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Effects of Lorentz Invariance Violation in Ultra High Energy Cosmic Ray Physics

Andrey Saveliev[1]

University of Hamburg

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[1]with Luca Maccione (DESY Hamburg) and Günter Sigl (Univ. Hamburg)

Contents

Possibilities of Lorentz Invariance Violation (LIV)

Lorentz invariance has been found to hold for the scales which are described by the Standard Model (SM) of particle physics, BUT

- Non-compactness of the Lorentz group
- LIV as a possible result from Quantum Gravity (QG)
  $\rightarrow$ Planck Mass ($M_{\mathrm{Pl}} \approx 1.22 \times 10^{28}\,\mathrm{eV}$) suppression

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- Lorentz invariance is not an axiom, but rather a consequence from four principles [Ignatowsky, 1910]:
  1. Relativity
  2. Isotropy of spacetime
  3. Homogeneity of spacetime
  4. Precausality

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- CPT violation implies LIV for local QFT [Greenberg, 2002]

Minimal Standard Model Extension

The **minimal Standard Model Extension (SME)** is an effective field theory which is motivated by QG. The most important ideas:

- SM should be the low-energy limit of SME
- Only SM fields are used
- Validity of various physical principles: Energy-momentum conservation, preserved passive Lorentz Transformations, gauge invariance, positive energies, ...
- Preferred reference frame, i.e. coupling of the fields to a unit vector u^α (e.g. with $u^i = 0$ for $i = 1, 2, 3$ for rotation symmetry conservation)

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$\Rightarrow$ Modification of the SM Lagrangian: $\mathcal{L}_{SME} = \mathcal{L}_{SM} + \Delta\mathcal{L}$, $\Delta\mathcal{L}$ containing in general a large number of possible terms (dimension 3 and 4 operators) which meet the requirements above [Colladay and Kostelecký, 1998]

Minimal Standard Model Extension and Beyond

Different kinds of extensions for SME - higher order operators [Mattingly, 2007]
One of the possible consequences of SME are modified dispersion relations (MDR). A simple case for just the photon sector of the modified Lagrangian is given by [Myers and Pospelov, 2003]

$$\mathcal{L}_{SME,\gamma} = \mathcal{L}_\gamma + \Delta\mathcal{L}_\gamma^{(5)} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\xi}{2M_{\mathrm{Pl}}} u^\mu F_{\mu\nu} \left(u \cdot \partial\right) \left(u_\alpha \tilde{F}^{\alpha\nu}\right) \, .$$

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Using the unit vector u given earlier, Lorentz Gauge and $E \approx p$ for a photon propagating along the z axis this gives

$$\epsilon^2 = k^2 \pm \xi\frac{k^3}{M_{\mathrm{Pl}}} ,$$

a modified dispersion relation.

Modified Dispersion Relations

These results give the motivation to assume a MDR to be in general of the form

$$E^2 = p^2 + m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\mathrm{Pl}}^n} \,.$$

One can now estimate at which critical energies E_{cr} these MDRs might result in a visible effect on particle propagation:

$$E_{cr} \approx \left(m^2 M_{\mathrm{Pl}}^n / \eta^{(n)} \right)^{\frac{1}{n+2}} \,.$$

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For $\eta^{(n)} \approx 1$ this gives

n	E_{cr} for ν_{e}	E_{cr} for e^-	E_{cr} for p^+
1	$\approx 10^9$ eV	$\approx 10^{13}$ eV	$\approx 10^{15}$ eV
2	$\approx 10^{14}$ eV	$\approx 10^{17}$ eV	$\approx 3 \times 10^{18}$ eV

[Jacobson et al., 2003]

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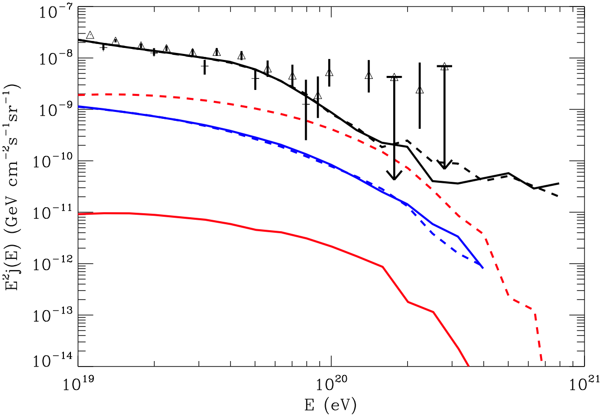
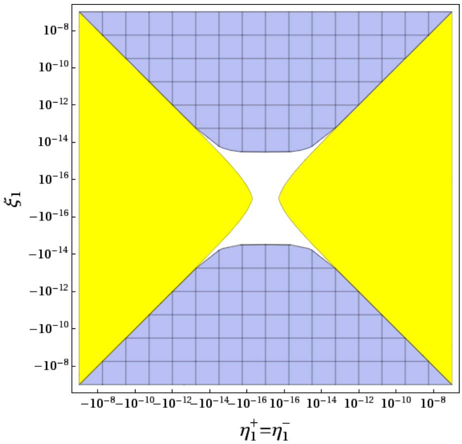
Still very high energies are needed $\rightarrow$ astrophysics/astroparticle physics

LIV Constraints - UHE Photons



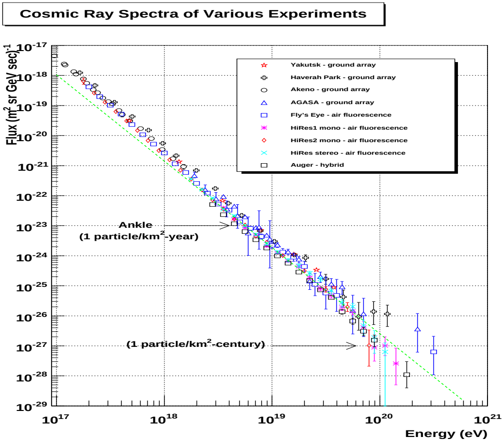
Expected **proton**, **neutrino** and **photon** fluxes with (solid) and without (dashed) pair production [Galaverni and Sigl, 2008b]

LIV Constraints - UHE Photons



Constraints from upper limits on the CR photon fraction (blue) and from a possible $10^{19}\mathrm{eV}$ photon detection (yellow) [Galaverni and Sigl, 2008a]

LIV Constraints - GZK Cutoff



[Hanlon, 2008]

LIV Constraints - GZK Cutoff

- The GZK suppression is predicted to appear at around $6 \times 10^{19}\mathrm{eV}$ due to the dominant Δ resonance production:

$$p + \gamma \to \Delta(1232\mathrm{MeV}) \to p + \pi^0$$
$$\to n + \pi^+$$

By choosing the right combination of LIV parameters it is possible to change the threshold momenta and as a result to "close" the Δ channel $\to$ Elimination of the GZK cutoff! [Bietenholz, 2008]

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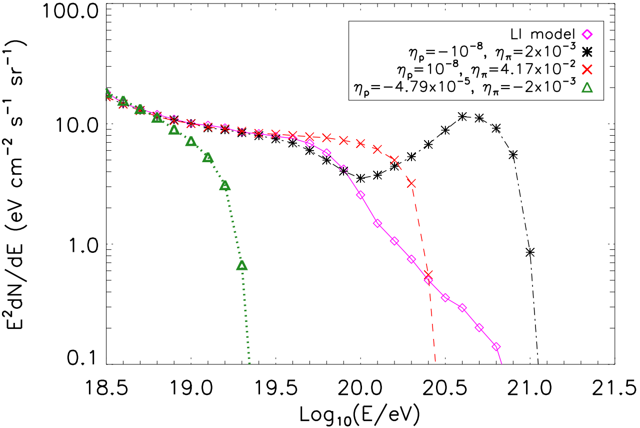
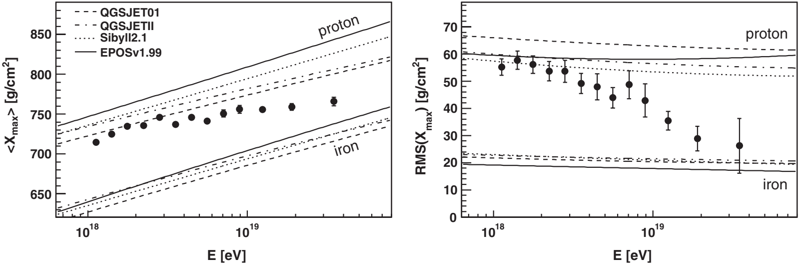
- LIV has also a crucial impact on the propagation lengths (especially due to Vacuum Cherenkov radiation) and therefore may change the observed spectrum dramatically.

LIV Constraints - GZK Cutoff



Constraints: $-10^{-3} \lesssim \eta_p \lesssim 10^{-6}$
[Maccione et al., 2009]

LIV for UHECR Nuclei



Recent results from the Pierre Auger Observatory showing the average value and the RMS of the air shower maximum distance X_{max} in the atmosphere indicating a heavy component at the highest energies. [Abraham et al., 2010]

LIV for UHECR Nuclei

Ultra High Energy Cosmic Rays (UHECRs) are the particles with the highest energies ever observed $\rightarrow$ Candidates for observing LIV effects

- The main reaction for UHECR nuclei is photodisintegration, in the simplest case:

$$ {}^{A}_{Z}N + \gamma \rightarrow {}^{A'}_{Z'}N' + {}^{B}_{W}N'' $$

with $A' = A - B$ and $Z' = Z - W$.

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  with $A' = A - B$ and $Z' = Z - W$.

However, due to LIV and the MDR for composite particles [Jacobson et al., 2003],

$$ E^2_{A,Z} = p^2_{A,Z} + m^2_{A,Z} + \frac{\eta}{A^2} \frac{p^{n+2}_{A,Z}}{M^n_{\mathrm{Pl}}} , $$

two new reactions may appear:

LIV for UHECR Nuclei

- Spontaneous Decay (SD) of LI-stable particles

$$ {}^{A}_{Z}N \to {}^{A'}_{Z'}N' + {}^{B}_{W}N'' $$

LIV for UHECR Nuclei

- Spontaneous Decay (SD) of LI-stable particles

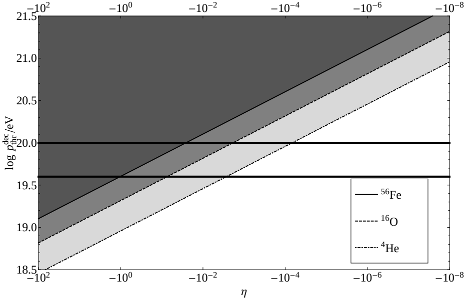
$$ {}^{A}_{Z}N \to {}^{A'}_{Z'}N' + {}^{B}_{W}N'' $$

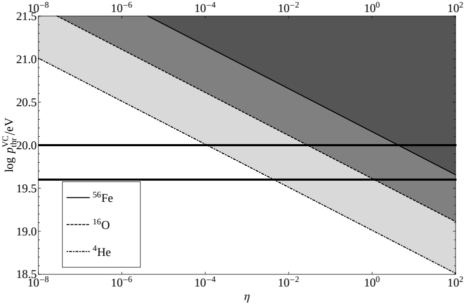
- Vacuum Cherenkov (VC) effect

$$ {}^{A}_{Z}N \to {}^{A}_{Z}N + \gamma $$

with threshold momentum $p_{thr,VC} = \left(\frac{m^2_{A,Z} M^n_{\mathrm{Pl}} A^2}{(n+1)\eta} \right)^{\frac{1}{n+2}}$

LIV for UHECR Nuclei





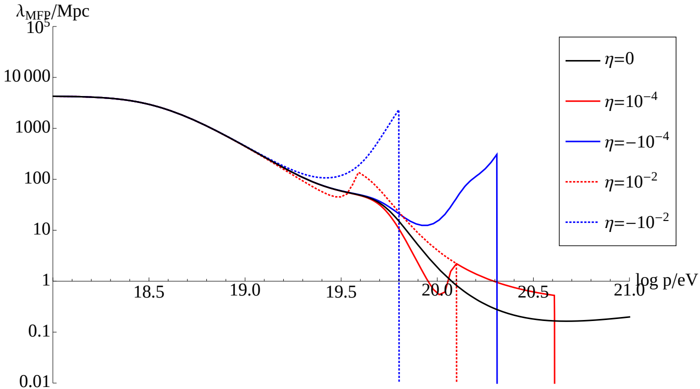
Constraints from Spontaneous Decay and VC radiation for $n = 2$ and single nucelon emission.

	$E_{max} = 10^{19.6}$ eV	$E_{max} = 10^{20}$ eV
^{4}He	$-3 \times 10^{-3} \lesssim \eta \lesssim 4 \times 10^{-3}$	$-7 \times 10^{-5} \lesssim \eta \lesssim 1 \times 10^{-4}$
^{16}O	$-7 \times 10^{-2} \lesssim \eta \lesssim 1$	$-2 \times 10^{-3} \lesssim \eta \lesssim 3 \times 10^{-2}$
^{56}Fe	$-1 \lesssim \eta \lesssim 200$	$-3 \times 10^{-2} \lesssim \eta \lesssim 4$

[Saveliev et al., 2011]

LIV for UHECR Nuclei

Typical impact on the mean free path (here shown for oxygen):



→ Still work to be done, e.g. computations of spectra.
[Saveliev et al., 2011]

Conclusions and Outlook

- LIV is an interesting concept to test physics beyond the SM (like QG)
- Due to preserved Lorentz invariance at low energies, LIV is predicted to be seen only at the highest energy scale, i.e. the best candidate is UHE Cosmic Ray physics
- Various constraints on LIV have been set for different particles and operator dimensions

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- LIV is an interesting concept to test physics beyond the SM (like QG)
- Due to preserved Lorentz invariance at low energies, LIV is predicted to be seen only at the highest energy scale, i.e. the best candidate is UHE Cosmic Ray physics
- Various constraints on LIV have been set for different particles and operator dimensions
- Still, due to high uncertainties in the UHECR measurements (rare events, composition, ...), future years of experiments may bring more reliable data
- Especially the investigation of LIV for heavy nuclei is just at its beginning