The influence of Lorentz Violation on UHE photon detection

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Based on

- Grigory Rubtsov, Petr Satunin, and Sergey Sibiryakov. "Calculation of cross sections in Lorentz-violating theories". Phys. Rev. D 86, 085012 (2012)
- Petr Satunin. "Width of photon decay in a magnetic field: Elementary semiclassical derivation and sensitivity to Lorentz violation". Phys. Rev. D 87, 105015 (2013)
- Grigory Rubtsov, Petr Satunin, and Sergey Sibiryakov. Constraining Lorentz Violation using possible UHE photon detection. arXiv:1306.xxxx

Lorentz Invariance Violation

Motivation

- Several approaches to quantum gravity predict Lorentz invariance violation (LV) at high energies (e.g. Horava-Lifshitz).

Horava, 2009

Blas, Pujolas, Sibiryakov, 2010

Kostelecky, Samuel, 1989

- Theories with violation of the Lorentz Symmetry as an effective theory

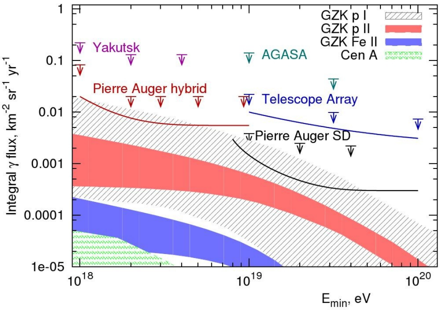
Kostelecky, Colladay, 1998

Coleman, Glashow, 1999

- Low-energy LV is strictly bounded *Data tables — Kostelecky, Russell, 2011*
- Weaker boundns on high-energy LV — the largest sensitivity in cosmic rays

UHE photons

- Energies $10^{18} - 10^{20}\,\mathrm{eV}$
- Not detected yet
- If reach the Earth, can be detected by surface detectors (Auger, TA)
- Possible sources:
  - Products of GZK process (if protons)
    $p\,\gamma_{CMB} \to p\,\pi^0$ or $p\,\gamma_{CMB} \to n\,\pi^+$; $\pi^0 \to \gamma\gamma$



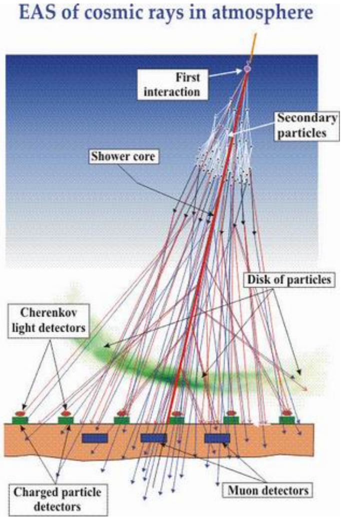
  - Exotics (Superheavy DM decay, Z-burst)

UHE photons detection

1st interaction:

$E_{ph} \leq 10^{19.5}$ eV — pair production on Coulomb field of a nuclei $\gamma N \rightarrow N e^{+} e^{-}$. Atmosphere shower started at ~ 10 km.

$E_{ph} \geq 10^{19.5}$ eV (depend on an angle) — pair production in geomagnetic field $\gamma \rightarrow e^{+} e^{-}$. Small 'preshower' at $\sim 10^3$ km; subsequent shower in the atmosphere.



Photon showers. Sensitivity to LV

Questions:

- Can we detect photon showers in the world without LV?
- What bounds we can establish if UHE photons be detected?

Consider LV, modifying dispersion.

3 possibilities:

- Photon decay. No UHE photons in CR. No showers

  Coleman, Glashow '98 ...

- Suppressed first interaction. Photons but no showers due to non-interaction
- LI-like showers. Tiny LV or fine-tuning

Model

- It's complicated to use full SME with nonminimal QED sector in calculations
- Assumptions: C, P and T unbroken, rotational symmetry in preferred (CMB) frame conserved, LV operators of dim. 4 and 6.
- Inspired by Horava-Lifshitz gravity

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu} - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\varkappa\bar{\psi}\gamma^{i}D_{i}\psi + \frac{ig}{M^2}D_{j}\bar{\psi}\gamma^{i}D_{i}D_{j}\psi + \frac{\xi}{4M^2}F_{kj}\partial_i^2 F^{kj}$$

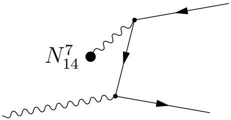
$$\Downarrow$$

Dispersion relations:

$$E_{\gamma}^2 = k^2 + \frac{\xi k^4}{M^2}, \qquad E_e^2 = m^2 + p^2\left(1+2\varkappa\right) + \frac{2gp^4}{M^2}.$$

Feynman rules modification see *Rubtsov, P.S., Sibiryakov, 2012*

Pair production on a nuclei $\gamma N \mapsto e^+ e^- N$



$$\omega_{LV} = -\varkappa k + \left(\frac{\xi}{2} - g\right)\frac{k^3}{M^2}, \qquad k \gg m$$

$$k\,|\omega_{LV}| \ll m^2 \quad \longrightarrow \quad \sigma = \frac{28}{9}\frac{Z^2\alpha^3}{m^2}\ln\frac{2k}{m}$$ *Bethe, Heitler, 1934*

$$k\,|\omega_{LV}| \gg \frac{m^2}{\alpha^2 Z^{2/3}} \quad \longrightarrow \quad \sigma = \frac{4Z^2\alpha^3}{3}\frac{1}{k|\omega_{LV}|}\left(\ln\frac{k|\omega_{LV}|}{m^2}\right)^2$$

$$m^2 \ll k\,|\omega_{LV}| \ll \frac{m^2}{\alpha^2 Z^{2/3}} \quad \longrightarrow \quad \sigma = \frac{8Z^2\alpha^3}{3}\frac{1}{k|\omega_{LV}|}\ln\frac{2k|\omega_{LV}|}{m^2}\ln\frac{1}{\alpha Z^{1/3}}$$

- Suppression $\sigma_{LV} \sim \sigma_{LI} \cdot \frac{m^2}{k|\omega_{LV}|}$

Photons showers. Numerical simulations

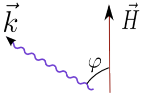
- Simulate $N < 6$ photon events in agreement with LI hypothesis
- Compare these events with expected signal for LV (KS test)
- Exclude LV parameters

	95% CL			99% CL		
N	$X_{max}, \frac{g}{cm^2}$	$\frac{\sigma^{LI}}{\sigma^{LV}}$	$-\omega_{LV}, 10^{-7}eV$	$X_{max}, \frac{g}{cm^2}$	$\frac{\sigma^{LI}}{\sigma^{LV}}$	$-\omega_{LV}, 10^{-7}eV$
1	-	-	-	-	-	-
2	1 880	18.6	16.76	-	-	-
3	1 380	8.6	5.79	1 970	20.4	18.91
4	1 270	6.4	3.69	1 600	13.0	10.38
5	1 225	5.5	2.88	1 490	10.8	8.03

Table: Exclusion bounds on X_{max} (maximal depth of a shower) and ω_{LV} on 95% and 99% CL if N 10^{19} eV photons are detected.

- Bound on positive $\omega_{LV} \lesssim \frac{2m^2}{k}$ from photon decay (see Galaverni, Sigl '08 other notations)

Photon decay in magnetic field



$$\vec{H} = (H, 0, 0)$$
$$\vec{k} = (k\cos\varphi, k\sin\varphi, 0)$$

Semiclassical 'Worldline instanton' method *Affleck, Alvarez, Manton, 1982*

$$\Gamma \propto \int_{p.b.c} Dx_\mu \, e^{-S[x_\mu]}$$

Semiclassics $\leftrightarrow$ saddle point approximation

$$LI \quad \leftrightarrow \quad \Gamma \propto \exp\left[-\frac{8m^3}{3keH\sin\varphi}\right].$$

$$LV \quad \leftrightarrow \quad \Gamma \propto \exp\left[-\frac{8m^3}{3keH\sin\varphi}\left(1-\frac{k\cdot\omega_{LV}}{2m^2}\right)^{3/2}\right].$$

- UHE photon registered with preshower signature $\rightarrow$ $|\omega_{LV}| < \frac{2m^2}{k}$

Bounds IF UHE photons be detected

Excellent bounds on some LV parameters...

ω	$10^{19}\,\mathrm{eV}$	$10^{20}\,\mathrm{eV}$	current
$\|\omega_{LV}\|$, eV	10^{-6}	10^{-8}	-
$\|\varkappa\| \sim \|c_{ii}\|$	10^{-26}	10^{-28}	10^{-17}
$M_{QG}^{(2)}$, GeV	10^{24}	10^{25}	10^{16}

... only if photons with energy ω be detected.

- but NO evidence for LV in the opposite case

Conclusions

- Even small LV strongly suppresses pair production (both in an electric field of a nuclei or in a weak magnetic field).
- Possible UHE photon detection can establish very strong two-sided bound on generic type of LV parameters
- Independent of any astrophysical model: UHE photon origin does not matter
- These calculations in more general model are complicated but possible..

Thank you for your attention