Gravitational lensing time delays as a tool for testing Lorentz Invariance Violation

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Introduction

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  possible breaking of basic symmetries of nature

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  - . . . and more useful form to search for low-energy effects:

$$\mathbf{E^2 \simeq m^2c^4 + p^2c^2 + F_i^{(1)}p^i + F_{ij}^{(2)}p^ip^j + F_{ijk}^{(3)}p^ip^jp^k + \ldots}$$

Modified dispersion relation

- **For rotational and translational invariant case:**

$$\mathbf{F^{(n)}} = \epsilon \mathbf{E^2} \left(\frac{\mathbf{E}}{\xi_\mathbf{n} \mathbf{E_{QG}}}\right)^\mathbf{n}$$

where:

- $\epsilon = \pm 1$ is a "sign parameter",
- $n = 1, 2, \ldots$
- ξ_n is a dimensionless parameter (related with the magnitude of LIV).

  We have only the lower bounds: $\xi_1 \gtrsim 0.01$ and $\xi_2 \gtrsim 10^{-9}$.

  Limit on higher values of n are too small.

  - **M. Rodriguez Martinez and Tsvi Piran, JCAP04(2006)006, [arXiv:astro-ph/0601219]**

Energy dependent group velocity

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- **Important conclusion:**

  in the presence of LIV photons of different energies

  travel with different velocities

  and consequently with different times of arrival:

$$t = \int_0^z [1 + \epsilon \frac{n+1}{2} \left(\frac{\mathbf{E_0}}{\xi_n E_{QG}} \right)^n (1+z')^n] \frac{dz'}{H(z')}$$

time delay

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$$\Delta t = \epsilon \frac{1}{2} \frac{n+1}{(\xi_n E_{QG})^n} \int_0^z (1+z')^n (\mathbf{E_2^n} - \mathbf{E_1^n}) \frac{dz'}{H(z')}$$

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- **To put any constraints on quantum gravity energy scale we need:**
  - fine-scale (millisecond) time structure,
  - hard spectrum (20 MeV and more),
  - cosmological distances.
    - **G. Amelino-Camelia, John Ellis, N.E. Mavromatos, D.V. Nanopoulos and Subir Sarkar, Nature 393 (1998) 763 [arXiv: astro-ph/9712103].**

LIV best laboratories

- **Experimental tool:**
  - pulsars,
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- **Short comparison:**

Source	Advantage	Problem
Pulsars	very well-defined time structure	only galactic distances
AGN's	TeV photons already detected	broad time structure
GRB's	cosmological distances	rather soft photons
	and fine-scale time structure	(up to MeV energy detected so far)

LIV best laboratories

Up-to-date best lower bounds on QG energy scale:

Crab pulsar (EGRET) [Philip Kaaret, (1999)]	$E_{QG} > 1.8 \times 10^{15}$ GeV
Mkn 421 (Whipple) [S.D. Biller et al., (1999)]	$E_{QG} > 6 \times 10^{16}$ GeV
Mkn 501 (MAGIC) [J. Albert et al., (2007)]	$E_{QG} > 0.17 \times 10^{18}$
Combined analysis of 35 GRBs (BATSE, HETE, and SWIFT) [John Ellis et al., (2006)]	$E_{QG} > 0.9 \times 10^{16}$ GeV
GRB 051221A (Swift-BAT and Konus-Wind) [M. Rodriguez Martinez, Tsvi Piran and Yonatan Oren, (2006)]	$E_{QG} \gtrsim 0.66 \times 10^{17}$ GeV

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  - **THE PROBLEM OF PAIR PRODUCTION:**
    Photons with energies above 10 TeV (like this from Mkn 501 BL Lac object) should have been annihilated with CMBR background photons via pair production.
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- BETTER TEMPORAL RESOLUTION
  - **INTRINSIC TIME LAGS:**

    How to distinguish LIV effects from any intrinsic (source) delay?

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- **EXTRA PROFIT:**
  - energies of such neutrinos are order of magnitude higher than GRB γ's
  - neutrino detectors like Ice Cube are extremely quiet in this energy range

    - **Uri Jacob and Tsvi Piran, 2007 Nature Phys. 3 87 [arXiv:hep-ph/0607145]**

The background cosmology impact

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- **But:** the problem of ”dark energy” triggered by current advances in observations

  leads to several cosmological scenarios.

- **Our ignorance concerning cosmological models creates systematic effect in time delay measurements:**

$$\Delta t = \int_0^z [\frac{m_\nu^2 c^4}{2E_{\nu 0}} \frac{1}{(1+z')^2} - \epsilon \frac{n+1}{2} \left(\frac{E_{\nu 0}}{\xi_n E_{QG}} \right)^n (1+z')^n] \frac{dz'}{\mathbf{H(z')}}$$

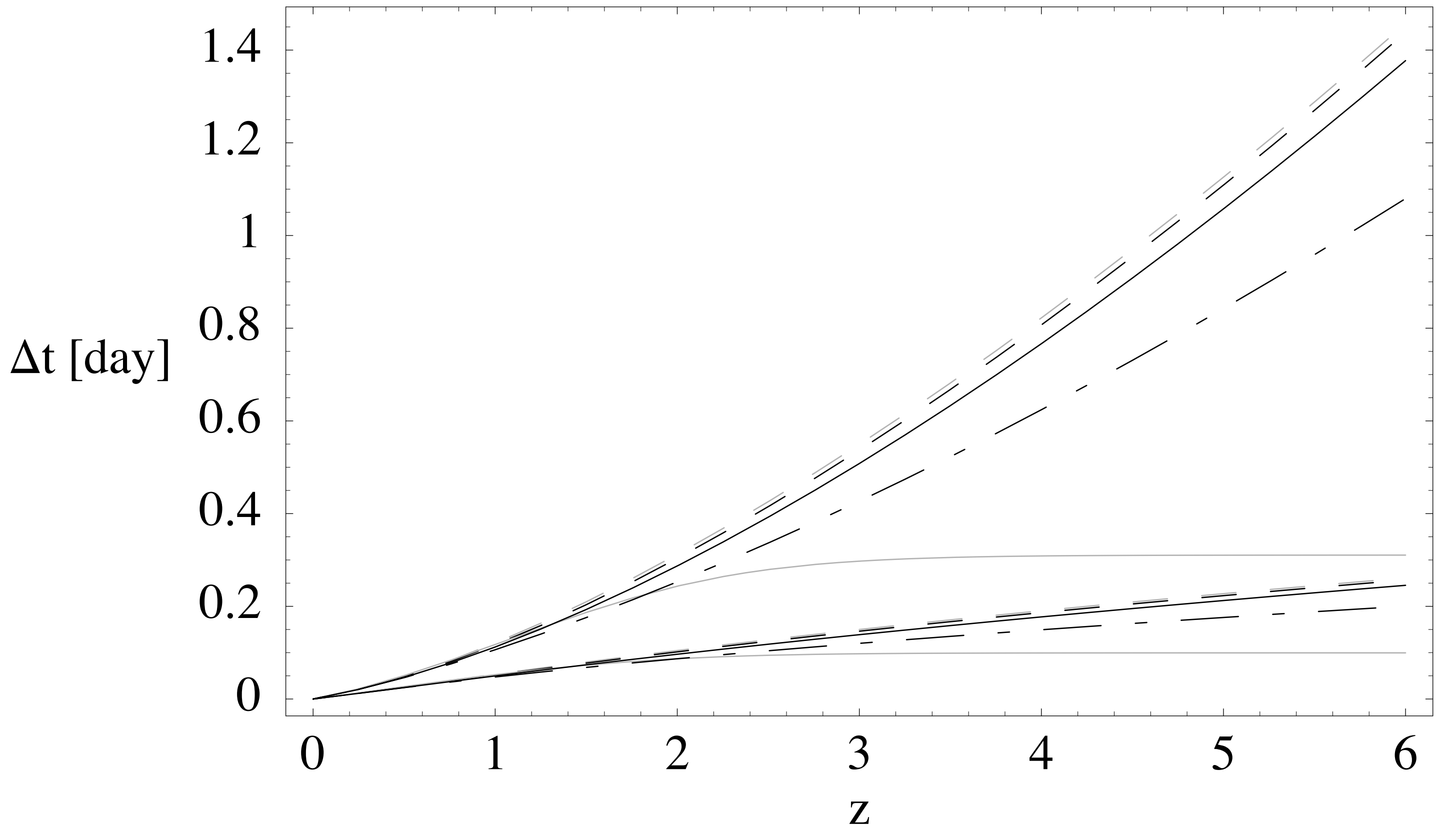
(time delay between 100 TeV neutrinos ($m_\nu = 1$ eV) and the low energy photon’s as a function of redshift in the different cosmological scenarios)

- **Marek Biesiada and Aleksandra Piórkowska,**
  2007 J. Cosmol. Astopart. Phys. JCAP05(2007)011

The background cosmology impact

Observed time delays for 100 Tev neutrinos as a function of redshift in different dark energy scenarios

(Upper curves correspond to $n = 2, \xi = 10^{-7}$, and the lower curves correspond to $n = 1, \xi = 1$)



How to get rid of intrinsic time lags?

- Statistical analysis of a sample of sources with known distance distribution.
  - **John Ellis et al., AA 402-409-424 (2003)**
  - **John Elliset al., Astropart. Phys. 25 (2006) 402-411, [arXiv:astro-ph/0510172]**
  - **John Elliset al., [arXiv:astro-ph/0712.2781] (Erratum)**

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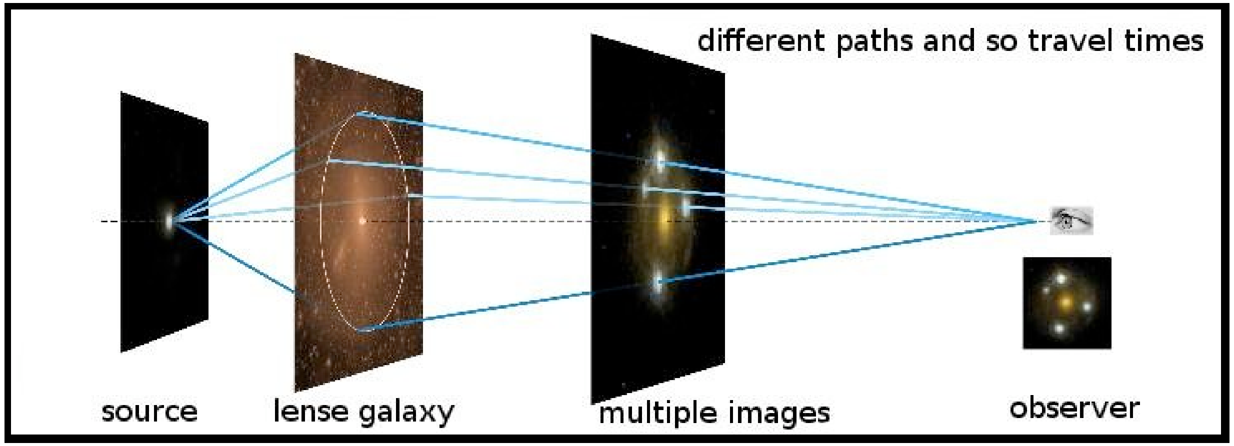
  - **John Elliset al., [arXiv:astro-ph/0712.2781] (Erratum)**
- **Other solution:**
  Observe time delays between lensed images in different energy channels.
  - **G. Amelino-Camelia, John Ellis, N.E. Mavromatos, D.V. Nanopoulos and Subir Sarkar, Nature 393 (1998) 763, [arXiv: astro-ph/9712103]**
  - **M. Biesiada and A. Piórkowska, [arXiv:astro-ph/0712.0941]**

Gravitational lensing time delays

- **Time delay between lensed images of the source:**
  - geometric delay due to bending the light rays
  - Shapiro time delay from the gravitational field
- **ACHROMATIC time delay in SIS model of the lens potential:**

$$\Delta t_{SIS} = \frac{2(1+z_l)}{c}\frac{D_l D_s}{D_{ls}}\vartheta_E \beta = \frac{8\pi}{H_0}\tilde{r}_l \beta \frac{\sigma^2}{c^2}$$



LIV induced time delays in GL

- **Gravitational lensing time delay in the presence of LIV would NO LONGER BE ACHROMATIC:**

$$\Delta t_{LIV,SIS} = \frac{8\pi}{H_0} \mathbf{\widetilde{r}_{LIV}}(\mathbf{z_l}) \beta \frac{\sigma^2}{c^2}$$

where:

$$\widetilde{r}_{LIV}(z_l) = \widetilde{r}_l + H_0 \frac{n+1}{2} \left(\frac{\mathbf{E}}{\xi_n E_{QG}} \right)^n \int_0^{z_l} \frac{(1+z')^n dz'}{H(z')}$$

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- **Restriction for $\mathbf{n = 1}$:**

  (LIV effect is extremely small)

$$\widetilde{\mathbf{r}}_{\mathbf{LIV}}(\mathbf{z_l}) = \widetilde{\mathbf{r}}_{\mathbf{l}} + \mathbf{H_0}\frac{\mathbf{E}}{\mathbf{E_{QG}}}\int_0^{\mathbf{z_l}}\frac{(\mathbf{1}+\mathbf{z}')\mathbf{dz}'}{\mathbf{H}(\mathbf{z}')}$$

LIV induced vs GL time delay

- **Assumptions:**
  - Only first order LIV effects
  - Observations in low energy:
    time delay between images equal to Δt_{SIS} (LIV corrections are negligible)
  - Monitoring of the same images in high energy (TeV) channel:
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- **The difference between LIV induced and gravitational lensing time delays:**

$$\Delta t_{LIV,SIS} - \Delta t_{SIS} = \frac{8\pi}{H_0}\beta\frac{\sigma^2}{c^2}\frac{E}{E_{QG}}\int_0^z \frac{(1+z')dz'}{H(z')}$$

LIV induced vs GL time delay

- **Estimates for HST 14176+5226:**
  - source → quasar, $\mathbf{z_{source} = 3.4}$
  - lens → elliptical galaxy, $\mathbf{z_{lens} = 0.809}$
  - from the lens model (best fitted to the observed images) based on a singular isothermal ellipsoid:
    $$\theta_{\mathbf{E}} = \mathbf{1''.489}$$
    $$\beta = \mathbf{0".13 = 8.4 \times 10^{-7}\ rad}$$
  - SUBARU / Keck optical spectroscopy measurements of the velocity dispersion in lensing galaxy gives:
    $$\sigma = \mathbf{290 \pm 8\ km/s}$$

$$\mathbf{\Delta t_{LIV,SIS}^{5\ TeV photons} - \Delta t_{SIS} = 3.7 \times 10^{-9}\ s}$$

$$\mathbf{\Delta t_{LIV,SIS}^{20\ TeV photons} - \Delta t_{SIS} = 1.5 \times 10^{-8}\ s}$$

LIV modification of image configurations

- **ANOTHER EFFECT:**
  images seen at different energies should be located at different positions
  - **Fermat's principle ->** images located at stationary points of the wavefront travel time functional, which is energy dependent in LIV .

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$$\Delta\theta_{E,LIV} = \theta_E \, \frac{E}{E_{QG}} \left(\frac{I^{(1)}(z_l, z_s)}{\widetilde{r}(z_l, z_s)} - \frac{I^{(1)}(z_s)}{\widetilde{r}(z_s)} \right)$$

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- **For realistic lens configurations like HST 14176+5226 this would give negligibly small corrections of order 10^{-16} arc sec**

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The idea looks very interesting, but at present seems experimentally unrealistic.