modulations could arise from the diffusion of galactic CRs out of the galaxy, and their search will allow to set constraints on the galactic/extragalactic transition. Moreover, two enhancements of the Auger Observatory are being done at present, one extending the field of view of the FD detectors to  $60^\circ$  elevation above the horizon with new telescopes (HEAT project) and the other being an infill of SD and muon detectors in a small part of the array (AMIGA project). Both developments will allow the observation of showers down into the region of the second knee.

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