

# Searching for New Physics with Ultrahigh Energy Cosmic Rays

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## Abstract.

Ultrahigh energy cosmic rays that produce giant extensive showers of charged particles and photons when they interact in the Earth's atmosphere provide a unique tool to search for new physics. Of particular interest is the possibility of detecting a very small violation of Lorentz invariance such as may be related to the structure of space-time near the Planck scale of  $\sim 10^{-35}\text{m}$ . We discuss here the possible signature of Lorentz invariance violation on the spectrum of ultrahigh energy cosmic rays as compared with present observations of giant air showers. We also discuss the possibilities of using more sensitive detection techniques to improve searches for Lorentz invariance violation in the future. Using the latest data from the Pierre Auger Observatory, we derive a best fit to the LIV parameter of  $3.0^{+1.5}_{-3.0} \times 10^{-23}$ , corresponding to an upper limit of  $4.5 \times 10^{-23}$  at a proton Lorentz factor of  $\sim 2 \times 10^{11}$ . This result has fundamental implications for quantum gravity models.

## 1. Introduction

### *1.1. Why Test Fundamental Physics at Ultrahigh Energies?*

Owing to the uncertainty principle, it has long been realized that the higher the particle energy attained, the smaller the scale of physics that can be probed. Thus, optical, UV and X-ray observations led to the understanding of the structure of the atom,  $\gamma$ -ray observations led to an understanding of the structure of the atomic nucleus, and deep inelastic scattering experiments with high energy electrons led to an understanding of the structure of the proton. Accelerator experiments have led to an understanding of quantum chromodynamics and it is hoped that the Large Hadron Collider [1] will eventually reveal new physics at the TeV scale. This could lead to the discovery of the predicted Higgs boson and supersymmetric particles. To go much beyond this scale of fundamental physics, to search for clues to a

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grand unification theory, and even Planck scale physics, one must turn to the extreme high energies provided by the cosmic generators with which Nature has provided us. In this focus paper, we will concentrate on searching for conjectured ultrahigh energy modifications of special relativity. This search will be based on obtaining data on the spectrum of cosmic rays at the highest energies observed and even beyond, using present and future detection techniques.

### *1.2. Theoretical Motivation for High Energy Violation of Lorentz Invariance*

The theory of relativity is, of course, one of the fundamental pillars of modern physics. However, because of the problems associated with merging relativity with quantum theory, it has long been felt that relativity will have to be modified in some way in order to construct a quantum theory of gravitation.

The group of Lorentz transformations delineated by special relativity can be described as a high energy modification of the unbounded group of Galilean transformations. Since the Lorentz group is also unbounded at the high boost (or high energy) end, in principle it may also be subject to modifications in the high boost limit. There is also a fundamental relationship between the Lorentz transformation group and the assumption that space-time is scale-free, since there is no fundamental length scale associated with the Lorentz group. However, as noted by Planck [2], there is a potentially fundamental scale associated with gravity, *viz.*, the Planck scale. Thus, there has been a particular interest in the possibility that a breakdown of Lorentz invariance (LI) may be associated with the Planck scale,  $\lambda_{Pl} = \sqrt{G\hbar/c^3} \sim 10^{-35}$  m, owing to various speculations regarding quantum gravity scenarios. This scale corresponds to an energy (mass) scale of  $M_{Pl} = \hbar c/\lambda_{Pl} \sim 10^{19}$  GeV.

It is at the Planck scale where quantum effects are expected to play a key role in determining the effective nature of space-time that emerges in the classical continuum limit. The idea that LI may indeed be only approximate has been explored within the context of a wide variety of suggested new Planck-scale physics scenarios. These include the concepts of deformed relativity, loop quantum gravity, non-commutative geometry, spin foam models, and some string theory models. Such theoretical explorations and their possible consequences, such as observable modifications in the energy-momentum dispersion relations for free particles and photons, have been discussed under the general heading of “Planck scale phenomenology”. There is an extensive literature on this subject. (See [3] for a review; some recent references are Refs. [4] – [6].)

### *1.3. Testing Special Relativity using Astrophysical Observations*

It has been proposed that violation of LI at a high energy such as the Planck scale could have astrophysical consequences that might be manifested in a suppressed form at an energy scale  $\ll M_{Pl}$  [7] – [12]. A surprising result of subsequent work has been the conclusion that several potential effects of Lorentz invariance violation (LIV) can be explored and tested

at energies many orders of magnitude below the energy of the Planck scale (See *e.g.*, Ref. [3, 13] and references therein.)

Among the relevant astrophysical tests, we focus here on the ultrahigh energy cosmic-ray sector. Astrophysically produced ultrahigh energy particles are the perfect vehicles to explore the potential for detection of possible violations of special relativity at ultrahigh energies. One may also search for possible evidence of Planck scale physics and quantum gravity through photon propagation effects [12],[4]. Such effects may be revealed by space-based observations from the *SWIFT*  $\gamma$ -ray burst detector (<http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html>), and the *Fermi* (<http://fermi.gsfc.nasa.gov/>)  $\gamma$ -ray Space Telescope [14]. We will concentrate here on present observations of ultrahigh energy cosmic rays. We will also discuss future satellite programs proposed to make observations of ultrahigh energy cosmic-ray air showers from space such as *JEM-EUSO* (Extreme Universe Space Observatory) [15] and *OWL* (Orbiting Wide-Angle Light Collectors) [16] (See section 7.)

## 2. Ultrahigh Energy Cosmic Rays

### 2.1. Extragalactic Origin of Ultrahigh Energy Cosmic Rays

Ultrahigh energy cosmic rays (UHECRs) produce giant air showers of charged particles when they impinge on the Earth's atmosphere. Observational studies of these showers have been undertaken using scintillator arrays and with atmospheric fluorescence detectors. In this manner the total energies and atomic weights of the primary particles can be determined from the shower characteristics. The total energy of the primary incoming particle can be deduced from the number of secondary charged particles produced at a fiducial distance from the shower axis or the amount of atmospheric fluorescence produced by the shower. A rough measurement of the atomic weight of the primary can be obtained from the determining the height of the initial interaction in the atmosphere.

The history of UHECR detection goes back almost half a century [17]. Owing to their observed global isotropy and ultrahigh energy that allows them to be unfettered by the galactic magnetic field, cosmic rays above 10 EeV ( $1 \text{ EeV} \equiv 10^{18} \text{ eV}$ ) are believed to be of extragalactic origin. This fact, together with the absence of a correlation of arrival directions with the galactic plane, indicates that if protons are the primary particles that make up the ultrahigh energy cosmic radiation, these protons should be of extragalactic origin.

The large air shower detector arrays and, in particular the *Auger* array, (<http://www.auger.org/>) (a.k.a. the Pierre Auger Observatory (PAO)) have opened up two potential new areas of research. One area is a new field of ultrahigh energy particle astronomy – the identification and exploration of powerful extragalactic sources capable of accelerating cosmic rays to energies above 1 joule per particle. The second area, which is the topic of this focus paper, is the field of potential new ultrahigh energy particle physics – the search for new physical processes that may occur at energies much greater than those

produced in man-made laboratories.

## 2.2. The “GZK Effect”

Shortly after the discovery of the 3K cosmogenic background radiation (CBR), Greisen [18] and Zatsepin and Kuz’min [19] predicted that pion-producing interactions of such cosmic ray protons with the CBR should produce a spectral cutoff at  $E \sim 50$  EeV. The flux of ultrahigh energy cosmic rays (UHECR) is expected to be attenuated by such photomeson producing interactions. This effect is generally known as the “GZK effect”. Owing to this effect, protons with energies above  $\sim 100$  EeV should be attenuated from distances beyond  $\sim 100$  Mpc because they interact with the CBR photons with a resonant photoproduction of pions [20].

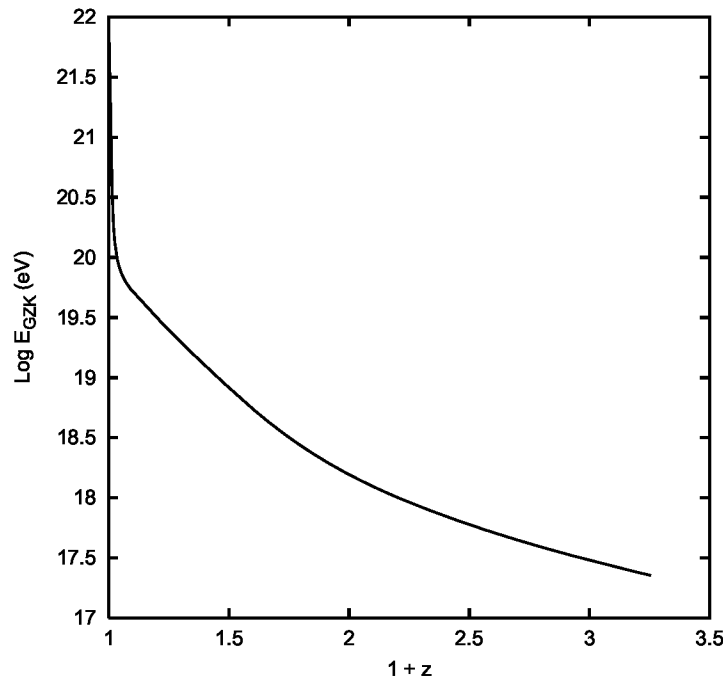
The flux and spectrum of the secondary ultrahigh energy neutrinos resulting from the decay of the photoproduced pions was also subsequently calculated [21, 22]. Photons with comparable ultrahigh energy have much smaller mean-free-paths because they pair-produce electrons and positrons by interacting with radio background photons and are thus attenuated. The attenuation length for photons is somewhat uncertain, because of the uncertainties in our knowledge of the flux and spectrum of the radio background [23, 24].

The GZK effect is not a true cutoff, but a suppression of the ultrahigh energy cosmic ray flux owing to an energy dependent propagation time against energy losses by such interactions, a time which is only  $\sim 300$  Myr for 100 EeV protons [20]. At high redshifts,  $z$ , the target photon density increases by  $(1+z)^3$  and both the photon and initial cosmic ray energies increase by  $(1+z)$ . A plot of the GZK energy as a function of redshift, calculated for the  $\Lambda$ CDM cosmology, is shown in Figure 1 [25]. If the source spectrum is hard enough, there could also be a relative enhancement just below the “GZK energy” owing to a “pileup” of cosmic rays starting out at higher energies and crowding up in energy space at or below the predicted GZK cutoff energy. At energies in the 1-10 EeV range, pair production interactions should take a bite out of the UHECR spectrum.

## 2.3. Astrophysical Studies of Fundamental Physics at Ultrahigh Energies

Some “trans-GZK” hadronic showers with energies above the predicted GZK cutoff energy have been reportedly observed by both scintillator and fluorescence detectors, particularly by the scintillator array group at Akeno [26], in apparent contradiction to the expected GZK attenuation effect. While there is less evidence for such interesting events from fluorescence detectors, the *Fly’s Eye* fluorescence detector reported the detection of a 320 EeV event [27], an energy that is a factor of  $\sim 5$  above the GZK cutoff energy. The evidence for such trans-GZK events has been a prime motivation for suggesting violation of Lorentz invariance at ultrahigh energies [7, 8].

However, the existence of a physically significant number of UHECR events at trans-GZK energies has recently been called into question. The latest *Auger* data [28],[29] as well as those from *HiRes*, [30], have both been interpreted as indicating a GZK cutoff. This has led



**Figure 1.** The GZK cutoff energy, defined as the energy predicted for a flux decrease of  $1/e$  owing to intergalactic photomeson production interactions, as a function of redshift [25].

many in the cosmic ray community to assume that there is no new physics to be discovered at ultrahigh energies. Thus, the emphasis in the field has been on ultrahigh energy particle *astronomy*, *i.e.*, the attempt to determine which nearby extragalactic objects accelerate and emit such high energy particles. However, the subject of this paper will be the search for *new physics* at ultrahigh energies. In particular, we will discuss the features in the ultrahigh energy cosmic ray spectrum that would be a signal of Lorentz violation and possible Planck scale physics and would also be compatible with present observational data.

### 3. Violating Lorentz Invariance - A Framework

In this paper we will take the phenomenological approach to exploring the effects of LIV pioneered by Coleman and Glashow [31]. They have proposed a simple formalism *via* postulating a small first order perturbation in the free-particle Lagrangian. This formalism has the advantages of (1) simplicity, (2) preserving the  $SU(3) \otimes SU(2) \otimes U(1)$  standard model of strong and electroweak interactions, (3) having the perturbative term in the

Lagrangian consist of operators of mass dimension four that thus preserves power counting renormalizability, and (4) being rotationally invariant in a preferred frame that can be taken to be the rest frame of the 2.7 K cosmic background radiation<sup>§</sup> This formalism has proven useful in exploring astrophysical data for testing LIV [31],[33].

Coleman and Glashow start with a standard-model free-particle Lagrangian,

$$\mathcal{L} = \partial_\mu \Psi^* \mathbf{Z} \partial^\mu \Psi - \Psi^* \mathbf{M}^2 \Psi \quad (1)$$

where  $\Psi$  is a column vector of  $n$  fields with U(1) invariance and the positive Hermitian matrices  $\mathbf{Z}$  and  $\mathbf{M}^2$  can be transformed so that  $\mathbf{Z}$  is the identity and  $\mathbf{M}^2$  is diagonalized to produce the standard theory of  $n$  decoupled free fields.

They then add a leading order perturbative, Lorentz violating term constructed from only spatial derivatives with rotational symmetry so that

$$\mathcal{L} \rightarrow \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi, \quad (2)$$

where  $\epsilon$  is a dimensionless Hermitian matrix that commutes with  $\mathbf{M}^2$  so that the fields remain separable and the resulting single particle energy-momentum eigenstates go from eigenstates of  $\mathbf{M}^2$  at low energy to eigenstates of  $\epsilon$  at high energies.

To leading order, this term shifts the poles of the propagator, resulting in the free particle dispersion relation

$$E^2 = \vec{p}^2 + m^2 + \epsilon \vec{p}^2. \quad (3)$$

This can be put in the standard form for the dispersion relation

$$E^2 = \vec{p}^2 c_{MAV}^2 + m^2 c_{MAV}^4, \quad (4)$$

by shifting the renormalized mass by the small amount  $m \rightarrow m/(1 + \epsilon)$  and shifting the velocity from  $c$  ( $=1$ ) by the amount  $c_{MAV} = \sqrt{1 + \epsilon} \simeq 1 + \epsilon/2$ .

The group velocity is given by

$$\frac{\partial E}{\partial |\vec{p}|} = \frac{|\vec{p}|}{\sqrt{|\vec{p}|^2 + m^2 c_{MAV}^2}} c_{MAV}, \quad (5)$$

which goes to  $c_{MAV}$  in the limit of large  $|\vec{p}|$ . Thus, Coleman and Glashow identify  $c_{MAV}$  to be the maximum attainable velocity of the free particle. Using this formalism, it becomes apparent that, in principle, different particles can have different maximum attainable velocities (MAVs) which can be different from  $c$ . Hereafter, we denote the MAV of a particle of type  $i$  by  $c_i$  and the difference

$$c_i - c_j = \frac{\epsilon_i - \epsilon_j}{2} \equiv \delta_{ij}. \quad (6)$$

There are other popular formalisms that are inspired by quantum gravity models or by speculations on the nature of space-time at the Planck scale. There are formidable

<sup>§</sup> See Ref. [32] for a generalization to the non-isotropic case.

obstacles to constructing a true quantum gravity theory. Among these is the problem of renormalizability [34]. Lagrangians involving operators of mass dimension greater than four are generally not renormalizable. However, in the context of an effective field theory, one can postulate Lagrangians containing operators of mass dimension  $\geq 5$  with suppression factors as multiples of  $M_{Pl}$  [13],[35]. This leads to dispersion relations having a series of smaller and smaller terms proportional to  $p^{n+2}/M_{Pl}^n \simeq E^{n+2}/M_{Pl}^n$ , with  $n \geq 1$ . The astrophysical implications of this formalism have been discussed in the literature [13], [36]-[42]. However, in relating LIV to the observational data on UHECRs, it is useful to use the simpler formalism of Coleman and Glashow (See, however, Section 6.2). Given the limited energy range of the UHECR data relevant to the GZK effect, this formalism can later be related to possible Planck scale phenomena and quantum gravity models of various sorts.

Let us consider the photomeson production process leading to the GZK effect. Near threshold, where single pion production dominates,

$$p + \gamma \rightarrow p + \pi. \quad (7)$$

Using the normal Lorentz invariant kinematics, the energy threshold for photomeson interactions of UHECR protons of initial laboratory energy  $E$  with low energy photons of the CBR with laboratory energy  $\omega$ , is determined by the relativistic invariance of the square of the total four-momentum of the proton-photon system. This relation, together with the threshold inelasticity relation  $E_\pi = m/(M + m)E$  for single pion production, yields the threshold conditions for head on collisions in the laboratory frame

$$4\omega E = m(2M + m) \quad (8)$$

for the proton, and

$$4\omega E_\pi = \frac{m^2(2M + m)}{M + m} \quad (9)$$

in terms of the pion energy, where  $M$  is the rest mass of the proton and  $m$  is the rest mass of the pion [20].

If LI is broken so that  $c_\pi > c_p$ , it follows from equations (3), (6) and (9) that the threshold energy for photomeson is altered because the square of the four-momentum is shifted from its LI form so that the threshold condition in terms of the pion energy becomes||

$$4\omega E_\pi = \frac{m^2(2M + m)}{M + m} + 2\delta_{\pi p} E_\pi^2 \quad (10)$$

Equation (10) is a quadratic equation with real roots only under the condition

$$\delta_{\pi p} \leq \frac{2\omega^2(M + m)}{m^2(2M + m)} \simeq \omega^2/m^2. \quad (11)$$

Defining  $\omega_0 \equiv kT_{CBR} = 2.35 \times 10^{-4}$  eV with  $T_{CBR} = 2.725 \pm 0.02$  K, equation (11) can be rewritten

$$\delta_{\pi p} \leq 3.23 \times 10^{-24} (\omega/\omega_0)^2. \quad (12)$$

|| We assume here that protons and pions are kinematically independent entities. For a treatment of these particles as composites of quarks and gluons, see Ref. [43].

#### 4. Kinematics

If LIV occurs and  $\delta_{\pi p} > 0$ , photomeson production can only take place for interactions of CBR photons with energies large enough to satisfy equation (12). This condition, together with equation (10), implies that while photomeson interactions leading to GZK suppression can occur for “lower energy” UHE protons interacting with higher energy CBR photons on the Wien tail of the spectrum, other interactions involving higher energy protons and photons with smaller values of  $\omega$  will be forbidden. Thus, the observed UHECR spectrum may exhibit the characteristics of GZK suppression near the normal GZK threshold, but the UHECR spectrum can “recover” at higher energies owing to the possibility that photomeson interactions at higher proton energies may be forbidden. We now consider a more detailed quantitative treatment of this possibility, *viz.*, GZK coexisting with LIV.

The kinematical relations governing photomeson interactions are changed in the presence of even a small violation of Lorentz invariance. Following equations (3) and (6), we denote

$$E^2 = p^2 + 2\delta_a p^2 + m_a^2 \quad (13)$$

where  $\delta_a$  is the difference between the MAV for the particle  $a$  and the speed of light in the low momentum limit ( $c = 1$ ).

The square of the cms energy of particle  $a$  is then given by

$$\sqrt{s_a} = \sqrt{E^2 - p^2} = \sqrt{2\delta_a p^2 + m_a^2} \geq 0. \quad (14)$$

Owing to LIV, in the cms the particle will not generally be at rest when  $p = 0$  because

$$v = \frac{\partial E}{\partial p} \neq \frac{p}{E}. \quad (15)$$

The modified kinematical relations containing LIV have a strong effect on the amount of energy transferred from an incoming proton to the pion produced in the subsequent interaction, *i.e.*, the inelasticity [45, 46]. The total inelasticity,  $K$ , is an average of  $K_\theta$ , which depends on the angle between the proton and photon momenta,  $\theta$ :

$$K = \frac{1}{\pi} \int_0^\pi K_\theta d\theta. \quad (16)$$

The primary effect of LIV on photopion production is a reduction of phase space allowed for the interaction. This results from the limits on the allowed range of interaction angles integrated over in order to obtain the total inelasticity from equation (16). For real-root solutions for interactions involving higher energy protons, the range of kinematically allowed angles in equation (16) becomes severely restricted. The modified inelasticity that results is the key in determining the effects of LIV on photopion production. The inelasticity rapidly drops for higher incident proton energies.

As shown in Ref. [31], in order to modify the effect of photopion production on the UHECR spectrum above the GZK energy we must have  $\delta_\pi > \delta_p$ , *i.e.*,  $\delta_{\pi p} > 0$ . We note that



a constraint can be put on  $\delta_{p\gamma}$  in the case where  $\delta_{p\gamma} > 0$ . In this case, protons will have a maximum allowed energy

$$E_{\max} = m_p \sqrt{1/2\delta_{p\gamma}}. \quad (17)$$

above which protons traveling faster than light will emit light at all frequencies by the process of ‘vacuum Čerenkov radiation’ [31], [33], [44]. This process occurs rapidly, so that the energy of the superluminal protons will rapidly fall back to energy  $E_{\max}$ . Therefore, because UHECRs, assumed here to be protons, have been observed up to an upper energy of  $E_U \simeq 320$  EeV [27], it follows that

$$\delta_{p\gamma} \leq \frac{m_p^2}{2E_U^2} \simeq 5 \times 10^{-24}. \quad (18)$$

Our requirement that  $\delta_{\pi p} > 0$  precludes the ‘quasi-vacuum Čerenkov radiation’ of pions, *via* the rapid, strong interaction, pion emission process,  $p \rightarrow N + \pi$ . This process would be allowed by LIV in the case where  $\delta_{\pi p}$  is negative, producing a sharp cutoff in the UHECR proton spectrum.

The empirical constraint given by equation (18) is independent of any constraint on  $\delta_{\pi p}$ . However, we note that if  $\delta_{\pi} \simeq \delta_p$ , no observable modification of the UHECR spectrum occurs. Therefore, we will assume that  $\delta_{\pi} > \delta_p$  at or near threshold as a requirement for clearly observing a potential LIV signal in the UHECR spectrum. This assumption is also made in Ref. [45]. We will thus take  $\delta_{\pi p} \equiv \delta_{\pi}$  in the case where  $\delta_p$  is small and positive as required by eq. (18). Indeed, it can be shown in this case that the dependence of the UHECR spectral shape on the  $\delta_{\pi p}$  parameter dominates over that on the  $\delta_p$  parameter [46].

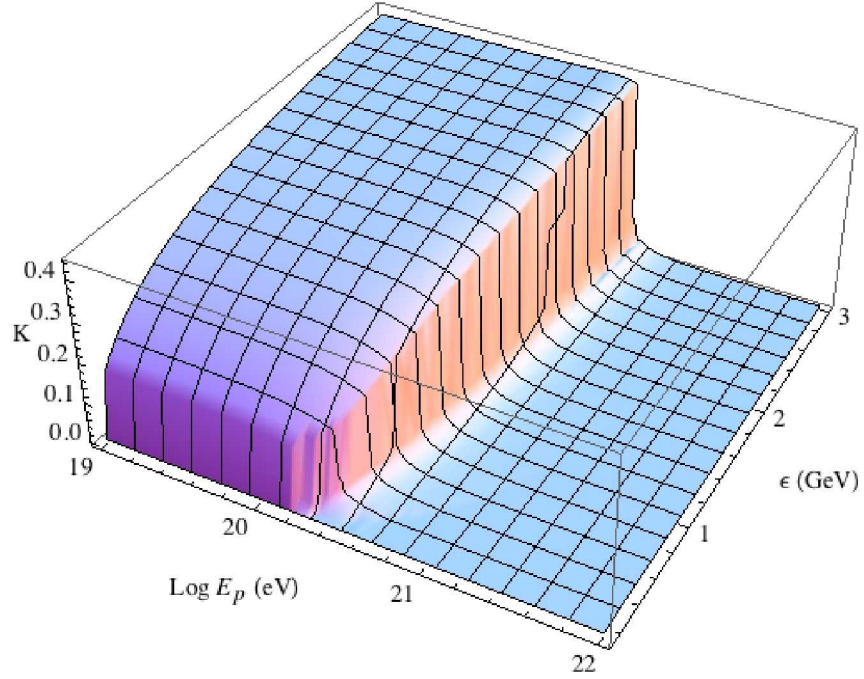
Figure 2 shows the calculated proton inelasticity modified by LIV for a value of  $\delta_{\pi p} = 3 \times 10^{-23}$  as a function of both CBR photon energy and proton energy [46]. Other choices for  $\delta_{\pi p}$  yield similar plots. The principal result of changing the value of  $\delta_{\pi p}$  is to change the energy at which LIV effects become significant. For a choice of  $\delta_{\pi p} = 3 \times 10^{-23}$ , there is no observable effect from LIV for  $E_p$  less than  $\sim 200$  EeV. Above this energy, the inelasticity precipitously drops as the LIV term in the pion rest energy approaches  $m_{\pi}$ .

With this modified inelasticity, the proton energy loss rate by photomeson production is given by

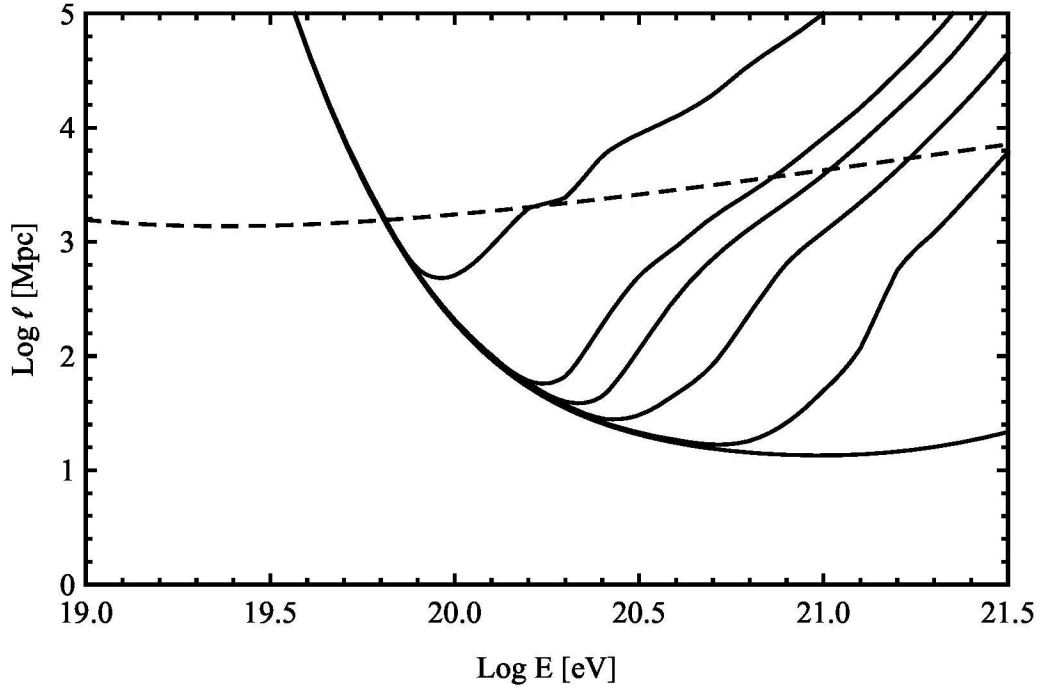
$$\frac{1}{E} \frac{dE}{dt} = -\frac{\omega_0 c}{2\pi^2 \gamma^2 \hbar^3 c^3} \int_{\eta}^{\infty} d\epsilon \epsilon \sigma(\epsilon) K(\epsilon) \ln[1 - e^{-\epsilon/2\gamma\omega_0}] \quad (19)$$

where we now use  $\epsilon$  to designate the energy of the photon in the cms,  $\eta$  is the photon threshold energy for the interaction in the cms, and  $\sigma(\epsilon)$  is the total  $\gamma$ -p cross section with contributions from direct pion production, multipion production, and the  $\Delta$  resonance.

The corresponding proton attenuation length is given by  $\ell = cE/r(E)$ , where the energy loss rate  $r(E) \equiv (dE/dt)$ . This attenuation length is plotted in Figure 3 for various values of  $\delta_{\pi p}$  along with the unmodified pair production attenuation length from pair production interactions,  $p + \gamma_{CBR} \rightarrow e^+ + e^-$ .



**Figure 2.** The calculated proton inelasticity modified by LIV for  $\delta_{\pi p} = 3 \times 10^{-23}$  as a function of CBR photon energy and proton energy [46].



**Figure 3.** The calculated proton attenuation lengths as a function proton energy modified by LIV for various values of  $\delta_{\pi p}$  (solid lines), shown with the attenuation length for pair production unmodified by LIV (dashed lines). From top to bottom, the curves are for  $\delta_{\pi p} = 1 \times 10^{-22}, 3 \times 10^{-23}, 2 \times 10^{-23}, 1 \times 10^{-23}, 3 \times 10^{-24}, 0$  (no Lorentz violation) [46].

## 5. UHECR Spectra with LIV and Comparison with Present Observations

Let us now calculate the modification of the UHECR spectrum produced by a very small amount of LIV. We perform an analytic calculation in order to determine the shape of the modified spectrum. It can be demonstrated that there is little difference between the results of using an analytic calculation *vs.* a Monte Carlo calculation (*e.g.*, see Ref. [47]). In order to take account of the probable redshift evolution of UHECR production in astronomical sources, we take account of the following considerations:

(i) The CBR photon number density increases as  $(1+z)^3$  and the CBR photon energies increase linearly with  $(1+z)$ . The corresponding energy loss for protons at any redshift  $z$  is thus given by

$$r_{\gamma p}(E, z) = (1+z)^3 r[(1+z)E]. \quad (20)$$

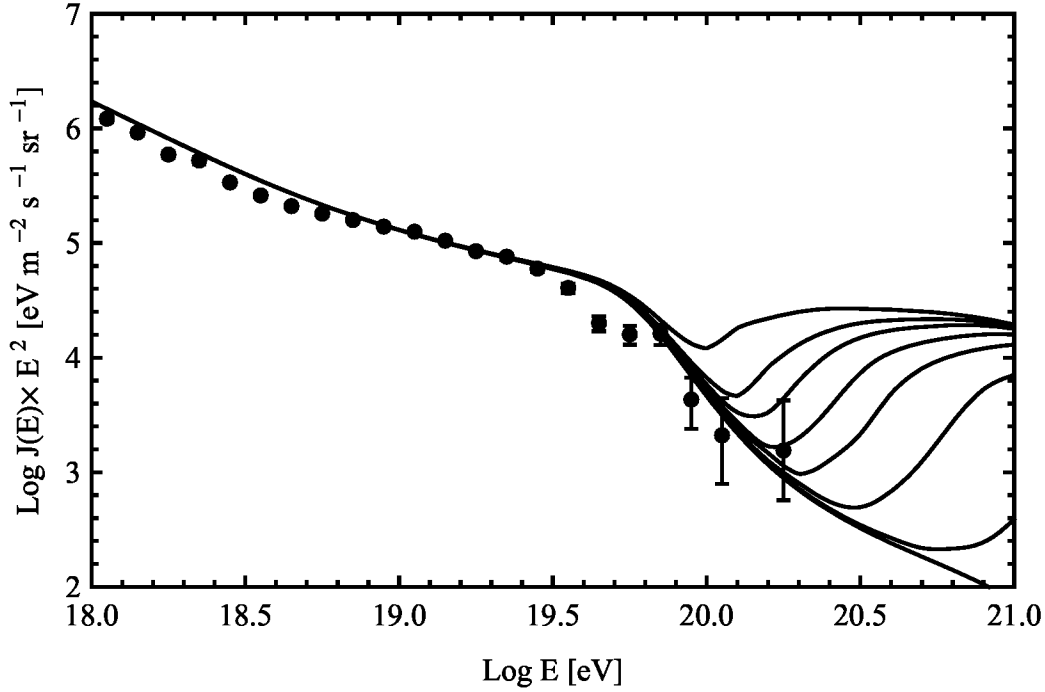
(ii) We assume that the average UHECR volume emissivity is of the energy and redshift dependent form given by  $q(E_i, z) = K(z)E_i^{-\Gamma}$  where  $E_i$  is the initial energy of the proton at the source and  $\Gamma = 2.55$ . For the source evolution, we assume  $K(z) \propto (1+z)^{3.6}$  with  $z \leq 2.5$  so that  $K(z)$  is roughly proportional to the empirically determined  $z$ -dependence of the star formation rate.  $K(z=0)$  and  $\Gamma$  are normalized fit the data below the GZK energy.

Using these assumptions, Scully and Stecker [46] have calculated the effect of LIV on the UHECR spectrum. The results are actually insensitive to the assumed redshift dependence because evolution does not affect the shape of the UHECR spectrum near the GZK cutoff energy [48, 49]. At higher energies where the attenuation length may again become large owing to an LIV effect, the effect of evolution turns out to be less than 10%. The curves calculated in Ref. [46] assuming various values of  $\delta_{\pi p}$ , are shown in Figure 4 along with the *Auger* data from Ref. [28]. They show that *even a very small amount of LIV that is consistent with both a GZK effect and with the present UHECR data can lead to a “recovery” of the UHECR spectrum at higher energies.*

### 5.1. Non-Protonic UHECR

Throughout this paper, we have made the assumption that the highest energy cosmic rays, *i.e.*, those above 100 EeV, are protons. The composition of these primary particles is presently unknown. The highest energy events for which composition measurements have been attempted are in the range between 40 and 50 EeV, and the composition of these events is uncertain [50]-[52].

We note that in the case where the UHECRs with total energy above  $\sim 100$  EeV are not protons, both the photomeson threshold and the LIV effects are moved to higher energies because (i) the threshold is dependent on  $\gamma \propto E/A$ , where  $A$  is the atomic weight of



**Figure 4.** Comparison of the latest Auger data with calculated spectra for various values of  $\delta_{\pi p}$ , taking  $\delta_p = 0$  (see text). From top to bottom, the curves give the predicted spectra for  $\delta_{\pi p} = 1 \times 10^{-22}, 6 \times 10^{-23}, 4.5 \times 10^{-23}, 3 \times 10^{-23}, 2 \times 10^{-23}, 1 \times 10^{-23}, 3 \times 10^{-24}, 0$  (no Lorentz violation) [46].

the UHECR [20], and (ii) it follows from equation (3) that the LIV effect depends on the individual nucleon momentum

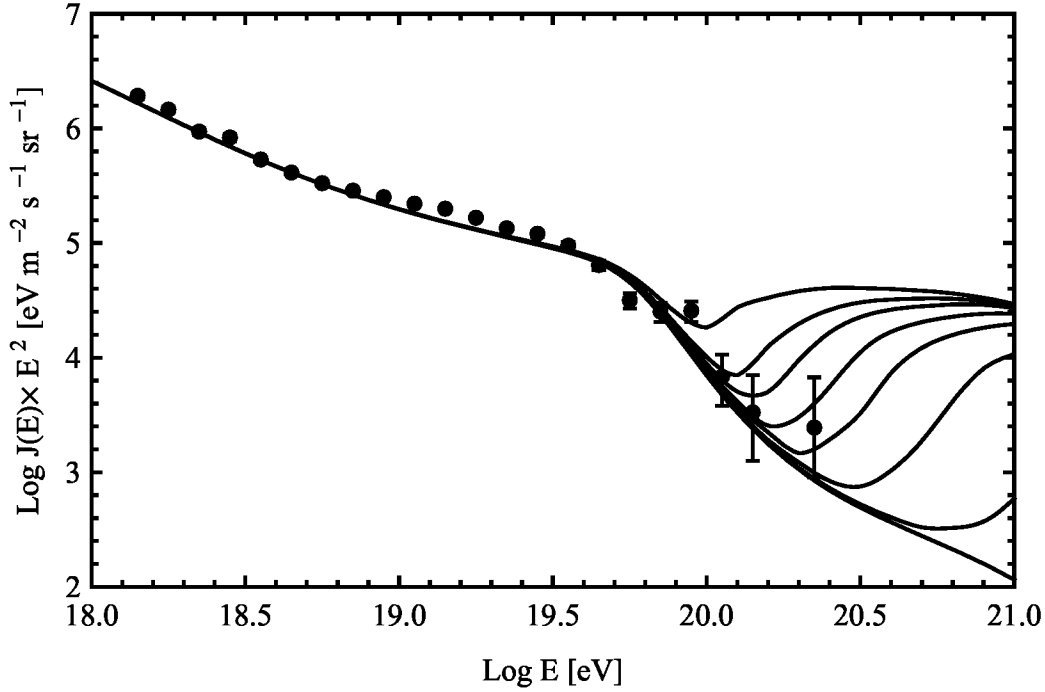
$$p_N \rightarrow E/A. \quad (21)$$

In the case of photodisintegration, LIV effects can play a role. We note that for single nucleon photodisintegration of iron nuclei, the threshold is at a higher energy than for the GZK effect [53, 24]. For He nuclei, on the other hand, the threshold energy is lower than the GZK energy [53].

## 6. Constraints on LIV

### 6.1. Allowed Range for the LIV Parameter $\delta_{\pi p}$

It has been suggested that a small amount of Lorentz invariance violation (LIV) could turn off photomeson interactions of ultrahigh energy cosmic rays (UHECRs) with photons of the cosmic background radiation and thereby eliminate the resulting sharp steepening in the spectrum of the highest energy CRs predicted by Greisen, Zatsepin and Kuzmin (GZK). Recent measurements of the UHECR spectrum reported by the *HiRes* [30] and *Auger* [28] collaborations, however, appear to indicate the presence of a GZK effect.

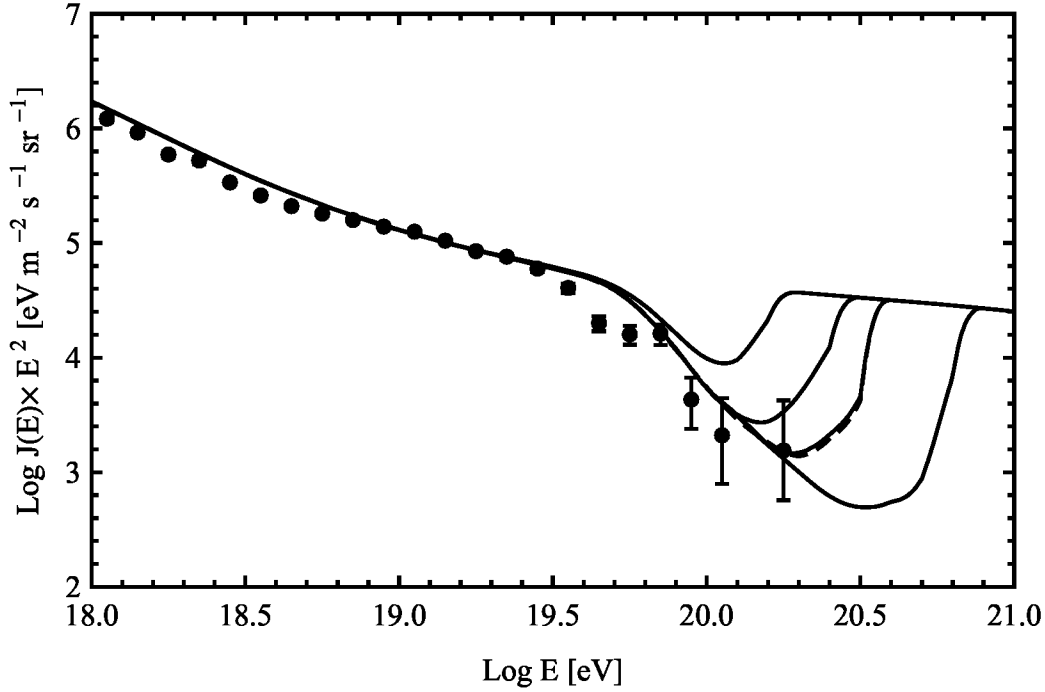


**Figure 5.** Comparison of the latest Auger data with the stated UHECR energies increased by 25% (see text) shown with the calculated spectra for various values of  $\delta_{\pi p}$ , taking  $\delta_p = 0$ . From top to bottom, the curves give the predicted spectra for  $\delta_{\pi p} = 1 \times 10^{-22}, 6 \times 10^{-23}, 4.5 \times 10^{-23}, 3 \times 10^{-23}, 2 \times 10^{-23}, 1 \times 10^{-23}, 3 \times 10^{-24}, 0$  (no Lorentz violation) [46].

A true determination of the implications of these recent measurements for the search for Lorentz invariance violation at ultrahigh energies requires a detailed analysis of the spectral features produced by modifications of the kinematical relationships caused by LIV at ultrahigh energies. Scully and Stecker [46] calculated modified UHECR spectra for various values of the Coleman-Glashow parameter,  $\delta_{\pi p}$ , defined as the difference between the maximum attainable velocities of the pion and the proton produced by LIV. They then compared the results with the experimental UHECR data.

We have updated these results using the very latest *Auger* data from the proceedings of the 2009 International Cosmic Ray Conference [28],[29]. This update is shown in Figure 4. The amount of presently observed GZK suppression in the UHECR data is consistent with the possible existence of a small amount of LIV. In order to quantify this, we determine the value of  $\delta_{\pi p}$  that results in the smallest  $\chi^2$  for the modeled UHECR spectral fit using the observational data from *Auger* [28] above the GZK energy. The best fit LIV parameter found was in the range given by  $\delta_{\pi p} = 3.0^{+1.5}_{-3.0} \times 10^{-23}$ , corresponding to an upper limit on  $\delta_{\pi p}$  of  $4.5 \times 10^{-23}$ . ¶ This result, as it stands, is slightly more constraining than that given in Ref. [46]. However, we note that the overall fit of the data to the theoretically expected spectrum is somewhat imperfect, even below the GZK energy and even for the case of no

¶ The *HiRes* data [30] do not reach a high enough energy to further restrict LIV.

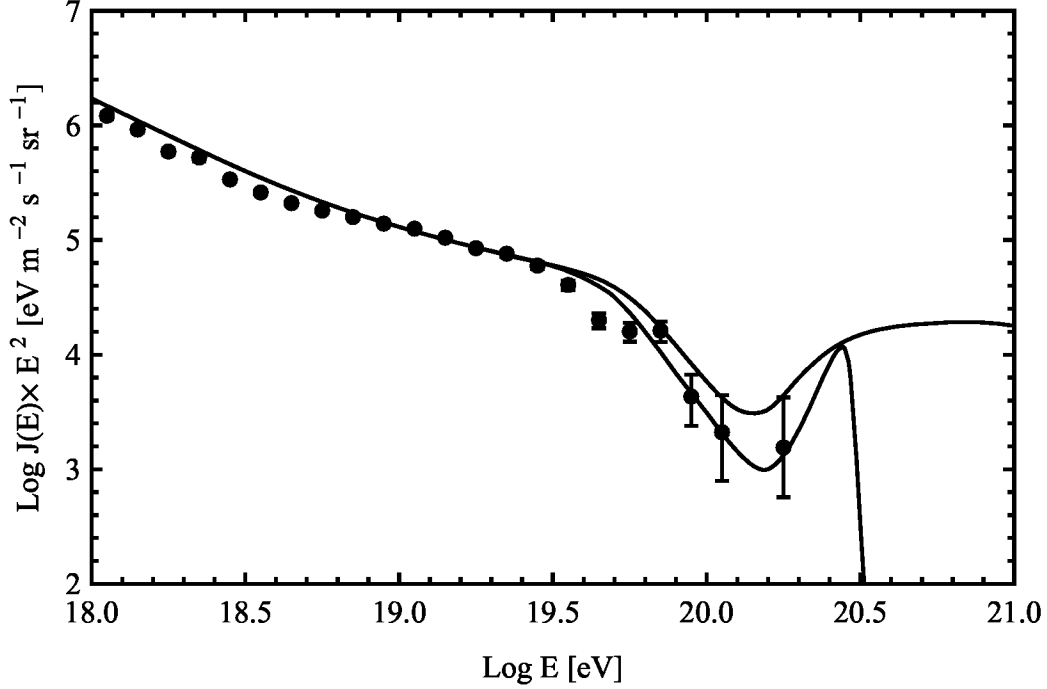


**Figure 6.** Comparison of the latest Auger data with calculated spectra for various negative values of  $\delta_p$ , taking  $\delta_\pi = 0$ . From top to bottom, the curves give the predicted spectra for  $\delta_p = -1 \times 10^{-23}, -5 \times 10^{-24}, -3 \times 10^{-24}, -1 \times 10^{-24}$ . We also show by a dashed curve the case where  $\delta_p = -3 \times 10^{-24}$  and  $\delta_\pi = -1 \times 10^{-24}$ .

LIV. It appears that the spectrum seems to steepen even below the GZK energy. As a conjecture, we have taken the liberty of assuming that the derived energy may be too low by about 25%, within the uncertainty of both systematic-plus statistical error given for the energy determination. By increasing the derived UHECR energies by 25%, we arrive at the plot shown in Figure 5, again shown with the theoretical curves. In Figure 5 one sees better agreement between the theoretical curves and the shifted data. The constraint on LIV would be only slightly reduced if this shift is assumed.

The results for LIV modified spectra given in Ref. [46] were calculated under the assumption that  $\delta_p \equiv \delta_{p\gamma} = 0$ . It follows from equation (14) that if  $\delta_p$  is slightly negative then the spectra are additionally modified because of the reduced cms energy of the proton for a given lab momentum. This affects the photomeson interaction rate in a different and stronger way than for the  $\delta_{p\gamma} = 0$  case shown in Fig. 4. Here, the reduced cms proton energy results in a reduction of the phase space allowed for the interactions when  $\sqrt{s_p}$  given by equation (14) is near zero.

The results for negative  $\delta_p$  are shown in Figure 6. They lie within the range of constraints on  $\delta_{\pi p}$  given above. However, it is clear that even a relatively small negative value for  $\delta_p$  has a stronger LIV effect on the UHECR spectrum than a positive value of  $\delta_\pi$ . We also show a case where  $\delta_p$  and  $\delta_\pi$  are both negative (dashed line in the figure). The dashed curve shows that the same  $\delta_p$  produces an almost identical effect on the spectrum in both cases, again



**Figure 7.** Comparison of the latest Auger data with calculated spectra for  $\delta_{\pi p} = 4.5 \times 10^{-23}$  and for  $\delta_p = 0$  and  $0.5 \times 10^{-23}$  as discussed in the text. In the later case the cutoff from the vacuum Čerenkov effect is apparent.

demonstrating that the negative  $\delta_p$  parameter gives the dominant LIV effect.

We also present here, for comparison, the spectrum for a slightly positive  $\delta_{p\gamma}$ . Figure 7 shows two curves for  $\delta_{\pi p} = 5 \times 10^{-23}$ . The spectrum with a vacuum Čerenkov radiation cutoff at 300 EeV is for  $\delta_{p\gamma} = 0.5 \times 10^{-23}$  (see equation (18)). The other curve assumes  $\delta_{p\gamma} = 0$  as in Figure 4.

## 6.2. Implications for Quantum Gravity Models

An effective field theory approximation for possible LIV effects induced by Planck-scale suppressed quantum gravity for  $E \ll M_{Pl}$  was considered in Ref. [42]. These authors explored the case where a perturbation to the energy-momentum dispersion relation for free particles would be produced by a CPT-even dimension six operator suppressed by a term proportional to  $M_{Pl}^{-2}$ . The resulting dispersion relation for a particle of type  $a$  is

$$E_a^2 = p_a^2 + m_a^2 + \eta_a \left( \frac{p^4}{M_{Pl}^2} \right) \quad (22)$$

In order to explore the implications of our constraints for quantum gravity, we will equate the perturbative terms in the dispersion relation given by our equation (13), for both protons and pions, with the equivalent dimension six dispersion relations given by equation (22). We note that the perturbative term in equation (22) has an energy dependence, whereas our dimension four case does not. However, since we are only comparing with UHECR data

over a very limited energy range around a fiducial energy  $E_f \sim 100$  EeV, we will make the identification at that energy.

Using this identification, we find that in most cases an LIV constraint of  $\delta_{\pi p} < 4.5 \times 10^{-23}$  at a proton fiducial energy of  $E_f \sim 100$  EeV indirectly implies a powerful limit on the representation of quantum gravity effects in an effective field theory formalism with Planck suppressed dimension six operators. Equating the perturbative terms in both the proton and pion dispersion relations

$$2\delta_{\pi p} \simeq (\eta_\pi - 25\eta_p) \left( \frac{0.2E_f}{M_{Pl}} \right)^2, \quad (23)$$

where we have adopted the terminology of Ref. [42] and we have taken the pion fiducial energy to be  $\sim 0.2E_f$ , as at the  $\Delta$  resonance [20]. Since we require  $\delta_{\pi p} > 0$  for GZK suppression, and  $\delta_p > 0$  in order to suppress proton vacuum Čerenkov radiation, equation (23) then implies that  $\delta_\pi > \delta_p$ , which is the assumption made in Refs. [45] and [46]. Equation (23) also indicates that LIV by dimension six operators is suppressed by a factor of at least  $\mathcal{O}(10^{-6}M_{Pl}^{-2})$ , except in the unlikely case that  $\eta_\pi - 25\eta_p \simeq 0$ . This suppression is over and above that of any dimension four terms in the dispersion relation as we have considered here. These results are in agreement with the conclusions of Ref. [42] who also find a suppression of  $\mathcal{O}(10^{-6}M_{Pl}^{-2})$ , except with the equivalent loophole. We note that in Ref. [42] a series of Monte Carlo runs are used in order to obtain their results. It can thus be concluded that an effective field theory representation of quantum gravity with dimension six operators that suppresses LIV by only a factor of  $M_{Pl}^2$  is effectively ruled out by the UHECR observations, as concluded in Ref. [42].

## 7. Beyond Constraints: Seeking LIV

As we have seen (see Figure 4), even a very small amount of LIV that is consistent with both a GZK effect and with the present UHECR data can lead to a “recovery” of the primary UHECR spectrum at higher energies. This is the clearest and the most sensitive evidence of an LIV signature. The “recovery” effect has also been deduced in Refs. [42] and [54]<sup>+</sup>. In order to find it (if it exists) three conditions must exist: (i) sensitive enough detectors need to be built, (ii) a primary UHECR spectrum that extends to high enough energies ( $\sim 1000$  EeV) must exist, and (iii) one must be able to distinguish the LIV signature from other possible effects.

### 7.1. Cosmic Zevatrons

In order to meet our third condition, we require the existence of powerful cosmic ray accelerators, the so-called zevatrons ( $1000 \text{ EeV} = 1 \text{ ZeV}$ ). In this “bottom up” scenario

<sup>+</sup> In Ref. [54], a recovery effect is also claimed for high proton energies in the case when  $\delta_{\pi p} < 0$ . However, we have noted that the ‘quasi-vacuum Čerenkov radiation’ of pions by protons in this case will cut off the proton spectrum and no “recovery” effect will occur.



for UHECR production, acceleration in extragalactic sources must account for the existence of observed UHECRs with energies reaching at least  $\sim 300$  EeV [27]. The most widely considered acceleration mechanism is shock acceleration, particularly in the lobes of powerful radio galaxies (*e.g.*, Refs. [55] – [57].) Blanford [56] discusses the problems associated with this “conventional” mechanism of accelerating particles to the highest observed energies. Other acceleration mechanisms have been proposed. In particular, it has recently been argued that the plasma wakefield acceleration mechanism, operating within relativistic AGN jets, is capable of accelerating particles to energies  $\sim 1$  ZeV [58]. If such zevatrons exist and produce particles of ZeV energies, given enough statistics from future detector studies, an LIV signal can be searched for.

## 7.2. Distinguishing an LIV Signal

**7.2.1. LIV vs the Top-Down Scenario:** Our signature signal of LIV is a “recovery” of the primary UHECR spectrum at higher energies (see Figure 4). Such an LIV signal must be distinguished from the presence of a higher energy component in the UHECR spectrum predicted to be produced by so-called “top-down” models. The top-down scenarios invoke the decay or annihilation of supermassive particles or topological or quantum remnants of the very early universe usually associated with some grand unification energy scale. Such processes result in the production of a high ratio of pions to nucleons from the resulting QCD fragmentation process (see , *e.g.*, [24] for a review). Owing to QCD fragmentation, top-down scenarios predict relatively large fluxes of UHE photons and neutrinos as compared to nucleons, as well as a significant diffuse GeV background flux that could be searched for by the *Fermi*  $\gamma$ -ray space telescope.

A higher energy UHECR component arising from top-down models can indeed be distinguished from the LIV effect. Contrary to the predictions of relatively copious pion production in the top-down scenario, the LIV effect cuts off UHE pion production at the higher energies and consequent UHE neutrino and photon production from UHE pion decay. We also note that LIV would therefore not produce a GeV photon flux.

In this regard, we note that the Pierre Auger Observatory collaboration has provided observational upper limits on the UHE photon flux [59, 60] that have already disfavored top-down models. The upper limits from the *Auger* array indicate that UHE photons make up at best only a small percentage of the total UHE flux. This contradicts predictions of top-down models that the flux of UHE photons should be larger than that of UHE protons. Upper limits on the UHE neutrino flux from *ANITA* also strongly disfavor top-down models [61], [62].

**7.2.2. LIV vs. Local Source Overdensity:** It is possible that the apparent modified GZK suppression in the data may be related to an overdensity of nearby sources related to a local supergalactic enhancement [20]. However, at this point in time, no clear correlation of

UHECR directions with nearby extragalactic sources exists.\* More and better data will be required in order to resolve this question. An LIV effect can be distinguished from a possible local source enhancement by looking for UHECRs at energies above  $\sim 200$  EeV, as can be seen from Figure 4. This is because the small amount of LIV that fits the observational UHECR spectra can lead to the signature recovery of the cosmic ray flux at higher energies than presently observed. Such a recovery is not expected in the case of a local overdensity. Searching for such a recovery effect will require obtaining a future data set containing a much higher number of UHECR air shower events.

## 8. Obtaining UHECR Data at Higher Energies

We now turn to examining the various techniques that can be used in the future in order to look for a signal of LIV using UHECR observations. As can be seen from the preceding discussion, observations of higher energy UHECRs with much better statistics than presently obtained are needed in order to search for the effects of miniscule Lorentz invariance violation on the UHECR spectrum.

### 8.1. Auger North

In the future, such an increased number of events may be obtained. The *Auger* collaboration has proposed to build an “*Auger North*” array that would be seven times larger than the present southern hemisphere Auger array (<http://www.augernorth.org>).

### 8.2. Future Space Based Detectors

Further into the future, space-based telescopes designed to look downward at large areas of the Earth’s atmosphere as a sensitive detector system for giant air-showers caused by trans-GZK cosmic rays. We look forward to these developments that may have important implications for fundamental high energy physics.

Two future potential spaced-based missions have been proposed to extend our knowledge of UHECRs to higher energies. One is *JEM-EUSO* (the Extreme Universe Space Observatory) [15], a one-satellite telescope mission proposed to be placed on the Japanese Experiment Module (JEM) on the International Space Station. The other is *OWL* (Orbiting Wide-angle Light Collectors) [16], a two satellite mission for stereo viewing, proposed for a future free-flyer mission. Such orbiting space-based telescopes with UV sensitive cameras will have wide fields-of-view (FOVs) in order to observe and use large volumes of the Earth’s atmosphere as a detecting medium. They will thus trace the atmospheric fluorescence trails of numbers of giant air showers produced by ultrahigh energy cosmic rays and neutrinos. Their large FOVs will allow the detection of the rare giant air showers with energies higher

\* A correlation with nearby AGN was hinted at in earlier Auger data [63]. However, the HiRes group has found no significant correlation [64] and no correlation has now been found in the more recent Auger data with an increased number of events (Westerhoff, private communication).

than those presently observed by ground-based detectors such as *Auger*. Such missions will thus potentially open up a new window on physics at the highest possible observed energies.

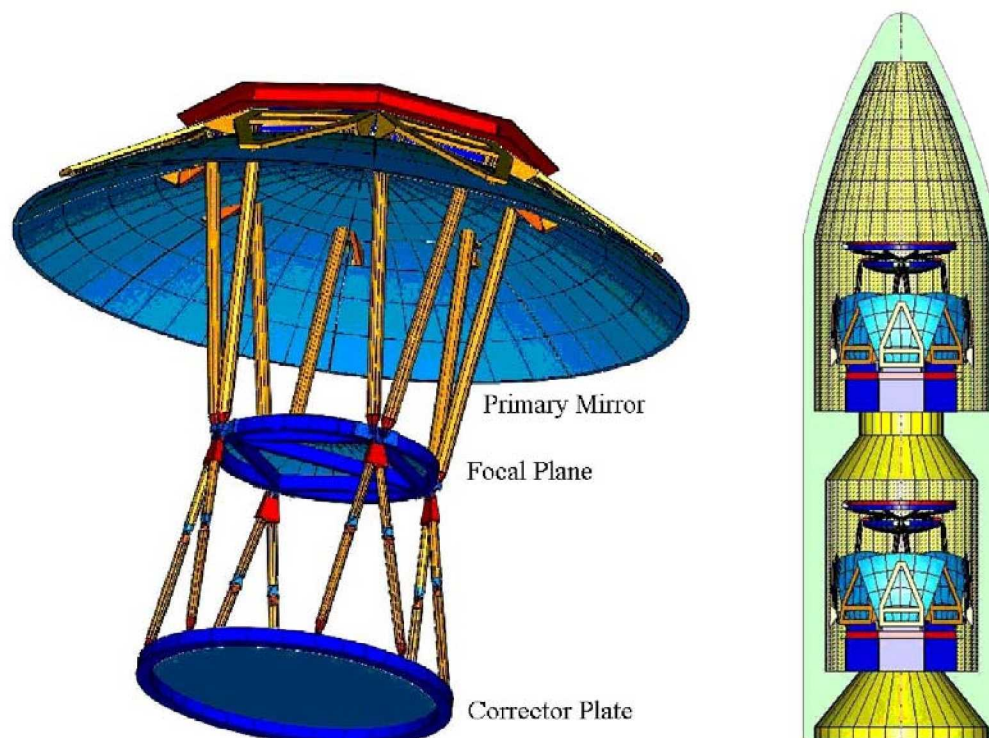
*8.2.1. The Extreme Universe Space Observatory JEM-EUSO:* *JEM-EUSO* has been selected as the candidate mission for the second utilization of the Japanese Experiment Module on the International Space Station. It is planned to be launched in 2013 by a Japanese heavy lift rocket. It will employ a double plastic Fresnel lens system telescope with a 30° FOV and will help to advance the technology of such missions. Further into the future, a proposed “*Super EUSO*” mission is in the preliminary planning stage.

*8.2.2. The OWL Mission Concept:* The *OWL* (Orbiting Wide-field Light-collectors), a proposed dual satellite mission to have a larger total aperture than *JEM-EUSO*, has been designed to be sensitive enough to obtain data on higher energy UHECRs and on ultrahigh energy neutrinos. Its detecting area and FOV will be large enough to provide the event statistics and extended energy range that are crucial to addressing these issues. To accomplish this, *OWL* will also make use of the Earth’s atmosphere as a huge “calorimeter” to make stereoscopic measurements of the atmospheric UV fluorescence produced by air shower particles. *OWL* is thus proposed to consist of a pair of satellites placed in tandem in a low inclination, medium altitude orbit. The *OWL* telescopes will point down at the Earth and will together point at a section of atmosphere about the size of the state of Texas ( $\sim 6 \times 10^5 \text{ km}^2$ ).

The baseline *OWL* instrument, shown in Figure 8 (left), is a large f/1 Schmidt camera with a 45° full FOV and a 3 meter entrance aperture. The entrance aperture will contain a Schmidt corrector. The deployable primary mirror has a 7 meter diameter. *OWL* would be normally operated in stereo mode and the two “OWL eye” instruments will view a common volume of atmosphere.

The satellites can be launched together on a Delta rocket into a proposed 1000 km circular orbit with an inclination of 10°. Figure 8 (right) shows both satellites stowed for launch as well as a depiction of one of the Schmidt telescopes. Stereoscopic observation resolves spatial ambiguities and allows determination of corrections for the effects of clouds. In stereo, fast timing provides supplementary information to reduce systematics and improve the resolution of the arrival direction of the UHECR. By using stereo, differences in atmospheric absorption or scattering of the UV light can be determined. Detector missions such as the proposed *OWL* mission can provide the statistics of UHECR events that would be needed in the 100 to 1000 EeV energy range to search for the effects of a very small amount of Lorentz invariance violation at the highest energies.

We look forward to such future detector developments. As we have seen, they may have important implications for fundamental high energy physics as well as the astrophysics of powerful extragalactic “zevatrons”.



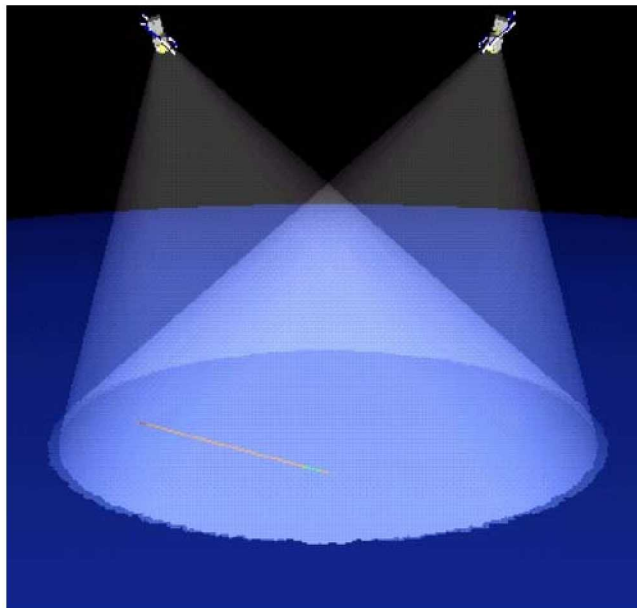
**Figure 8.** Left: Schematic of the Schmidt optics that form an *OWL* “eye” in the deployed configuration. The spacecraft bus, light shield, and shutter are not shown. Right: Schematic of the stowed *OWL* satellites in the launch vehicle.

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**Figure 9.** Two OWL satellites in low-Earth orbit observing the fluorescent track of a giant air shower. The shaded cones illustrate the field-of-view for each satellite.

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