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# Ultra-High Energy Cosmic Rays and Symmetries of Spacetime

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**High energy cosmic rays allow probing phenomena that are inacessible to accelerators. Observation of cosmic rays, presumebly protons, with energies beyond $4 \times 10^{19}\ eV$, the so-called Greisen-Zatsepin-Kuzmin (GZK) cut-off, give origin to two puzzles: How do particles accelerate to such energies ? Are their sources within $50 - 100\ Mpc$ from Earth, or Lorentz invariance is actually a broken symmetry ?**

The recent observation [1, 2, 3, 4] of cosmic rays with energies beyond the GZK cut-off [5] poses, besides the puzzle of understanding the mechanism that allows accelerating cosmic particles, presumebly protons, to such energies, the interesting side riddle of either locating viable sources at distances within, $D_{Source} \lesssim 50 - 100\ Mpc$ [6], or verifying, in an independent way, the violation of Lorentz invariance [7, 8, 9, 10]. Indeed, as is already well known, the latter comes about as only through the violation of that spacetime symmetry one can have energy-dependent effects that suppress processes such as the resonant scattering reaction with photons of the Cosmic Microwave Background (CMB), e.g. $p + \gamma_{2.73K} \rightarrow \Delta_{1232}$, which are central in establishing the GZK cut-off. The astrophysical alternative is, as mentioned above, to identify a set of nearby sources so that the travelling time of the emitted particles is shorter than the attenuation time due to particle photoproduction on the CMB. Given the energy of the observed ultra-high energy cosmic rays (UHECRs) and the Hilla's criteria [11] on the energy, size and intensity of the magnetic field involved, $E_{18} \leq \frac{1}{2}\beta Z B(\mu G) L(kpc)$ - where $E_{18}$ is the maximum energy measured in units of $10^{18}\ eV$, $\beta$ is the velocity of the shock wave relative to $c$ and $Z$ is the atomic number - it implies that, within a volume of radius $50 - 100\ Mpc$ about the Earth, only neutron stars, active galactic nuclei (AGN), gamma-ray bursts (GRBs) and cluster of galaxies are feasible acceleration sites [11, 12]. This astrophysical alternative has been recently advocated in Ref. [13], where it is further argued that the near isotropy of the arrival directions of the observed UHECRs can be attributed to extragalactical magnetic fields near the Milky Way that are strong enough to deflect and isotropise the incoming directions of UHECRs from sources within $D_{Source}$ [2]. Apart from the

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[2] Isotropy is a sensitive issue from the observational point of view [14] and rather crucial in the discussion about the origin of the UHECRs as scenarios for their production naturally generate anisotropies (see e.g. [15]).

fact that observations, such as the age of the bulk of the cosmic rays in the galaxy inferred from the observed isotopic ratios $Al^{26}/Al^{27}$ and $Be^{10}/Be^{9}$ and the small cosmic rays densities at the Magellanic clouds, indicate that the Milk Way *cannot* be embedded in a $\sim \mu G$ magnetic halo/slab of the local super cluster [16], the main argument against this proposal is the mismatch in the energy fluxes of observed UHECRs and of the potential sources. Indeed, assuming, for instance, that the energy output in UHECRs owe its origin to GRBs and is about $E \sim 10^{52}\ erg$, a $\Lambda$CDM model and that the GRB rate is proportional to the star formation, it follows that the resulting flux is, $\Phi \leq 3 \times 10^{-3}\ eV\ cm^{-2}\ s^{-1}\ sr^{-1}$ [16], about four orders of magnitude smaller than the observed flux of UHECRs. Similar arguments and knowledge of the AGN evolution function is sufficient to also exclude those objects.

Another astrophysical proposal suggests that relativistic jets from hypothetical GRBs in the Milk Way that do not point in our direction, accelerate UHECRs in our galactic halo [17]. No other evidence of this nearby population of GRBs is known and, from the knowledge of GRBs acquired from the recent observation of their afterglows, it has became clear that GRBs all have an identifiable host galaxy. Hence, from the flux argument discussed above, it follows that invoking a local population of GRBs means one is almost claiming a special status for our galaxy.

A further difficulty related with the astrophysical route is that studies where correlations between observed UHECRs and potential candidates were sought are, so far, inconclusive in what concerns correlations with large scale structure [18] and high redshift sources [19]. Of course, these negative results might be attributed to the small size of the available samples.

It seems, therefore, fair to conjecture that, given the abovementioned arguments, the breaking of Lorentz invariance should also be seriously considered. Lorentz invariance is one of the most fundamental symmetries of physics and is an underlying ingredient of all known physical descriptions of nature. However, more recently, there has been evidence in the context of string/M-theory that this symmetry can be spontaneously broken due to nontrivial solutions in the field theory of open strings [20] and interactions that may emerge in a scenario where our world is wrapped in a tilting 3-brane [21]. The resulting novel interactions may have striking implications at low-energy [22, 23]. Putative violations of the Lorentz invariance may also lead to the breaking of CPT symmetry [24]. Interestingly, this last possibility can be verified experimentally in neutral-meson experiments [25], Penning-trap measurements and hydrogen-antihydrogen spectroscopy (see [26] for an updated review). The breaking of CPT symmetry also allows for an explanation of the baryon asymmetry of the Universe [27]. An extension of the Standard Model (SM) that incorporates possible violations of Lorentz and CPT symmetries was built in Ref. [28].

The violation of these fundamental symmetries naturally raise the question of how to phenomenologically test them. Astrophysics may play an essential role in this respect as it will soon be possible to make correlated astrophysical observations involving high-energy radiation and, for instance, neutrinos which will make viable direct astrophysical tests of Lorentz invariance (see e.g. [10, 29]) and references therein).

From the experimental point of view, the most stringent limit on the violation of Lorentz symmetry arises from measurements of the time dependence of the quadrupole splitting of nuclear Zeeman levels along Earth's orbit giving origin to the impressive limit on deviations from the Lorentz invariance, $\delta < 3 \times 10^{-22}$ [30], and even more stringent bounds according to a recent assessment [31].

Bounds on the violation of Lorentz symmetry can be also extracted from ultra-high energy cosmic rays, from which a limit on the difference of the maximum propagation velocity of different particles is obtained, e.g. for the $\Delta_{1232}$ resonance, $c_p - c_\Delta \equiv \epsilon_{p\Delta} \simeq 1.7 \times 10^{-25}$ [8] and from the search of neutrino oscillations, $|\epsilon| \lesssim few \times 10^{-22}$ [32]. These limits can be turned into bounds on parameters of the Lorentz-violating extension of the SM [10]. Actually, in the context of that extension, and also in some quantum gravity and stringy induced models (see [29, 33]), deformations on the relativistic dispersion relation are obtained that, give origin, for certain instances, to threshold effects that allow evading the GZK cut-off [8, 10, 34, 35], to a time delay in the arrival of signals from faraway sources carried by different particles [10], and to bounds on the quantum gravity scale [29, 33]. As discussed in [10], a distinct feature of the Lorentz violating extension of the SM of Ref. [28] is that it leads to a time delay in the arrival of signals carried by different particles that is energy *independent*, in opposition to what was expected from general arguments [10], and has a dependence on the *chirality* of the particles involved.

# References


[1] N. Hayashida et al., (AGASA Collab.), *Phys. Rev. Lett.* **73**, 3491 (1994);
M. Takeda et al., (AGASA Collab.), *Phys. Rev. Lett.* **81**, 1163 (1998).

[2] D.J. Bird et al., (Fly's Eye Collab.), *Phys. Rev. Lett.* **71**, 3401 (1993); *Ap. J.* **424**, 491 (1994); **441**, 144 (1995).

[3] M.A. Lawrence, R.J.O. Reid and A.A. Watson (Haverah Park Collab.), *J. Phys.* **G17**, 733 (1991).

[4] N.N. Efimov et al., (Yakutsk Collab.), ICRR Symposium on Astrophysical Aspects of the Most Energetic Cosmic Rays, eds. N. Nagano and F. Takahara (World Scientific, 1991).

[5] K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966);
G.T. Zatsepin, V.A. Kuzmin, JETP Lett. **41**, 78 (1966).

[6] C.T. Hill, D. Schramm, T. Walker, *Phys. Rev.* **D36**, 1007 (1987).

[7] H. Sato, T. Tati, *Progr. Theor. Phys.* **47**, 1788 (1972).

[8] S. Coleman, S.L. Glashow, *Phys. Lett.* **B405**, 249 (1997); *Phys. Rev.* **D59**, 116008 (1999).

[9] L. Gonzales-Mestres, "Deformed Lorentz Symmetry and Ultra-High Energy Cosmic Rays ", hep-ph/9905430.

[10] O. Bertolami, C.S. Carvalho, *Phys. Rev.* **D61**, 103002 (2000).

[11] A.M. Hillas, *Ann. Rev. Astron. Astrophys.* **22**, 425 (1984).

[12] J.W. Cronin, *Rev. Mod. Phys.* **71**, S165 (1999).

[13] G.R. Farrar, T Piran *Phys. Rev. Lett.* **84**, 3527 (2000).

[14] G. Medina-Tanco, "Ultra-high energy cosmic rays: are they isotropic ?", astro-ph/0009336.

[15] A.V. Olinto, "The Mistery of Ultra-High Energy Cosmic Rays", astro-ph/0003013.

[16] A. Dar, Comment on "Violation of the Greisen-Zatsepin-Kuzmin Cutoff: A Tempest in a (Magnetic) Teapot ?", astro-ph/0006013.

[17] A. Dar, A. Plaga, *Astron. and Astrophys.* **349**, 257 (1999).

[18] E. Waxman, K.B. Fisher, T. Piran, *Ap. J.* **483**, 1 (1997).

[19] G. Sigl, D.F. Torres, L.A. Anchordoqui and G.E. Romero, "Testing the correlation of ultra-high energy cosmic rays with high redshift sources", astro-ph/0008363.

[20] V.A. Kostelecký, S. Samuel, *Phys. Rev.* **D39**, 683 (1989); *Phys. Rev. Lett.* **63**, 224 (1989).

[21] G. Dvali and M. Shifman, "Tilting the Brane, or Some Cosmological Consequences of the Brane World", hep-th/9904021.

[22] O. Bertolami, *Class. Quantum Gravity* **14**, 2748 (1997).

[23] O. Bertolami, D.F. Mota, *Phys. Lett.* **B455**, 96 (1999).

[24] V.A. Kostelecký, R. Potting, *Phys. Rev.* **D51**, 3923 (1995); *Phys. Lett.* **B381**, 389 (1996).

[25] D. Colladay, V.A. Kostelecký, *Phys. Lett.* **B344**, 259 (1995); *Phys. Rev.* **D52**, 6224 (1995); V.A. Kostelecký, R. Van Kooten, *Phys. Rev.* **D54**, 5585 (1996).

[26] R. Bluhm, "Lorentz and CPT Tests in Atomic Physics" hep-ph/0006033.

[27] O. Bertolami, D. Colladay, V.A. Kostelecký, R. Potting, *Phys. Lett.* **B395**, 178 (1997).

[28] D. Colladay, V.A. Kostelecký, *Phys. Rev.* **D55**, 6760 (1997); **D58**, 116002 (1998).

[29] G. Amelino-Camelia and T. Piran, "Cosmic rays and $TeV$ photons as probes of quantum properties of space-time", hep-ph/0006210.

[30] S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, E.N. Fortson, *Phys. Rev. Lett.* **57**, 3125 (1986).

[31] V.A. Kostelecký, C.D. Lane, *Phys. Rev.* **D60**, 116010 (1999).

[32] E.B. Brucker et al., *Phys. Rev.* **D34**, 2183 (1986);

S.L. Glashow, A. Halprin, P.I. Krastev, C.N. Leung, J. Pantaleone, *Phys. Rev.* **D56**, 2433 (1997).

[33] N. Mavromatos, "Testing a (Stringy) Model of Quantum Gravity", gr-qc/0009045.

[34] R. Aloisio, P. Blasi, P.L. Ghia, A.F. Grillo, "Probing the Structure of Space-Time with Cosmic Rays", astro-ph/0001258.

[35] H. Sato, "Extremely High Energy and Violation of Lorentz Invariance", astro-ph/0005218.