Ultra-high energy photons and the tests of Lorentz-invariance

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Outline

- Introduction
- LIV model and interactions
- Accelerator and astro-physics constraints
- Constraints with UHE photons

Introduction: UHE photons and Lorentz invariance

- Why Lorentz invariance violation?
  - Several approaches to quantum gravity predict LIV at high energies (e.g. Horava-Lifshitz).
- Why ultra-high energy cosmic rays?
  - The largest observable energy in the laboratory system: up to 10^{11} GeV
- Why photons?
  - Photon and electron are observed fundamental particles.
  - Interactions are well understood (QED).

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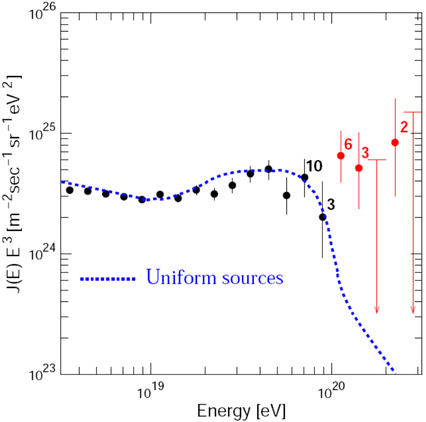
Historical intro: GZK effect

Greisen, 1966; Zatsepin, Kuzmin, 1966

End of Cosmic Ray Spectrum predicted for $E \gtrsim 10^{19.7}$ eV.

$$p + \gamma_{2.7K} \to \Delta(1232) \to n + \pi^+$$
$$\to p + \pi^0$$



AGASA spectrum, 2003

Takeda, M. et al., Astropart. Phys 19(2003)

- Expected 1.9 event
- Observed 11 events above 10^{20} eV

Historical intro: GZK cut-off evasion

$$p + \gamma_{2.7K} \to \Delta(1232) \to n + \pi^+$$
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- If Lorentz-invariance is broken, the reaction threshold may be upshifted ⇒ no observed cut-off.

Coleman, Glashow, Phys.Rev.D 59, 1999

- After: cut-off observed in three independent experiments:

HiRes: PRL 100 (2008), Astropart. Phys. 32 (2010)
Pierre Auger: PRL 101 (2008) & Phys. Lett. B 685 (2010)
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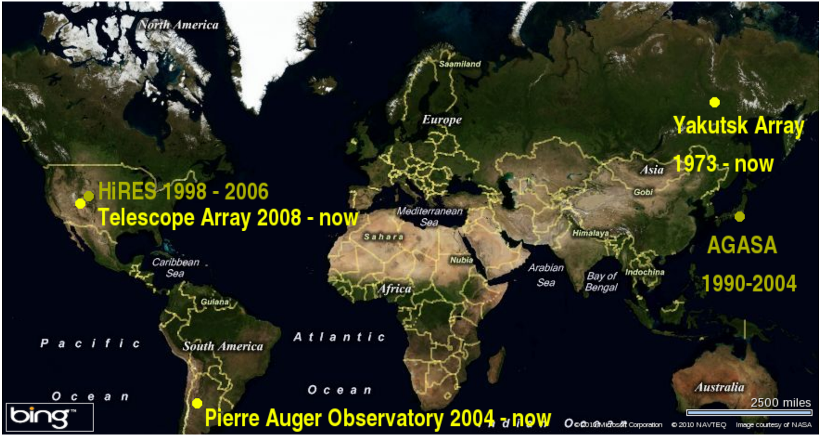
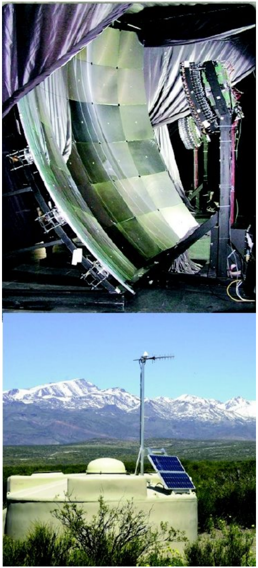
Intro: UHECR experiments today



Intro: UHECR experiments today

Yakutsk array

Pierre Auger



Telescope Array

Ultra-high energy photons

- $10^{18} - 10^{19}$ photons are everpresent secondaries of GZK process

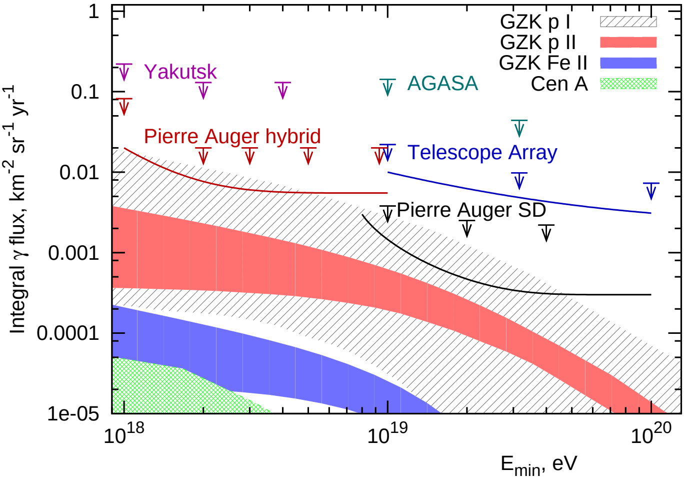
$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow n + \pi^{+}$$
$$\rightarrow p + \pi^{0}$$

$$\pi^{0} \rightarrow \gamma\gamma$$

- No GZK photons observed yet, but existing limits are coming close to predicted flux

Note: GZK-photons are produced effectively only in case of proton primaries while UHECR composition is generally unknown (there is disagreement between experiments)

UHE photon search status



line – proposed sensitivity for 2015

J. Alvarez-Muñiz et al., Review of Multimessenger WG, UHECR 2012, CERN

- A chance to observe cosmogenic UHE photons soon

Model

We consider Lorentz-violated QED with dispersion relations:

$$\gamma: \qquad E_\gamma^2 = k^2 + \frac{\xi k^4}{M_{Pl}^2}$$

$$e^\pm: \qquad E_e^2 = p^2(1+2\varkappa) + m^2 + \frac{2gp^4}{M_{Pl}^2}$$

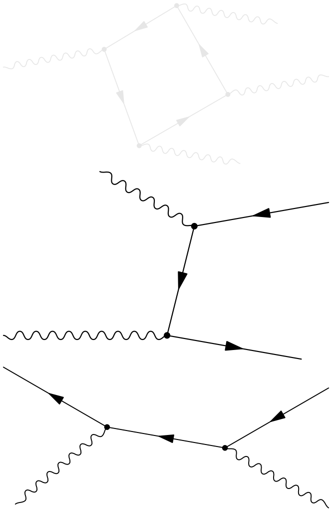
- Dispersion relations are considered as an effective theory
- We look for possible large violation: $|\xi|, |g| \gg 1$
- Violation in hadronic sector is not discussed here

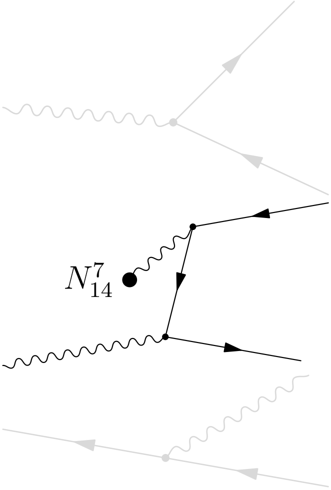
Effective mass may be defined as:

$$m_{eff,\gamma}^2(k) = \frac{\xi k^4}{M_{Pl}^2}$$

$$m_{eff,e^\pm}^2(p) = m^2 + \frac{2gp^4}{M_{Pl}^2}$$

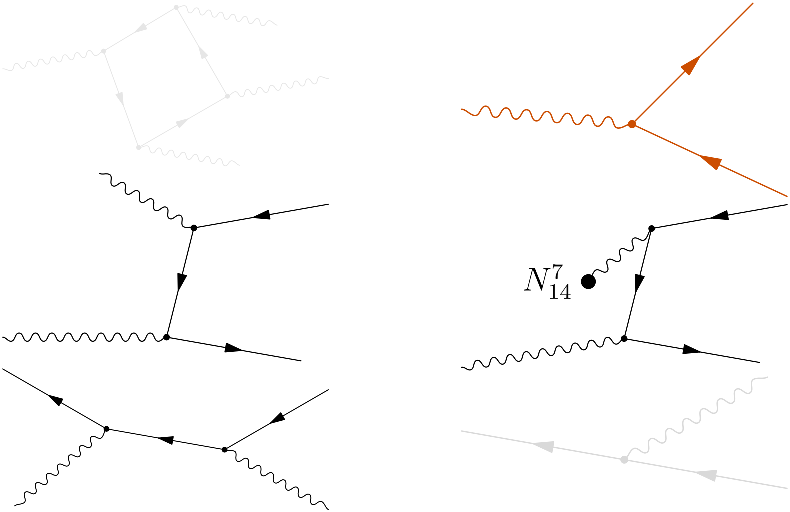
QED reactions, $\xi = 0$, $g = 0$





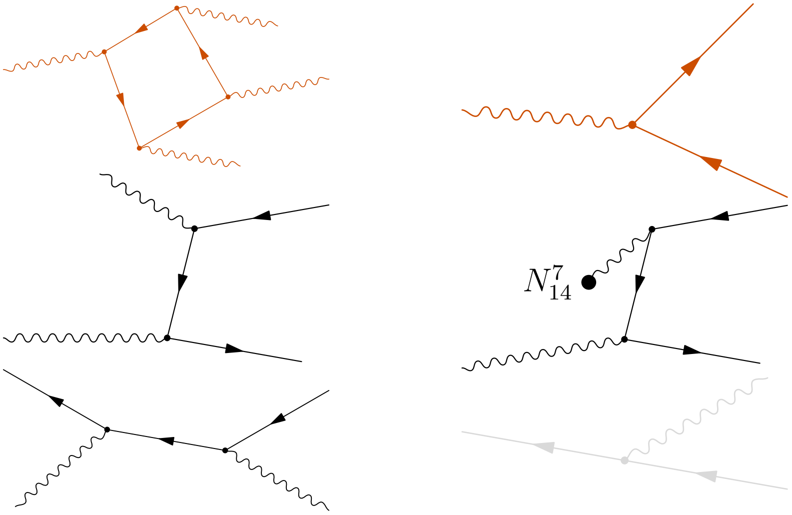
$E_\gamma^2 = k^2 + \xi k^4 / M_{Pl}^2$ $\qquad$ $E_e^2 = p^2 + m^2 + 2gp^4 / M_{Pl}^2$

QED reactions, $\xi = 0$, $g < -1$



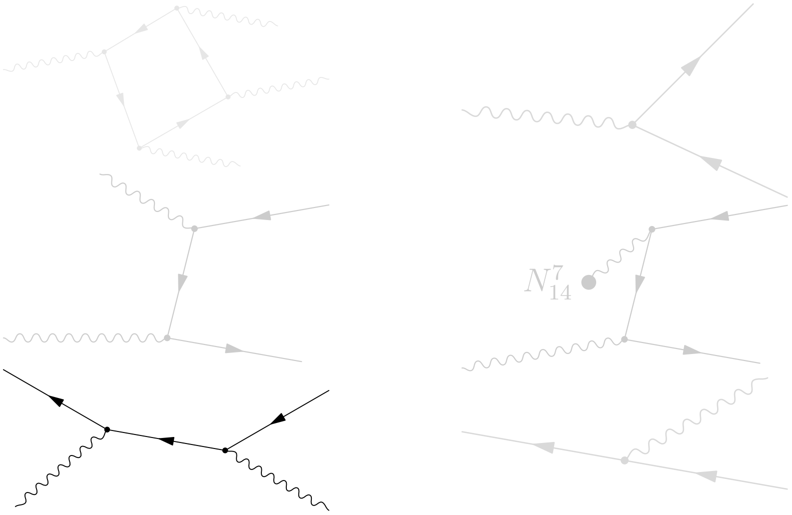
$E_\gamma^2 = k^2 + \xi k^4 / M_{Pl}^2$ $\quad$ $E_e^2 = p^2 + m^2 + 2gp^4 / M_{Pl}^2$

QED reactions, $\xi > 1$, $g = 0$



$E_\gamma^2 = k^2 + \xi k^4 / M_{Pl}^2 \qquad E_e^2 = p^2 + m^2 + 2gp^4 / M_{Pl}^2$

QED reactions, $\xi < -1$, $g = 0$



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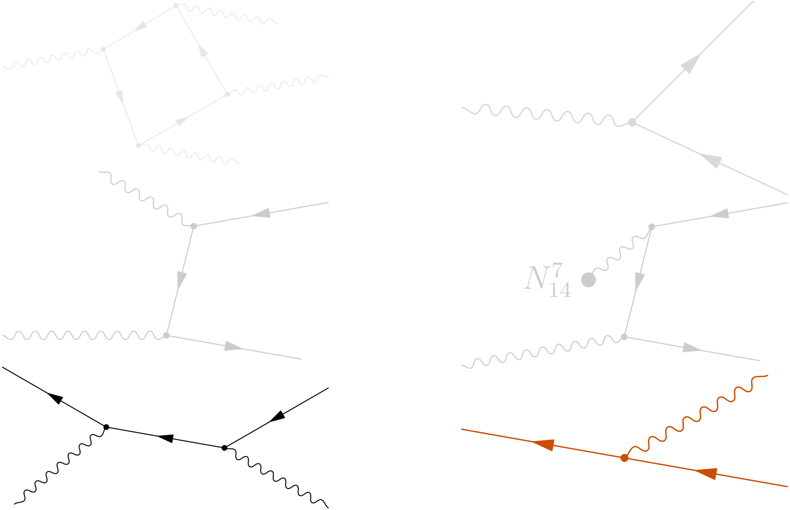

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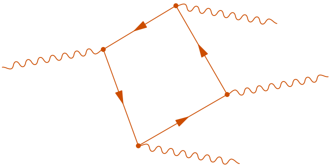
$\gamma \to 3\gamma$

$$\Gamma\left(\gamma \to 3\gamma\right) \simeq \left(\frac{2\xi_{em}^2}{45}\right)^2 \frac{1}{3!2^{11}\pi^9} \frac{\xi^5 E_\gamma^{19}}{m^8 M_{Pl}^{10}\left(1 + \varkappa\frac{E_\gamma^2}{m^2} + 2g\frac{E_\gamma^4}{m^2 M_{Pl}^2}\right)^4} \cdot f$$

- no threshold
- rapidly grows with energy
- photons escape detection



Gelmini, Nussinov, Yaguna, JCAP 0506, 2005

Laboratory limits

- **LEP** understands very well synchrotron energy losses of electrons with $E = 91$ GeV. Synchrotron energy losses per turn:

$$\Delta E = \frac{4\pi e^2}{3r} \left(\frac{1}{1 - v^2} \right)^2$$

v – electron group velocity, $r = 4300$ m.
  - The losses are known up fractional uncertainty 6×10^{-4}.
  - This results in the constraint on $\varkappa$:

$$|\varkappa| < 4 \times 10^{-15}$$

Altschul, Phys.Rev.D 80, 2009

- Spectroscopy of atomic dysprosium
  - two nearly degenerate states: $4f^{10}5d6s$ and $4f^{9}5d^{2}6s$
  - strongest constraints on electron speed of light

$$|\varkappa| < 10^{-17}$$

Hohensee et al., arXiv:1303.2747

Astrophysics limits

- Two peaks in Crab Nebula's photon spectrum are believed to be a product of 1500 TeV electrons: synchrotron and inverse Compton. The fit of the synchrotron spectrum gives:

$$|g| < 10^6$$

Liberati et al, Phys.Rev.Lett. 109, 2012

- Timing of transient events (GRB, AGN flares). Compare arrival time of photons with different energies.

$$|\xi| < 3.6 \times 10^{16}$$

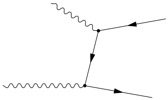
HESS Collaboration, Astropart.Phys.34:738-747,2011

- Observation of 50 TeV photons from Crab (2 kpc) limits γ splitting:

$$\xi < 10^{11}$$

Gelmini,Nussinov,Yaguna, JCAP 0506,2005

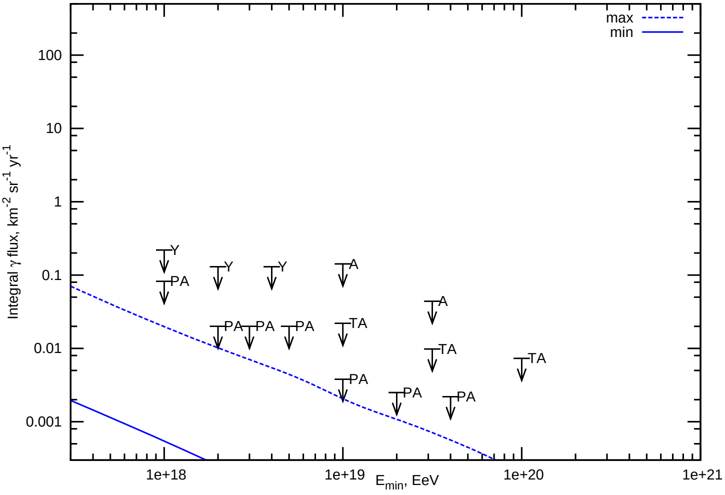
Photons in LIV model

- Photons undergo e^+e^- pair production on intergalactic backgrounds (CMB, IR, radio). 
- In LIV case, the threshold of the reaction may be upshifted and Universe becomes transparent for UHE photons.
- In the latter case, expected flux on Earth exceeds alreasy existing limits.

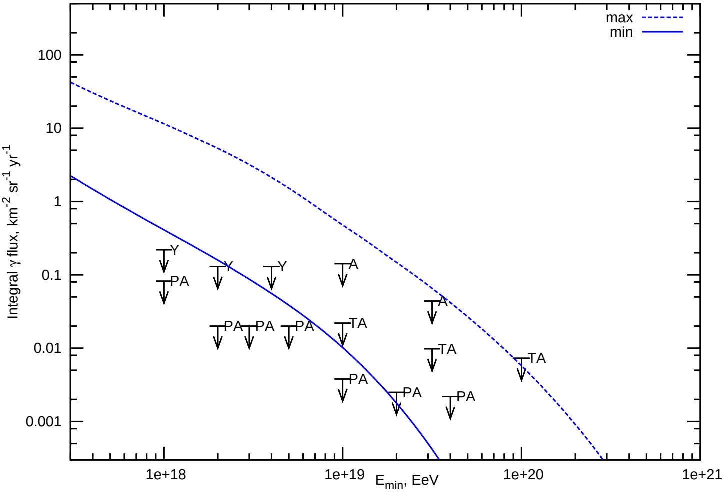
$$\xi - g/2 > -10^{-6}$$

Galaverni, Sigl, Phys.Rev.D. 78, 2008

UHE photons: pair production **ON**



UHE photons: pair production **OFF**



UHE photon detection effects

- What we learn if we detect several UHE photons?
  - Photon doesn't decay: $\xi - g/2 < 10^{-8}$
  - Photon doesn't split
  - Photon interacts with the atmosphere
  - We possibly detect interaction with geomagnetic field (PRESHOWER), which is sensitive to Lorentz violation

P. Satunin, arXiv:1301.5707

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Pair production in the Coulomb field

- Bethe-Heitler process (LI)

$$\sigma_{BH} = \frac{28Z^2\alpha^3}{9m^2}\left(\log\frac{183}{Z^{1/3}} - \frac{1}{42}\right)$$

- LV:

$$\sigma_{BH}^{LV} \simeq \frac{8Z^2\alpha^3}{3k|\omega_{LV}|}\log\frac{1}{\alpha Z^{1/3}}\cdot\log\frac{k|\omega_{LV}|}{m^2}, \quad k\omega_{LV} \ll -m^2$$

$$\omega_{LV} = -\varkappa k + \frac{\xi k^3}{2M^2} - \frac{gk^3}{M^2}.$$

GR, Satunin, Sibiryakov, Phys.Rev.D 86 2012

- Cross-section suppression leads to non-observation of photons or deeper photon showers

LIV constraints from atmosphere interaction

- If one detects UHE photon, one knows X_{max} (directly or indireclty)
- X_{max} is determined by σ_{BH}^{LV}
- If LI holds: detection of 2 photons will show that the cross-section is close to QED prediction
- Limit achievable with two 10^{19} eV photons (barring accidental cancelations):
  $\varkappa < 10^{-25}, \quad g < 10^{-7}, \quad \xi < -2 \cdot 10^{-7}$ */PRELIMINARY/*

GR,Satunin,Sibiryakov, to appear

Conclusions

- Photon interaction in the atmosphere is sensitive to Lorentz invariance
- Pair production cross-section on the Coulomb field is calculated in LV QED
- Detection of several UHE photons will place strongest constraints on Lorentz invariance violation

Backup slides

LIV QED Lagrangian

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

where

$$D_{\mu}\psi = (\partial_{\mu} + ieA_{\mu})\psi .$$