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The Pierre Auger Observatory and Planck Scale: myths and facts.

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Cosmic Ray (CR) Physics at the highest energies can provide a link to physics beyond Planck Scale. However this fact has sometimes generated false expectations and statements. With the use of the latest data from the Pierre Auger Observatory, the largest CR experiment in the world, I discuss the present status of the CR - Planck Scale correlation.

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1. Ultra High Energy Cosmic Rays and Planck Scale Physics

Since late sixties, cosmic ray experiments are detecting extremely high energy particles, up to energies of the order of $10^{19}-10^{20}\ eV$. These are *macroscopic* energies, the highest energies reached by single particles in the present universe. Only near the inflation era in the early universe similar energies are found.

The Linear Collider will reach TeV energies in an accelerator some 10 km long; to reach $10^{20}\ eV$ one would need with this technology an accelerator $\approx 10^9$ km long, approximately ten times the radius of Earth orbit; so hopes to produce that much energy in a man-made accelerator ar very faint, to say the best. Even from the more modest point of view of Center Of Momentum energy, one such particle interacting with the Earth's atmosphere has a COM energy far larger than that attainable at LHC.

Soon after the discovery of the Cosmic Microwave Background Radiation in 1965, Zatsepin and Kuzmin and independently Greisen [1], discovered that the Universe would become opaque to extremely high energy protons, since they would interact with the background photons and photoproduce pions; the threshold for the onset of this process, in the frame in which CMBR appears isotropic, is $E_{GZK} \approx 6\cdot 10^{19}\ eV$.

It is evident that the verification of this effect would be a test of relativistic frame invariance. The process responsible of the pion production is in fact a low energy process in a terrestial frame, and indeed one of the most studied: pion photoproduction requires $\approx 100\ MeV$ photons on a standing proton target. Due to the fact that the median energy of CMBR photons is $\approx 10^{-3}\ eV$ the photopion production can only happen ia a boosted frame, the boost needed corresponding to a Lorentz factor $\gamma_L \approx 10^{11}$. Therefore, finding the so-called GZK cut-off would amount to verify relativistic frame invariance up to this Lorentz boost. Not finding it would open the door to many possibilities, among wich also the possibility that Lorentz invariance is violated or modified. This is a very robust prediction, since essentially the only ingredient is the invariance of physics in different inertial frames, while it is independent on details of interactions.

This was realized soon after the Greisen, Zatsepin and Kuzmin papers. In fact in a relatively little known paper, D.A. Kirzhnitz and V.A. Chechin ("Ultra High Energy Cosmic Rays and a possible generalization of Relativistic theory" [2]) in 1972 wrote:

"Primary protons are expected to be strongly slowed down by the interaction with the background thermal radiation .." and added " ..The point is that primary protons have a uniquely large Lorentz factor $\gamma > 5\cdot 10^{10}$ larger by many orders of magnitude than in any other experiment...". On the phenomenological consequences they wrote: "...However no break is observed in the CR spectrum in this region. It is premature in this circumstance..".

In their paper they developed a deformation of relativistic invariance in some aspects similar to modern Deformed Special Relativity [3],[4], but they needed to introduce quite a low breaking mass to explain the asserted experimental situation. On the other hand the experiments of the epoch had both very low statistics, and poor energy calibration; therefore these considerations remained very speculative at that time.

In the following, I will concentrate on the exhamination of the experimental status of the GZK feature as well as the consequences that can be derived with respect to Planck Scale Physics.

To make quantitative the relation between the photopion threshold and Planck Scale Physics, it is customary to introduce modified dispersion relations:

$$E^2 - p^2 = m^2 + \mu^2(p, M)$$

where $p = \sqrt{(}p_i p^i)$ and rotational invariance is assumed (see for instance [5]). In linearly Lorentz Invariant theory $\mu^2(p) = 0$, while in violating/deformed theories it can be a function of momenta; we have chosen to express relativistic invariance deformations in terms of the mass M, a natural value being $M = M_P$ (Planck mass) while LI is recovered at $M \to \infty$. This is the simplest modification of particle dispersion relations and implicitely assumes equal modifications for all particles. More general approches (*e.g.* in effective field theories [6]) produce a larger space for violations parameters and richer models. We are here discussing only very general concepts, and will not enter in these important details that have been extensively discussed in the literature.

Notice that relevant effects on the propagation of particles are expected when $\mu^2(p) \approx m^2$; for instance, if $\mu^2(p) = \pm \frac{p^3}{M_p}$ this happens around $10^{13}\ eV$. Of course this is only a dimensional argument: both particle dependent and independent dimentionless coefficients will be in general present.

In general, relativistic frame invariance is lost, unless also the composition law of momenta are modified appropriately. This is the approach followed in Deformed Special Relativity.

In the LIV case, assuming unmodified energy-momentum conservation, the GZK threshold [1] changes, in general depending on the energy (momentum) of the projectile and the modification can be so large that the photoproduction process becomes forbidden at high enough energies. For instance for a dispersion relation:

$$E^2 - p^2 = m^2 \pm \frac{p^3}{M_P}$$

the (schematic) behaviour of the threshold in this simple model is represented in figure 1.

In DSR case, the underlying relativistic frame invariance severely limits the effects on the calculation of thresholds, pushing it essentially to the Planck scale [7].

So the position of the GZK feature can test Planck scale physics.

2. Two wrong but tenacious myths about GZK feature.

The spectrum of cosmic rays extends from approximately 1 Gev or less to more than $10^{20}\ eV$, with a broken power law spectrum

$$dn/dE \propto E^{-\gamma(E)}$$

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[1] Clearly in this case the computation of the threshold must be performed in a fixed referece frame, generally that in which CMBR is isotropic with respect to Earth.

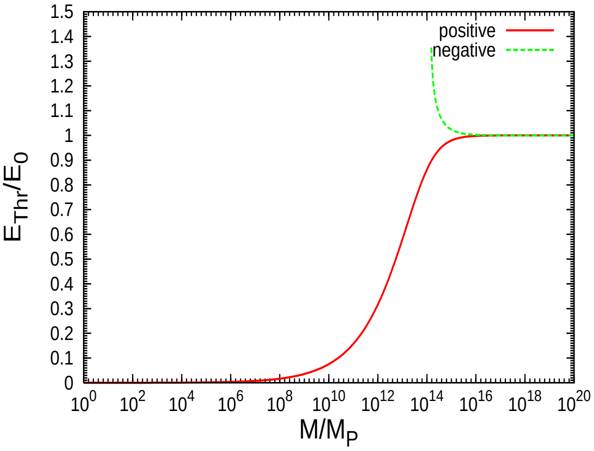

Figure 1: Variation of threshold for pion photoproduction with the breaking parameter M for violations O(1/M).

with $\gamma \approx 2.7$ $(E < 5 \cdot 10^{15})$, $\gamma \approx 3$ $(5 \cdot 10^{15} < E < 5 \cdot 10^{18})$, $\gamma \approx 2.7$ $(E > 5 \cdot 10^{18})$, although in the last region the errors are very large. A compilation of different experimental results concerning the CR spectrum is reported in figure 1, where the flux is multiplied by $E^{2.7}$ to magnify the structures [8]. The general trend, as well as some discrepancy at least in the interpretation of different experimental results, are evident. Cosmic Ray experiments are difficult, and relating their results, even nominally in the same energy range, is almost always tricky.
Above $\approx 6 \cdot 10^{19}$ *eV* the GZK "cut-off" is expected.

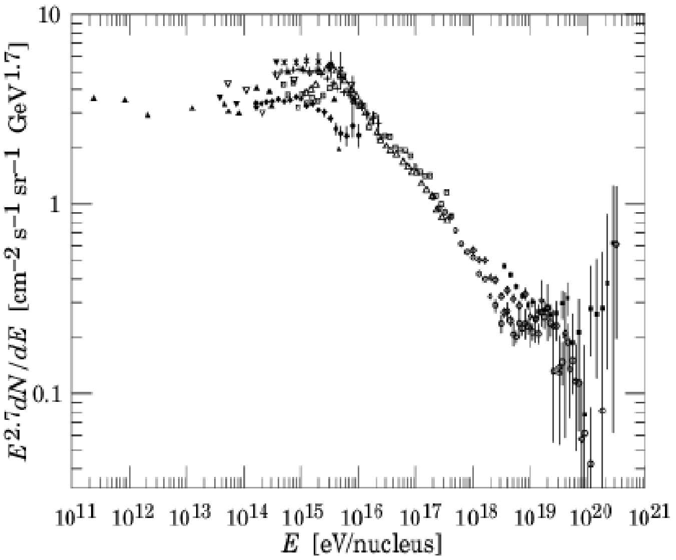

Figure 2: Compilation of the 'all particle' spectrum of Cosmic Rays from different experiments, where 'all particle' means that each nucleus is counted once, irrespective of its atomic number Different symbols relate to different experiments [8].

The first myth in fact relates to the structure of the spectrum around the GZK threshold, and can be formulated in the following way: *"Would the existence of CR particles with energies larger than the GZK threshold contrddict the existence of the effect?"*

In the customary way of plotting the differential CR spectrum multiplied by $E^{2.7}$ as in figure 2, the GZK feature appears as a dramatic decrease. However things are really different. A primary proton generated with an energy well above the GZK threshold will have $\approx 6\ Mpc$ interaction length and lose $\approx 10-20\%$ of its energy for each interaction. Therefore it will go below the GZK threshold after $\approx 50-100\ Mpc$; this distance is sometimes called the GZK "horizon". A little of thought then convinces ourselves that the spectrum decrease is related to the ratio of the GZK horizon to the visible Universe. To be more quantitative, one has to take into account the effect of redshift, the behaviour of the source spectrum and evolution effects of the sources (see [9]). The bottom line of this reasoning is that the (model dependent) expected decrease of the CR spectrum is a factor $O(10)$ over a range of energies around the GZK threshold: so the definition of *cut-off* is misleading, and super-GZK events are indeed expected, although in reduced number, this being simply the effect of the fact that the measured C.R. spectrum is a superposition of unresolved sources. Only in the case in which we could measure the spectrum from a single source with reasonable statistics, then we would see instead an exponential cut-off for those sources outside the GZK horizon.

The formulation of the second myth can be expressed as: *"Does the existence of a sudden dip in the spectrum implie* by itself *a verification of the GZK feature?*

To answer to this quetion one has to take into account what are the possible sources of particles of the energies we are here discussing. Concerning the sources of CR there is a general consensus that up to $\approx 5\ 10^{15}\ eV$ the production is via shock acceleration in galactic Super Novae remnants (although a direct, clear-cut experimental evidence still lacks), while above some $10^{18}\ eV$ the Galactic Magnetic field is unable to confine protons, so if CRs are protons they are likely of extragalactic origin. There is however very little certainty on the origin of the extreme high energies particles. It is really hard to conceive mechanisms capable (in astrophysical contexts) to accelerate particles at these energies, and the number of possible sources is very low, if not null. So, mechanisms ("top-down") in which the highest energy particles are produced through the decay of some (superheavy) remnant of the Big Bang have been invented. These mechanisms have their own problems however.

We in fact do not know the origin of CR particles, nor exactly their nature, at these extreme energies. In particular, if particles are accelerated in astrophysical sources, then it is expected that their spectrum is cut somewhere, if not because the engine that accelerates could not have been operating for more than the life of the Universe. We do not know where this (real) cut-off is but it is certainly not many orders of magnitude above $10^{20}\ eV$. So there is a slight but not irrelevant possibilty that a possible decrease of the spectrum is an effect of a cut in the sources.

The GZK feature would be unambigously detected if: i) the spectrum continues at higher energies although depressed; ii) or the pile-up of particles generated at higher energies, which lose most of their energy going below the photopion production threshold, will be detected; iii) finally a statistically significant correlation of (most of the) detected events is found with astrophysical sources within the GZK horizon.

If particles are due to the decay of superheavy parents (top-down models) then they are expected to be mostly photons. This will be discussed in the next section.

In any case either the confirmation of the GZK feature is experimentally demanding (cases i and ii) or requires measurements of different observables apart the spectrum; as always, in Cosmic Ray Physics, several measurements of different variables are needed, and this much more in the extreme energy part of the spectrum, where we have at present little (if any) knowledge of the possible sources.

3. The present experimental situation.

The situation concerning the GZK feature has been controversial for almost a decade. The former largest experiments, AGASA [10] and HiRes [11] still disagree in their latest reanalysis, although to a statistically unfirm level.

The Pierre Auger Observatory [2] has presented at the last International Cosmic Ray Conference several papers related to the spectrum of Cosmic Rays. Let start from the spectrum itself.

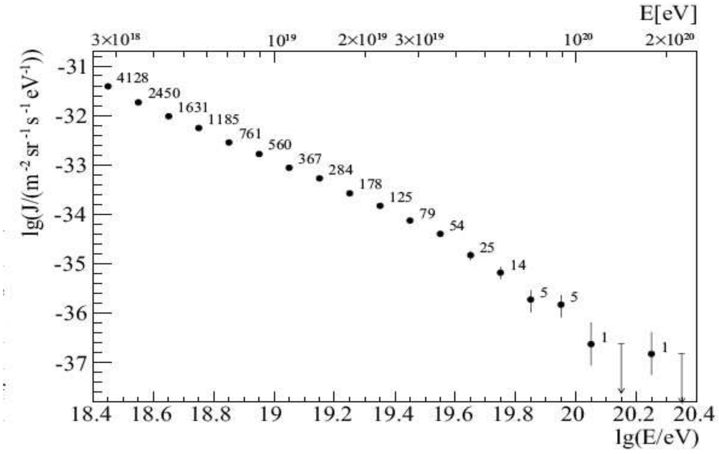

Figure 3: The spectrum reported by the Auger experiment.

In figure 3 is reported the differerential spectrum [13] from $\approx 2.5\ 10^{18}$ eV to the higest energy events. Already from this plot two points are quite evident:

- a drop of the spectrum is evident starting around $\approx\ 5\ 10^{19}$ eV
- there are (a few) events above 10^{20} eV

The drop becomes more evident if one multiplies the spectrum by some power of the energy (figure 4). A continuation of the spectrum with the same slope as at lower energies is excluded at the 6σ level.

Is this enough to assess the presence of the GZK feature? In the next figure the end of the spectrum is plotted, superimposed to an unbiased fit and several theoretical predictions, that take into account the GZK feature [14]. Within the present limited statistics (27 events above the spectrum

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[2] The Observatory has been described in several papers, for instance [12] and we refer to these papers for its description.

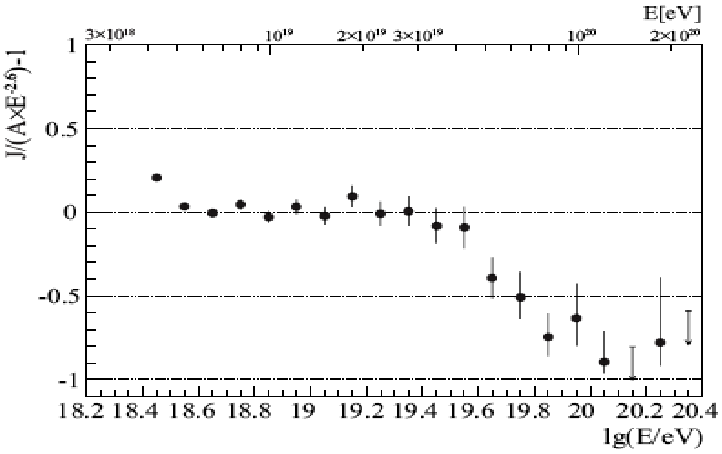

Figure 4: The statistical significance of the high energy decrease.

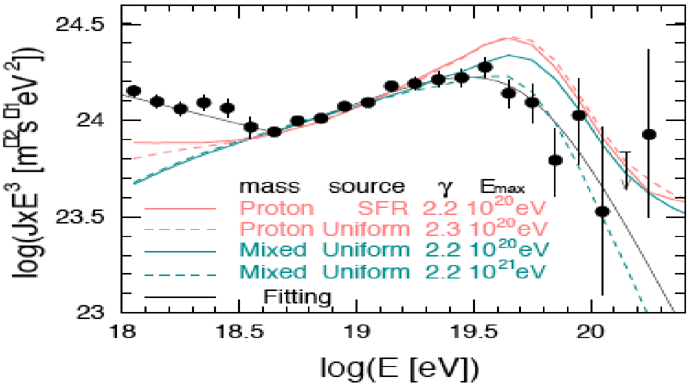

Figure 5: The highest energy part of the spectrum compared with theoretical models. The continuous line is a fit with exponentially cut-off power spectrum.

steepening) the difference among the models and from models and data is not realy statitically significant. However from the spectrum alone it is still not possible to conclude that the data confirm the existence of the GZK feature.

An important feature is the nature of the particles at highest energies: were they photons, this would support the top-down models, in which the produced particles are mostly photons. Auger, by using both the fluorescence and surface detectors, can put a strong limit on the photon content of the flux [15, 16]. In fact, no photon events were recorded. In figure 6 I report the limits obtained by the experiment, compared with some top-down limits. It is quite evident that it starts to be unlikely that the top-down mechanism contributes dominantly to the end of the measured spectrum, although a sub-dominant contribution cannot be excluded.

However the most exciting result, that can also have profound implications for the existence of the GZK drop, has been very recently released. Being the top-down models disfavoured, the

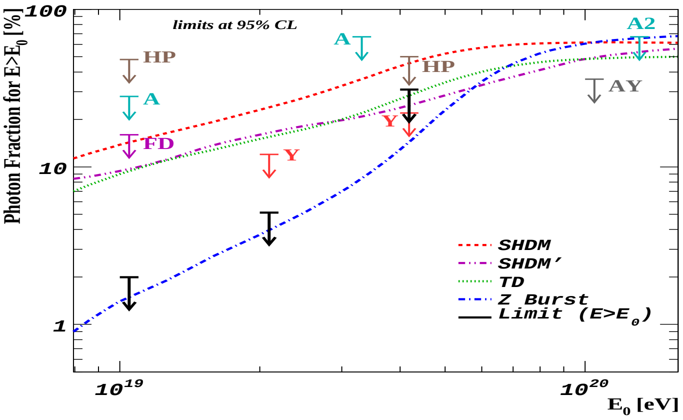

Figure 6: Limits on the photon fraction from the Auger Observatory, compared with som top-down models.

question of what are the sources of cosmic rays remains unanswered. It is therefore mandatory for an experiment like the P. Auger Observatory, to look for cosmic sources. There have been several previous attempts, without compelling results.

If the cosmic ray particles are nuclei, then they are deflected by magnetic fields in their travel from the sources to detection. Little is known about intergalactic magnetic fields, but they are certainly smaller than a few nG. However the Galactic magnetic field ($\approx 3\mu G$) is better known and will influence the propagation of the particles. If they are protons, however, from most of the directions (excluding the galactic plane) the angular deviation would be of few degress so it will become possible to detect their pointing to sources.

The search has been performed by first finding some evidence of correlation through a scan on the parameter space (energy, angular deviation from source and their redshift). Of course this scan

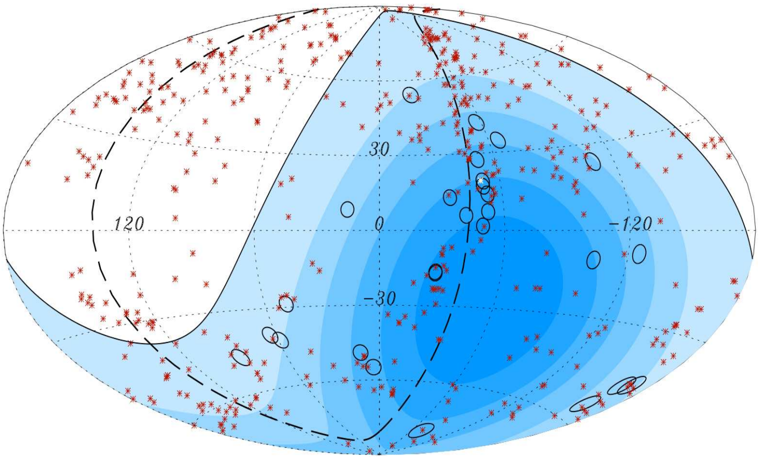

Figure 7: Sky distribution of Auger events (dots, with a 3° circle), $E > 57\ 10^{19} eV$ superimposed to the positions of the AGNs ($z \leq 0.018$) in the Veron-Veron Cetty catalogue. The solid line limits the acceptance region of the experiments, while equal colour regions have same acceptance.

makes diffcult to assess the real probability of the signal found, that consisted in 13 correlating events found in 15 events at an energy $\geq 5.7\ 10^{19} eV$ within $\approx 3^{\circ}$ from AGNs [17] at $z \leq 0.018$, while 3 were extected. On this basis a new search was started by fixing these parameters, and prescribing the end of the search when the probability was below a fixed value. This was reached during this year [18]. In figure 7 I present a skymap of the events (27 up to end of August 2007) superimposed to the AGNs positions. The probability of the *a priori* selected events to come from an isotropic distribution is $< 1\%$. A reanalysis of all the events gives much lower probabilities, but these are *a posteriory* probabilities.
The fact that the correlation is strongest for $z < 0.018$ $(D < 75\,Mpc)$ and weakens in larger volumes is an indication that the sources visible in high energy cosmic rays are contained in a limited volume, that would confirm the presence of the GZK feature.
Although this result is extremely interesting, it has to be confirmed by a larger statistics and further analyses. Also the nature of the primary particles (there is some indication that they might be heavier nuclei [19] and this would partly spoil the correlation) and the systematics of their energy assignement have to be clarified.

4. Conclusions.

The connection between Cosmic Ray Physics at the extreme energies and Planck Scale Physics is extremely intriguing and potentially powerful. However the difficulties and subtleties of Cosmic Ray Physics have often been overlooked, giving some times rise to false expectations. Cosmic Ray Physics on one hand is the only available arena were particles of energies up to 10^{20} eV are produced. On the other hand, Cosmic Ray experiments are truely difficult, and more at the highest energies; short cuts are not allowed, and only when several different measurements are put together one can reach sensible and statistically sound conclusions. This is the case of the evidence (or not) of the GZK thresold. The Pierre Auger Observatory is addressing this (among many other) issue with unprecented sensitivity. After one equivalent year of data taking several pieces of information start to converge towards a confirmation of the GZK feature, and maybe the Cosmic Ray Astronomy is beginning.
With the confirmation of the GZK feature, Lorentz Invariance Violations are severly contrained. In the simple picture described above, i.e. equal violation parameters for nucleons and pions with M as the only free parameter, $O(1/M)$ and $O(1/M^2)$ terms are essentially forbidden: in the case of the milder $1/M^2$ violation $M \approx 500 - 1000\ M_P$ depending on the accuracy with wich the GZK is reproduced in any given model of sources [5]. Of course in more realistic models there will be (even in the cases above) some regions of the space of violation parameters that are still allowed and it will be interesting to study if there are possible phenomenological consequences in these models. Milder violations than $O(1/M^2)$ are essentially unconstrained, but likely to lack of any phenomenological effects. On the other hand, essentially all the variants of deformations of invariance are not touched by the Cosmic Ray results. It is particularly intriguing that these indications regarding physics at the smallest distances are coming in part from the detection of particles produced by very distant astrophysical objects.

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