# THE MOST POWERFUL PARTICLES IN THE UNIVERSE: A COSMIC SMASH

## LAS PARTÍCULAS MÁS PODEROSAS DEL UNIVERSO: UN REMATE CÓSMICO

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Hemos celebrado recientemente el centenario del descubrimiento de los rayos cósmicos. Aparecen por todas partes en el Universo, y ocurren con energías muy diferentes, incluyendo las partículas más energéticas que existen. Sin embargo, la teoría predice una supresión abrupta (o "corte") por encima de cierta energía gigantesca. Esto resulta difícil de verificar, las mediciones son controvertidas, pero nos ofrece una oportunidad única de comprobar conceptos establecidos en la Física —como la invarianza de Lorentz— en condiciones extremas. Si las observaciones contradicen a la larga este "corte", este pudiera implicar la revisión de un pilar fundamental de la Física.

Recently we celebrated the centennial of the discovery of *cosmic rays*. They are whizzing all around the Universe, and they occur at very different energies, including the highest particle energies that exist. However, theory predicts an abrupt suppression (a "cutoff") above a specific huge energy. This is difficult to verify, the measurements are controversial, but it provides a unique opportunity to probe established concepts of physics —like Lorentz Invariance— under extreme conditions. If the observations will ultimately *contradict* this "cutoff", this could require a fundamental pillar of physics to be revised.

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## I. DISCOVERY OF COSMIC RAYS AND AIR SHOWERS

Throughout our lives we are surrounded —and penetrated— by various types of radiation. Mankind was already aware of that in the beginning of the 20th century, when instruments (like the electroscope) were developed to detect ionizing radiation, and sources inside the Earth (like the alkaline metal radium) were identified. But does all the radiation around us originate from the Earth?

If this was the case, the radiation intensity should decrease rapidly with the height above ground. In 1910 the German Jesuit Theodor Wulf performed tests on top of the Eiffel tower, but they did *not* confirm the expected decrease. People criticized, however, that the presence of tons of metal might have affected his results. More stringent experiments were done on balloons; in particular in 1912 the Austrian scientist Viktor Hess observed in seven balloon journeys that the ionizing radiation decreases only mildly up to a height of about 2000 m above ground, but as he rose even higher (up to 5350 m) it gradually *increased* again. He interpreted this observation correctly: significant radiation must come from outside the Earth. Comparing data taken at day and night, and during an eclipse, he also concluded that the sun cannot be a relevant source of these *cosmic rays*.

As a further milestone, in 1938 the French physicist Pierre Auger noticed that Geiger counters which were well separated (by tens or hundreds of meters) often detected radiation practically at the same time. He explained this effect as follows: a powerful cosmic ray particle (a "primary particle") arrives from outer space and hits the terrestrial atmosphere. Its violent collision with molecules of the air triggers a cascade of "secondary particles", which we call an *air shower*. Auger noticed that he had detected secondary particles belonging to the same air shower, which arrive on ground almost simultaneously. The formation of an air shower is illustrated in Figure 2.

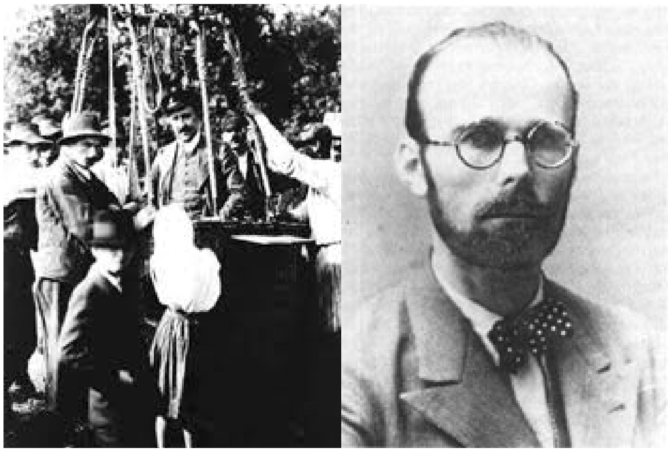

Figure 1: Viktor Hess (on the left) and Pierre Auger (on the right), the men who discovered the cosmic rays and the air showers, respectively.

It can be compared to a white "primary" billiard ball, which hits (in the beginning of a game) a number of colored balls, so its momentum is transferred and distributed over numerous "secondary" balls. However, in an air shower new "balls" are created in the collision, and in the subsequent evolution; the more powerful the primary particle, the more secondary particles emerge.

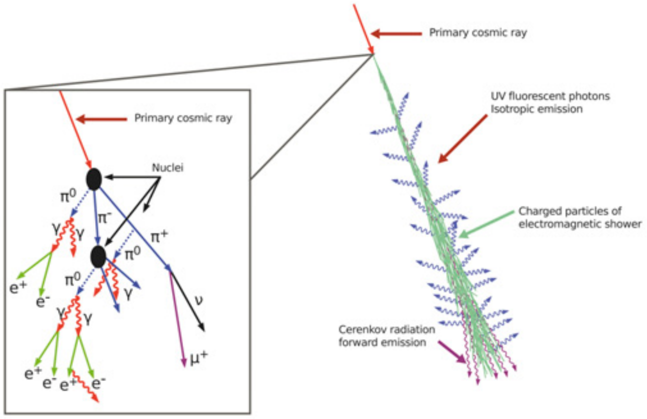

Figure 2: Illustration of an air shower. We recognize the so-called fluorescence light (UV or bluish), and the generation of light particles named pions ( $\pi$ ), which rapidly decay into even lighter leptons ( $e, \mu, \nu$ ) and photons ( $\gamma$ ).

By analyzing his data taken at sea level and in the Swiss alps, Auger conjectured that some primary particle energies should be at least of the order of $10^{15}$ eV.[1]

The kinetic energy is a measure for how much work is needed to accelerate an object from rest to a given speed. For comparison, a table tennis ball with a speed of 34 cm/s has the same kinetic energy, $10^{15}$ eV , but a $5.4 \cdot 10^{23}$ times larger mass, if we assume the primary cosmic ray particle to be a proton (we recall that the tiny nucleus of a hydrogen atom consists of a proton).

## II. THE PROFILE OF THE COSMIC FLUX

Today we know about cosmic rays in the energy range of $E \approx 10^9 \ldots 10^{20}$ eV . Up to now we only know of their existence, but very little about their origin.[2] The top energy, about $10^{20}$ eV, is 100 000 times larger than Auger's estimate. This corresponds to the kinetic energy of a tennis ball with 85 km/h, a table tennis ball with 392 km/h (for comparison, the hardest smashes in professional table tennis games attain about 100 km/h).

One assumes the high energy cosmic rays to consist to about 90 % of protons, and to 9 % of helium nuclei. They are whizzing all around the Universe, in all directions, at any time. We may wonder how many there are, *i.e.* how many cosmic ray particles cross a given area per time. This is what we denote as the cosmic *flux*. Over the entire energy range, this flux follows closely a curve proportional to $1/E^3$ , see Figure 3. So if we double the energy at which we measure the flux, it will decrease by a factor of 8. The validity of such a simple rule over such a huge range is very remarkable; the ratio between its lowest and highest energies corresponds to the ratio between the size of a human body and our distance from the sun. This is impressive, but the reason for this rule is not understood.

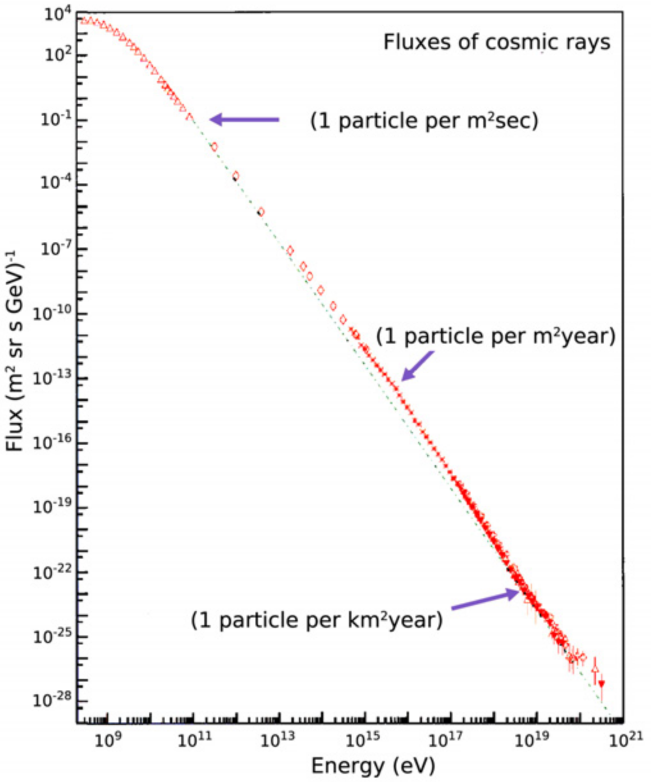

Figure 3: The flux of cosmic rays as a function of the energy. Over a very broad energy interval it falls off approximately proportional to $1/E^3$ (dashed line). Around $E = 6 \cdot 10^{19}$ eV an abrupt flux reduction is predicted; this is the GZK cutoff.

Around $10^{12}$ eV the flux is 10 primary particle per minute and $m^2$ (convenient for measurements), but as we approach the upper end of the known spectrum, say between $10^{18}$ and $10^{19}$ eV, we are left with only 1 primary particle per year and $km^2$; here the detection takes a large area, and a lot of patience. But what happens at *even higher energy*, does the flux continue with the same $1/E^3$ power law and we just haven't measured it well so far?

## III. FROM THE COSMIC MICROWAVE BACKGROUND TO THE PREDICTION OF THE "GZK CUTOFF"

In 1965 Arnold Penzias and Robert Wilson discovered (accidentally) the Cosmic Microwave Background (CMB), which is a relic of the Early Universe: its photons (the quanta of electromagnetic radiation) decoupled some 380 000 years after the Big Bang, when the Universe only had 0.0028% of its age today. This photon radiation cooled down ever since, so at present the CMB —and therefore the Universe— has a temperature of 2.73 K.[3] This means that one $cm^3$ contains in average 411 CMB photons, with a mean wave length of 1.9 mm, which corresponds to a tiny energy of 0.0006 eV.

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[1] An electron volt (eV) is the energy that it takes to displace an object with the electric charge of an electron against the voltage of 1 V. It is a very small unit of energy, which is commonly used in quantum physics. We can convert it to macroscopic units as follows: $6.2 \cdot 10^{18}$ eV = 1 J = 1 kg m²/s², and $10^{18}$ means 1 000 000 000 000 000 000 (18 zeros).

[2] Radiation at lower energy is also present, and here the sun does contribute significantly, but we do not denote that as "cosmic rays".

[3] The absolute temperature minimum is 0 K = -273.15 ºC, hence the CMB temperature corresponds to -270.42 ºC.

Figure 4: From left to right: Kenneth Greisen (1918 – 2007), Georgiy Zatsepin (1917 – 2010) and Vadim Kuz'min (born in 1937), the theoretical physicists who predicted in 1966 the "GZK cutoff" for the cosmic ray spectrum.

One year later, this discovery led to an epoch-making theoretical work, independently by Kenneth Greisen at Cornell University (state of New York), and by Georgiy Zatsepin and Vadim Kuz'min at the Lebedev Institute in Moscow [1]: they (we denote them as GZK) predicted the cosmic ray spectrum to have a "cutoff" around $E_{\text{GZK}} = 6 \cdot 10^{19}$ eV , *i.e.* they predicted that the flux above $E_{\text{GZK}}$ should nearly vanish. These two papers have a renowned status, although they were both short, with hardly any formulae, but with a groundbreaking idea.

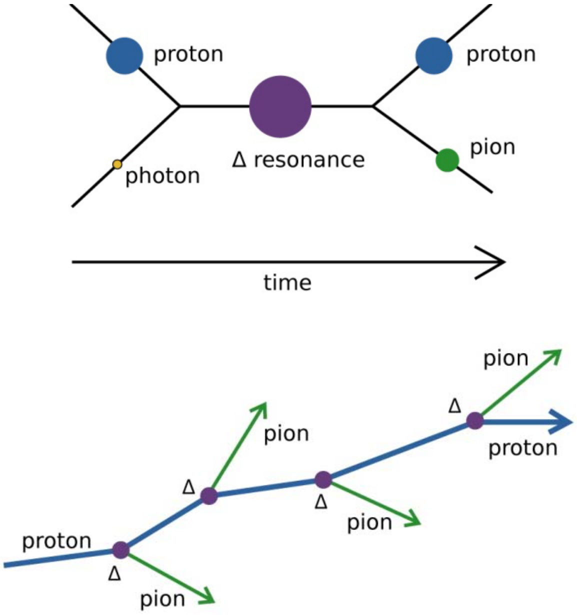

Figure 5: Above: The scheme of photopion production due to the collision of an ultra high energy proton with a CMB photon. Below: Trajectory of a super-GZK proton (a proton with energy above $E_{\text{GZK}}$ ) through the CMB, suffering energy attenuation due to repetitive photopion production.

Their point was that the scattering of protons with photons can generate a heavier particle, which we now denote as a "Δ resonance" (similar to a violin string vibrating above its fundamental frequency). It is short-lived, and its decay reproduces the proton, along with an (aforementioned) lighter particle called pion ("photopion production"), as illustrated in Figure 5 above.[4] The pion carries away part of the energy, typically about 20 %.[5] $E_{\text{GZK}}$ is just the threshold energy for a cosmic proton to create such a Δ resonance when hitting head-on a (relatively energetic) CMB photon. So if a proton with an even higher energy travels through the Universe, it will undergo this process again and again, and lose energy each time, until it drops below $E_{\text{GZK}}$ . This step-wise attenuation is sketched in Figure 5 below.

As a rough picture, we could imagine a car driving very fast, above the speed limit. As a consequence it touches obstacles here and there, say without a bad accident, but losing speed each time. This is repeated until the car has slowed down below the speed limit, then it does not suffer from further collisions anymore. So at the end of a long road, all cars will necessarily arrive with an allowed speed.

Considering the photon density that we mentioned above, and the target area ("cross section") for a proton-photon collision leading to a Δ resonance (around $10^{-28}$ cm$^2$), the mean free path length —between two such collisions— for a proton just above $E_{\text{GZK}}$ is around 15 Mpc.[6] If the initial proton energy is much higher, the energy attenuation is much more rapid, since photopion production is more frequent, and the proton loses more energy each time. In that case also the emission of several pions is possible (cf. footnote 5).

One concludes that protons can travel maximally about $L_{\max} = 100\,\text{Mpc}$ with super-GZK energy, $E > E_{\text{GZK}}$. If the primary ray consists of heavier nuclei, this maximal distance is shorter, because such a nucleus tends to break apart under scattering, such that its fragments lose even more energy.[7]

$L_{\max}$ is a long distance compared to the radius of our galactic plane of about 0.015 Mpc, but it is short compared to the radius of the visible Universe, which is around 14000 Mpc. So if sources of ultra high energy cosmic rays are spread homogeneously in the Universe, the flux that we observe on Earth should have a strong extra suppression as the energy exceeds $E_{\text{GZK}}$ , pushing its intensity well below the extrapolated $1/E^3$ rule. This is not a strict cutoff —although it is referred to as the "GZK-cutoff"— but it is an interesting and explicit prediction. Its verification, however, is a tough challenge for our best observatories, due to the tiny flux at $E > E_{\text{GZK}}$ (cf. Section 2).

## IV. OBSERVATIONS OF ULTRA HIGH ENERGY COSMIC RAYS IN THE 20TH CENTURY

In 1963, already before this prediction was put forward, one super-GZK event with an estimated energy of $10^{20}$ eV was reported by John Linsley, based on an air shower detected in

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[4] Photopion production can also occur in a less direct way, where Δ first decays into a pion and a neutron, and the latter is converted subsequently into a proton through β-decay. These two channels together cover 99.4 % of the Δ decays.

[5] For proton energies well above $E_{\text{GZK}}$ also higher resonances are possible, where the decay may yield several pions, so that the proton loses even more energy.

[6] One parsec (pc) is a standard length unit in astronomy, which corresponds to $3.1 \cdot 10^{16}$ m, or 3.3 light-years. 1 Mpc = $10^6$ pc means one million of parsecs.

[7] Nevertheless the recent literature also considers iron nuclei (Fe) as possible primary particles of ultra high energy cosmic rays.

the desert of New Mexico (USA). This issue attracted interest world-wide. Greisen expressed his surprise about that, and added that he did not expect any events at even higher energy.

Nevertheless, in 1971 another super-GZK event was observed in Tokyo, this time with even higher energy. This inspired the construction of a large observatory near the Japanese town Akeno, which is called AGASA (Akeno Giant Air Shower Array). Until the end of the last century AGASA dominated the world data about ultra high energy cosmic rays. It recorded about two dozens of new super-GZK events, and compatibility with the $1/E^3$ rule also beyond GZK, *in contrast to the prediction* [2]. This picture was essentially supported by somewhat smaller installations in Yakutsk (Russia) and Haverah Park (England). The world record is generally considered a primary particle with $3 \cdot 10^{20}$ eV, reported in 1991 by the Fly's Eye detector in Utah (USA), which was designed like the compound eye of an insect.

We are lucky that such ultra high energy rays form air shower about 15 km above ground, so that their energy is dispersed over many secondary particles, rather than hitting us directly. In macroscopic terms, this energy world record corresponds to 48 J, and to the kinetic energy of a tennis ball with a considerable speed of 147 km/h. If the ball drops in vacuum from a tower of 85 m height, it will hit the ground with this speed (with air resistance it never gets that fast). This is still not the maximal speed in a professional tennis game; the second service of Novak Djokovic —currently the tennis star number one— is around 160 km/h, and his first service sometimes exceeds 200 km/h. According to AGASA even that energy should be reached by single cosmic protons.

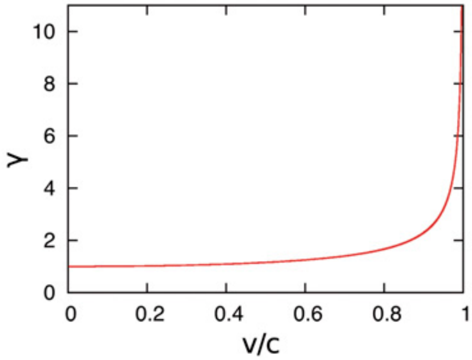

Figure 6: The boost factor $\gamma$ as a function of the relative speed $v$ in a Lorentz transformation. This speed is displayed in units of $c$, the speed of light. $\gamma = 1/\sqrt{1-v^2/c^2}$ is close to 1 if $v \ll c$, but it diverges as $v$ approaches $c$.

## V. DOUBTS ABOUT A FUNDAMENTAL LAW OF PHYSICS?

Is this true, despite the stringent theoretical argument by Greisen, Zatsepin and Kuz'min? This scenario fascinates physicists, since it would be a clear indication of a phenomenon at tremendous energy, which is incompatible with our established theories, so its explanation would require *new physics*. Several ideas were elaborated to explain the possible failure of this prediction. The most prominent approach is a *violation of Lorentz Invariance,* see *e.g.* Ref. [3], and Ref. [4] for a recent review.

Lorentz Invariance means that observers moving with constant speed relative to each other —for instance living on different space stations— perceive the same laws of physics, hence there is no "preferred" reference frame. This is one of the most fundamental pillars of our physical concepts. The observed quantities are transformed according to simple formulae of Einstein's Theory of Relativity ("Lorentz transformation"). In particular the speed of light, $c \simeq 3 \cdot 10^8$ m/s, must be invariant.[8] A Lorentz transformation is characterized by a boost factor called $\gamma$, which translates for instance a length, a time period or an energy as it is perceived by the two observers. $\gamma$ grows monotonously with the relative speed between the observers, *i.e.* a faster speed implies a larger $\gamma$. It goes towards infinity when this relative velocity approaches the speed of light, see Figure 6. So in this case the perceptions of the two observers —*e.g.* of the length of a given object— are drastically different.

The validity of Lorentz Invariance is very well tested and confirmed with our most powerful particle accelerators up to $\gamma$-factors around $10^5$, in particular due to the Large Electron-Positron Collider (LEP), which was operating at CERN in Geneva from 1989 to 2000.[9] This excludes "preferred reference frames" at that level. Here the observers move relative to each other with 99.999999995 % of the speed of light. (No massive object can ever attain exactly the speed of light —that would require an infinite amount of energy.)

What does this imply for ultra high energy cosmic rays? So far we have tacitly assumed Lorentz Invariance to hold. For example, the mean free path length of a cosmic super-GZK proton —before performing the next photopion production— that we mentioned in Section 3 (some 15 Mpc) is based on measurements of the proton-photon cross section in laboratories. Actually our accelerators cannot provide such tremendous proton energies. Even the most powerful accelerator in history, the LHC (referred to in footnote 9) stays far below that. One may use, however, protons at rest and expose them to a photon beam of about $200\,\mathrm{MeV} = 2 \cdot 10^8$ eV, which is equivalent, *if* we assume Lorentz Invariance to hold. This is rather easy for experimentalists, it was done already in the 1950s, so Greisen, Zatsepin and Kuz'min could refer to the result. Also the computation of the energy loss of an ultra high energy proton under photopion production that we mentioned in Section 3 (about 20 %) is based on Lorentz Invariance.

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[8] This property is different from the non-relativistic "Galilean transformation", which was used until the beginning of the 20th century. That is a simplification, where any observer perceives the same distance, time interval etc. (the boost factor is set to $\gamma = 1$). It corresponds to setting the speed of light to $c = \infty$, which is a good approximation as long as the speed $v$ under consideration is much slower, $v \ll c$, cf. Figure 6.

[9] The now operating Large Hadron Collider (LHC, also at CERN) attains even higher energies, but for particles and nuclei which are much heavier than the electron and positron, so LEP still holds the *speed* world record in laboratories.

However, the transformation factor between a proton at rest, and with an energy around $E_{\mathrm{GZK}}$, amounts to $\gamma = E_{\mathrm{GZK}} / m_{\mathrm{p}} \approx 10^{11}$, *far* beyond the boost factors that have ever been tested ($m_{\mathrm{p}} \simeq 9.38 \cdot 10^{8}$ eV is the proton mass). A proton with energy $E_{\mathrm{GZK}}$ moves with 99.99999999999999999995 % of the speed of light. So could Lorentz Invariance be an excellent approximation up to $\gamma \approx 10^{5}$, which still requires some modification at much larger $\gamma$ values?

The possible *absence* of the GZK cutoff for cosmic rays could be a hint for this scenario. This question has to be addressed experimentally, and it is a fascinating opportunity to probe our established theory under truly extreme conditions, which are by no means accessible in our laboratories.

## VI. THE PHENOMENOLOGICAL SITUATION TODAY

In the beginning of the 21st century the phenomenological situation changed, when the HiRes (High Resolution) Observatory in Utah (USA) started to dominate the world data [5]. Its results favor the conclusion *opposite* to AGASA, *i.e.* the "boring scenario" where the GZK cutoff is confirmed, no new physics is needed, and Djokovic's service is not challenged by cosmic protons. In the contrary, this would provide indirect evidence *for* the validity of Lorentz Invariance, even at such tremendous speed transformations.

How could this discrepancy with AGASA and other observatories occur? A possible explanation is that they used different techniques: AGASA, Yakutsk and Haverah Park detected on ground secondary particles of powerful air showers. As a rough rule, such a shower involves (in its maximum) about 1 particle for each GeV of the primary particle (1 GeV = $10^{9}$ eV), so that a $10^{20}$ eV proton can give rise to a shower of up to $10^{11}$ secondary particles (in this respect, the colored billiard balls cannot compete). After detecting some of these secondary particles, fast computers and sophisticated numerical methods are used to reconstruct the most likely point where the shower took its maximum. That indicates the nature of the primary particle (or nucleus) —the heavier it is, the higher the shower maximum. This numerical reconstruction of the air shower evolution also provides an estimate for the primary particle energy —obviously with some uncertainty.

On the other hand, HiRes monitored a weak bluish or ultraviolet "fluorescence light" (see Figure 2). It originates in nitrogen molecules in the air, which are excited by an air shower, and which emit this light when returning to their ground state. The virtue is that the shower is observed at an early stage, so it does not need to be reconstructed afterwards numerically. On the other hand, this observation is only possible in nights without clouds and without much moon shine, hence it provides only modest statistics.

In order to settle this controversy, the *Pierre Auger Observatory* in Argentina now combines *both* techniques [6]. On ground 1600 water tanks detect secondary particles and capture many high energy cosmic rays. Their installation was completed in 2008, and its data set now exceeds by far the previous world statistics. Moreover 24 fluorescence telescopes search for "golden events" which are observed by both systems; they are very helpful in verifying the estimate for the primary particle energy. Thus the systematic error is around 22 %, which is harmless in this business, where one deals with magnitudes. Up to now the Pierre Auger Observatory has accumulated a lot of data, in particular it has identified well over 100 primary particles with energies close to or above $E_{\mathrm{GZK}}$. However, even with these new data the statistics is still not sufficient for an ultimately conclusive answer to the question if there really is a GZK cutoff for the energy of cosmic rays. We add a short discussion in the Appendix.

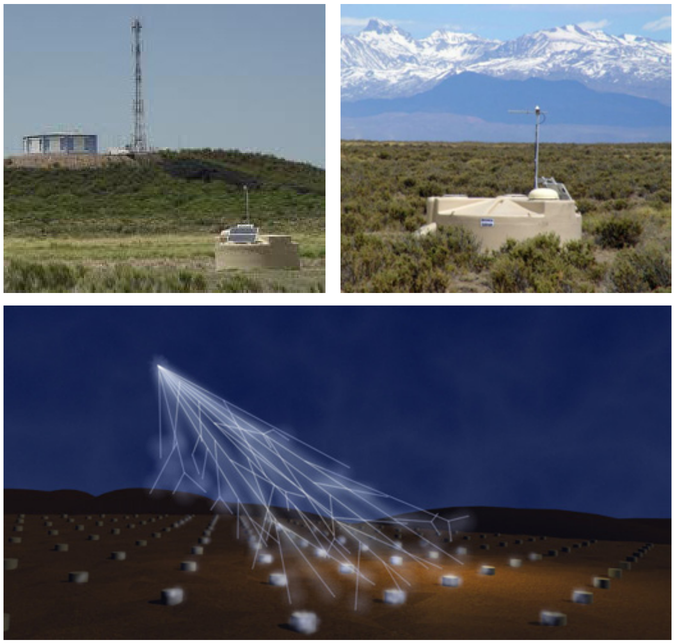

Figure 7: Images of the Pierre Auger Observatory in the "Pampa Amarilla" (Yellow Prairie) of the province of Mendoza, Argentina. It is now the dominant observatory in the search for ultra high energy cosmic rays. The collaboration involves almost 500 scientist in 19 countries. Above, on the left: one of the 24 fluorescence telescopes (on the hill), with cameras monitoring the weak bluish light that an air shower emits. Above, on the right: a cylindric tank, dark inside, with 12 000 l of water, able to detect secondary particles. 1600 such tanks are spread over an area of 3000 km, on a triangular grid with spacing 1.5 km, in order to capture multiple secondary particles of a powerful air shower. Below: an artistic illustration.

## VII. OUTLOOK

New experiments are in preparation, such as JEM-EUSO (Japanese Experiment Module – Extreme Universe Space Observatory) or OWL (Orbiting Wide-angle Light-collectors): now the idea is to observe the air shower formation from above, *i.e.* from satellites, which should provide more precise information. They will monitor the showers from the beginning, without being obstructed by clouds.

Hopefully this will at last answer the outstanding question about the existence of the GZK cutoff, which has fascinated scientists for almost half a century [4]. Then we should finally know whether or not our established physical framework —with Lorentz Invariance as a cornerstone— needs to be revised, and whether or not cosmic protons can compete with services, or even smashes, in a professional tennis game.

I am indebted to Alberto Güijosa, Marco Panero and Uwe-Jens Wiese for useful comments, and to Aline Guevara for her help with the figures. A shorter version of this article in Spanish, with co-author Angélica Bahena Blas, is accepted for publication in CIENCIA, Revista de la Academia Mexicana de Ciencia.[10]

## APPENDIX: THE FLUX OF ULTRA HIGH ENERGY COSMIC RAYS

The Pierre Auger Observatory operated in part since 2003. In 2007 it released preliminary results, which supported the scenario advocated by HiRes: the GZK cutoff seemed to be confirmed, although a number of new super GZK events were found.

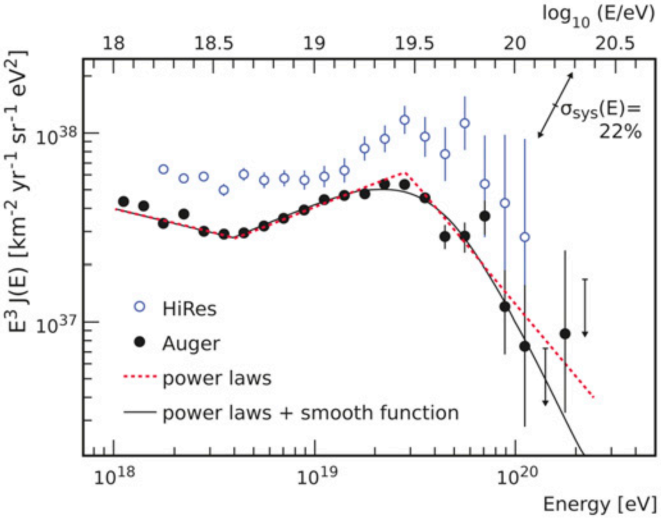

Figure 8: The flux of cosmic rays in the ultra high energy regime, multiplied by the factor $E^3$ (where $E$ is the energy), according to the Observatories HiRes and Pierre Auger [6].

However, meanwhile the Pierre Auger Observatory has accumulated more and more statistics, and the conclusion about the ultra high energy cosmic flux is still not really compelling. Some excess —compared to the $1/E^3$ rule— is clearly observed just above $4 \cdot 10^{18}$ eV, see Figure 8. Above $3 \cdot 10^{19}$ eV $\approx E_{GZK}$ the flux drops quite sharply, which *can* be regarded as evidence for the "boring scenario" (confirmation of the GZK cutoff). However, if we extrapolate the flux from $E < 4 \cdot 10^{18}$ eV into the super-GZK regime, it is well compatible with the data. Hence this excess could also be viewed as a limited pile-up (as it also occurs at lower energies, see Figure 3), while the power law over an extended energy range (up to deviations) might still be in business.

Therefore, even with the new data by the Pierre Auger Observatory, the statistics is still too poor for a final answer to the question if there really is a GZK cutoff for the energy of cosmic rays. Moreover, even if an extraordinary flux suppression above $E_{GZK}$ will be confirmed (which is currently considered the more likely scenario), one could still question if this is really a consequence of the GZK effect, or if the sources do hardly provide cosmic rays with even higher energy.

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