Does our knowledge about background cosmology matter for testing fundamental physics?

Aleksandra Piórkowska
Department of Astrophysics and Cosmology,
University of Silesia, Poland

apiorko@us.edu.pl

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Important issue for fundamental physics

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  possible breaking of basic symmetries of nature

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  - ...with the general form:

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

$$\mathbf{E^2 \simeq m^2c^4 + p^2c^2 + F^{(1)}_i p^i + F^{(2)}_{ij} p^i p^j + F^{(3)}_{ijk} p^i p^j p^k + \dots}$$

Modified dispersion relation

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

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

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

- **Interesting implication:**

  modified dispersion relation makes group velocity

  of relativistic particles energy dependent:

$$v(t) = \frac{\partial E}{\partial p} \simeq c(1+z)[1 - \frac{1}{2}\frac{m^2c^4}{E_0^2(1+z)^2} + \frac{1}{2}(n+1)\epsilon\left(\frac{\mathbf{E_0}}{\xi_n E_{QG}}\right)^n(1+z)^n]$$

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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:

$$t = \frac{1}{c}\int_{t_e}^{t_0} v(t)dt = \int_0^z [1 - \frac{m^2c^4}{2E_0^2}\frac{1}{(1+z')^2} + \epsilon\frac{n+1}{2}\left(\frac{\mathbf{E_0}}{\xi_n E_{QG}}\right)^n(1+z')^n]\frac{dz'}{H(z')}$$

time delay

- **Time delay between two photons with energy difference ΔE:**

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

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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,
  - Active Galactic Nuclei (AGN’s) - blazars (BL Lac),
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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

Challenges for time delay technique

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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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    Does cosmological model matter for time delay analysis?

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- BETTER TEMPORAL RESOLUTION
  - **INTRINSIC TIME LAGS:**

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

To tackle the problem with pair production

- **We can use very high energy (100 TeV up to 10^4 TeV) neutrinos from GRB’s instead of photons**

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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]

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]**

Time delay from statistical analysis of sources

- **Idea:**
  - We can separate time delay into two independent parts:

$$\Delta t_{obs} = \Delta t_{LIV} + \Delta t_{intrinsic}$$

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- **Idea:**
  - We can separate time delay into two independent parts:

$$\Delta t_{obs} = \Delta t_{LIV} + \Delta t_{intrinsic}$$

  - Then (in the simplest case $n = 1$):

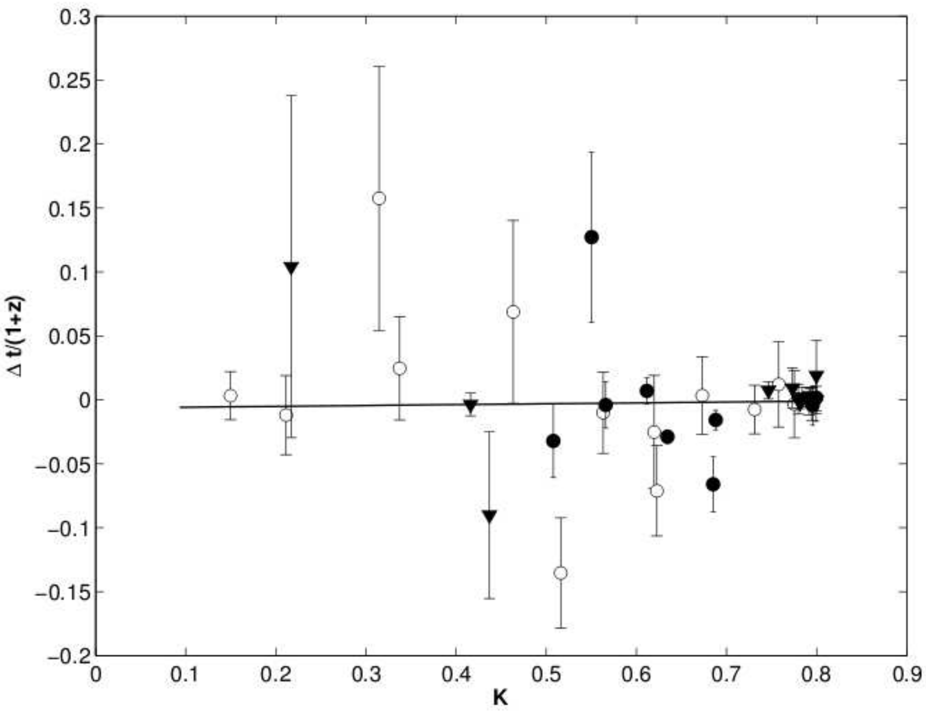
$$\mathbf{\frac{\Delta t_{obs}}{1+z} = a_{LIV} K + b}$$

where:

$$\mathbf{K = \frac{1}{1+z}\int_0^z \frac{(1+z')dz'}{H(z')}}$$

$$\mathbf{a_{LIV} = \frac{\Delta E}{E_{QG}}}$$

Time delay from statistical analysis of sources



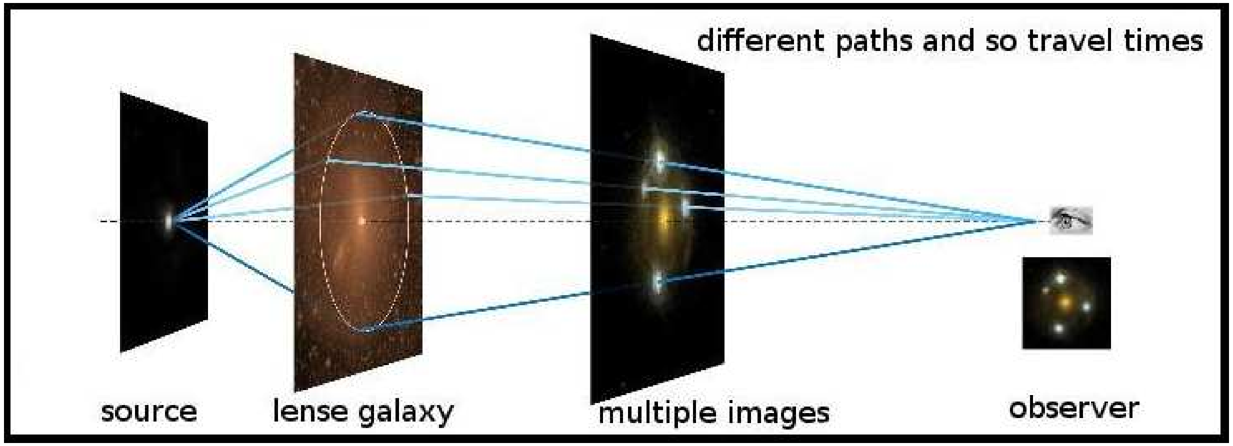
$$\mathbf{\Delta t_{obs}^{tot} = (0.0068 \pm 0.0067)K - (0.0065 \pm 0.0046)}$$

$$\mathbf{E_{QG} > 1.4 \times 10^{16} GeV}$$

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:**

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



Gravitational lensing time delays

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

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

where:

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

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

(LIV effect is extremely small)

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

Gravitational lensing time delays

- **The difference between LIV induced and gravitational lensing time delays:**

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

where:

- Δt_{SIS} from observations in low energies (LIV corrections are negligible)
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- **Estimates for HST 14176+5226:**

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

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

The background cosmology impact

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  ΛCDM (”concordance”) model

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  . . . time delay between 100 TeV neutrinos ($m_\nu = 1$ eV) and the low energy photons as a function of redshift depends on background cosmology:

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

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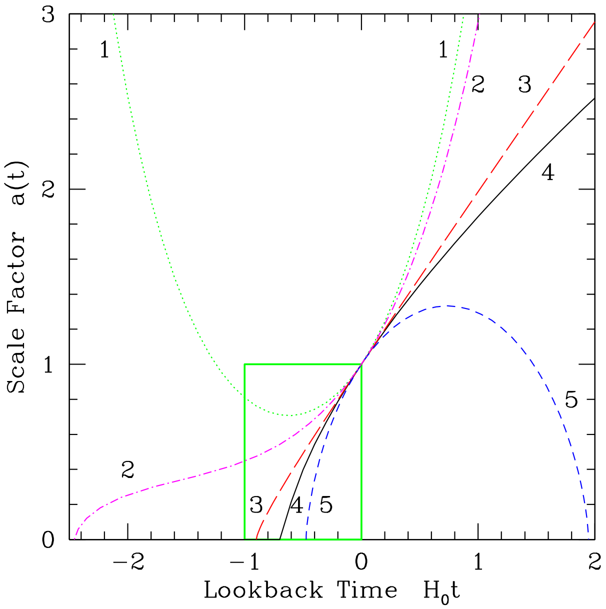
- **Does our ignorance concerning cosmological models create systematic effects in time delay analysis?**

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

The background cosmology impact

The evolution of the Universe mapping:



The first models

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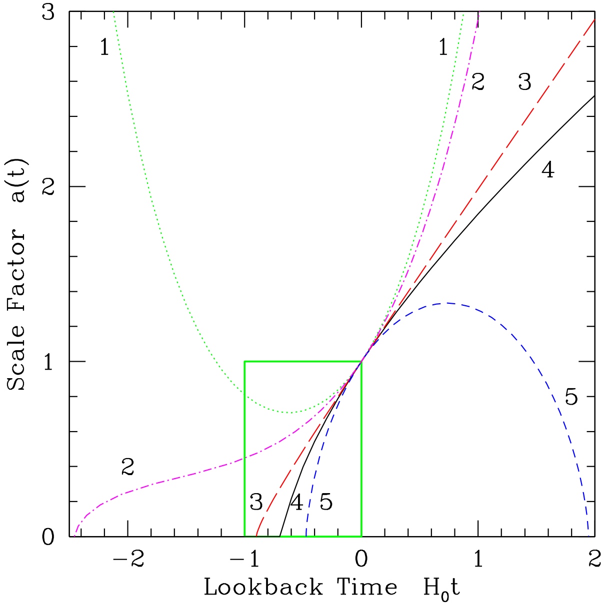

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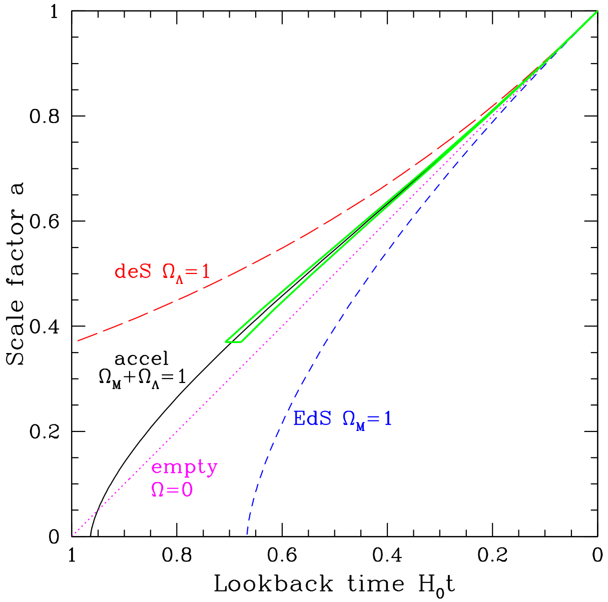

The early 'Big Bang' models

pictures from Linder [arXiv:0801.2968]

The background cosmology impact

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  Discovery of the acceleration of the cosmic expansion form SNIa Hubble diagram

  by two independent groups:

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  Formal results:

  - $\Omega_M = 0.24 \pm 0.10$ if $\Omega = 1$ ($\Omega_\Lambda = 0.76 \pm 0.10$ a$> 7\sigma$ detection)
  - $\Omega_M = -0.35 \pm 0.18$ if $\Omega_\Lambda = 0$ - this case is unphysical!

    - **S. Weinberg, Rev. Mod. Phys. 61, 1, 1989**
    - **E. Linder, [arXiv:0810.1754]**
    - **A. Filippenko, [arXiv:astro-ph/0109399]**

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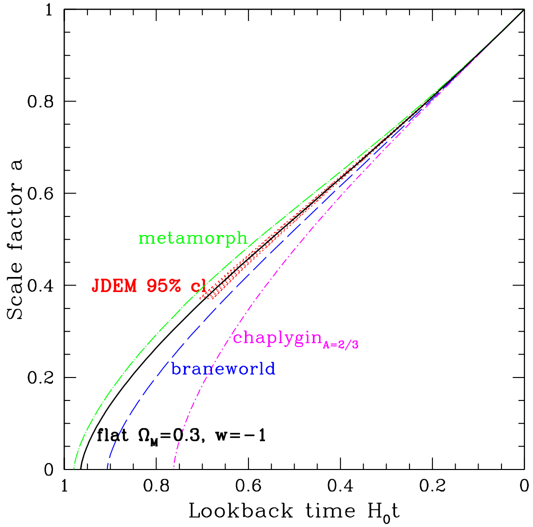
    (being constant, why does it start dominating at the present epoch?)
  - **we have enormous discrepancy between facts and expectations**

    (assuming that Λ represents quantum-mechanical energy of the vacuum it should be 55 orders of magnitude larger than observed!)
  - **CURRENT DATA DO NOT TELL US THAT Λ IS THE ONLY SOLUTION!**

- **S. Weinberg, Rev. Mod. Phys. 61, 1, 1989**
- **E. Linder, [arXiv:astro-ph/0208512]**
- **E. Linder, [arXiv:0810.1754]**
- **D. Rubin et al., [arXiv:0817.1108]**

The background cosmology impact

- **Cosmological scenarios which are in play:**
  - Models with hypothetical candidates for dark energy:
    - cosmological constant Λ
    - quintessence - evolving scalar fields
    - Chaplygin gas
  - Modification of gravity theory like brane world scenarios



picture from Linder [arXiv:0801.2968]

The background cosmology impact

Expansion rates H(z) in four cosmological models tested:

Model	$H^2(z)$
ΛCDM	$H_0^2\left[\Omega_m\,(1+z)^3+\Omega_\Lambda\right]$
Quint.	$H_0^2\left[\Omega_m\,(1+z)^3+\Omega_Q\,(1+z)^{3(1+w)}\right]$
Var. Quint.	$H_0^2\left[\Omega_m\,(1+z)^3+\Omega_Q\,(1+z)^{3(1+w_0-w_1)}\,\exp(3w_1z)\right]$
Chap. Gas	$H_0^2\left[\Omega_m(1+z)^3+\Omega_{Ch}\left(A_0+(1-A_0)(1+z)^{3(1+\alpha)}\right)^{\frac{1}{1+\alpha}}\right]$
Brane	$H_0^2\left[(\sqrt{\Omega_m(1+z)^3+\Omega_{r_c}}+\sqrt{\Omega_{r_c}})^2\right]$

The background cosmology impact

Values of the parameters of four cosmological models tested

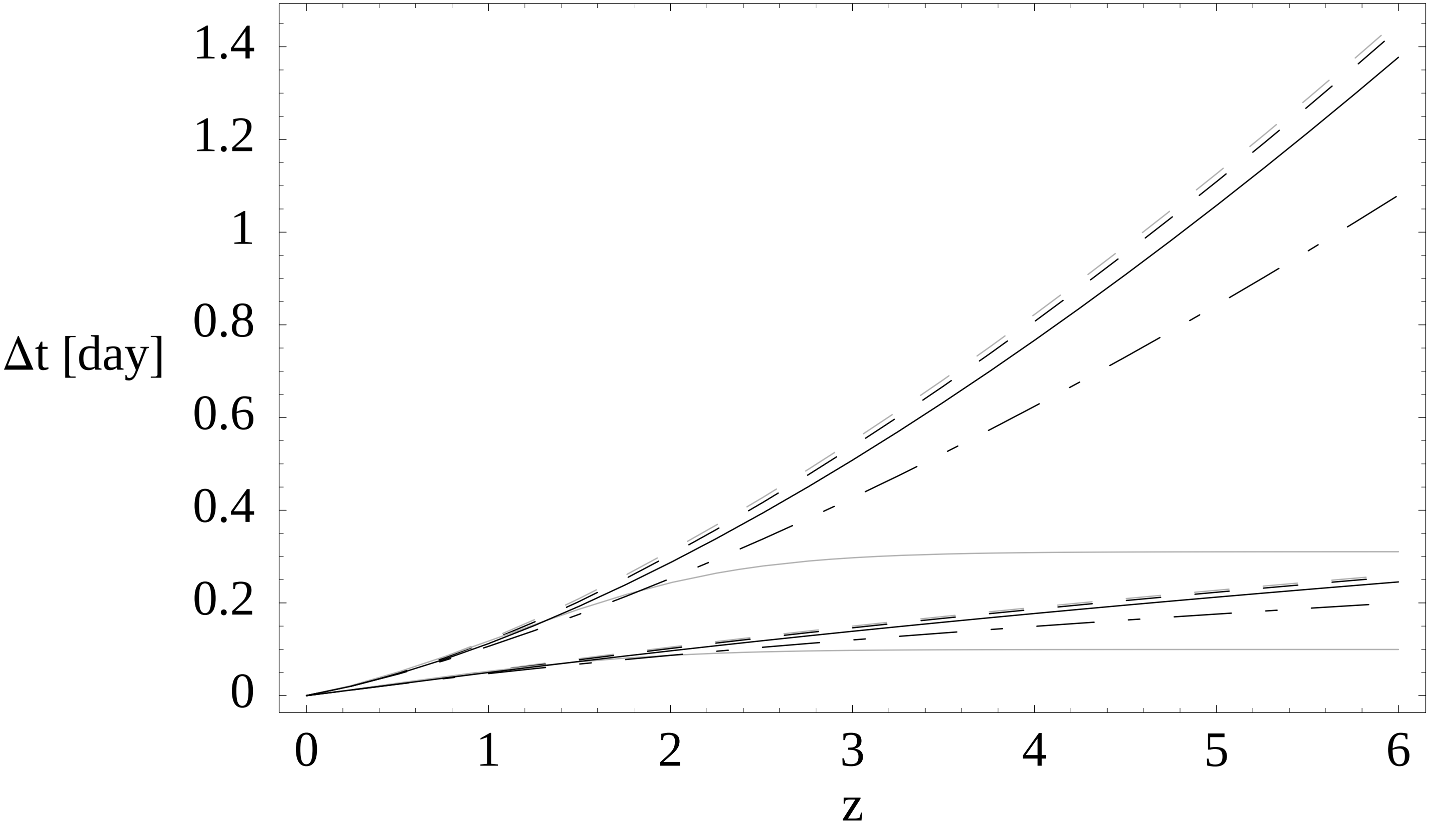
(best fitted to current SNIa and CMBR data):

Model	$H^2(z)$
ΛCDM	$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$
Quint.	$w = -0.87$
Var. Quint.	$w_0 = -1.5$ and $w_1 = 2.1$
Chap. Gas	$\alpha = 1$ and $A_0 = 0.83$
Brane	$r_c = 1.4 H_0^{-1}$ and $\Omega_{r_c} = \frac{1}{4}(1 - \Omega_m)^2$

The background cosmology impact

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

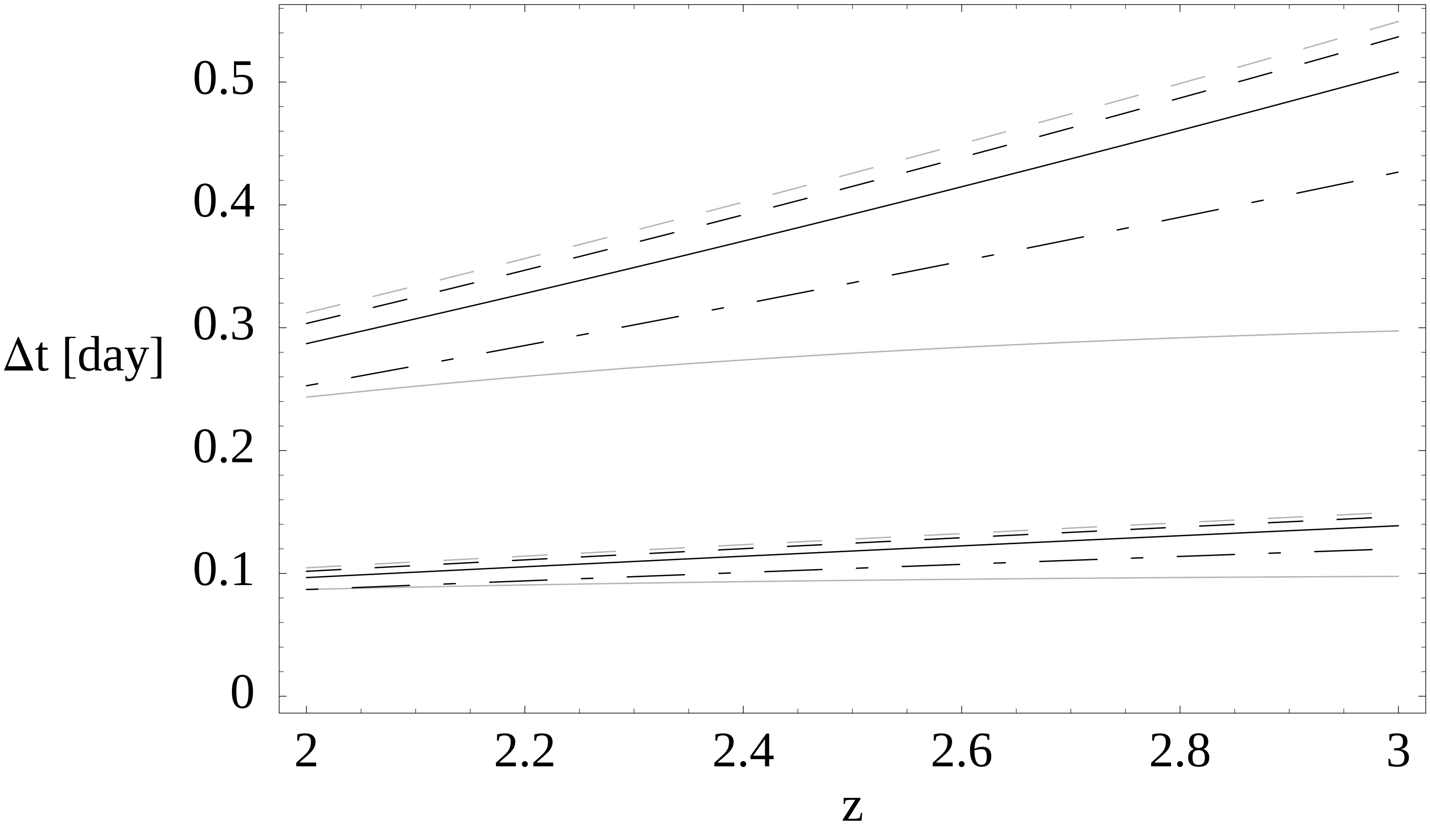
(Upper curves correspond to $n = 2, \xi = 10^{-7}$, and the lower curves correspond to $n = 1, \xi = 1$)



The background cosmology impact

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

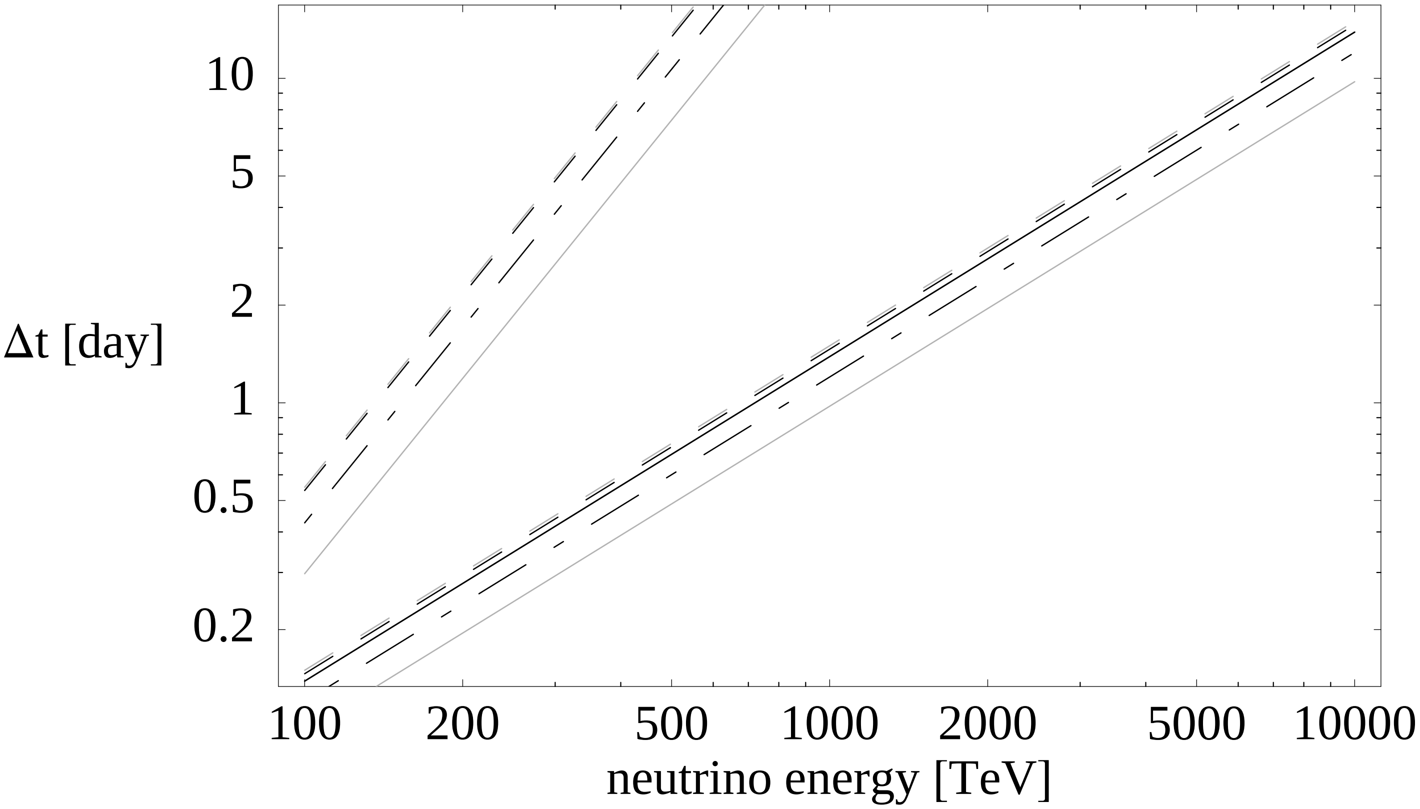
(Upper curves correspond to $n = 2, \xi = 10^{-7}$, and the lower curves correspond to $n = 1, \xi = 1$)



The background cosmology impact

Time delays as a function of neutrino energy in different dark energy scenarios (for a source located at z=3)

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



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- **For the case of gravitational lensing:**

  we can calculate time delay formula for the five cosmological models (already used):

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

but the effect is many orders of magnitude smaller than LIV

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but the effect is many orders of magnitude smaller than LIV

- time delay is created in the lens plane (low redshifts)

The background cosmology impact

- **For the case of statistical analysis of sources:**
  - **Could the effect be an artifact of incorrectly assuming ΛCDM model?**

$$\frac{\Delta t_{obs}}{1+z} = a_{LIV} K + b$$

where:

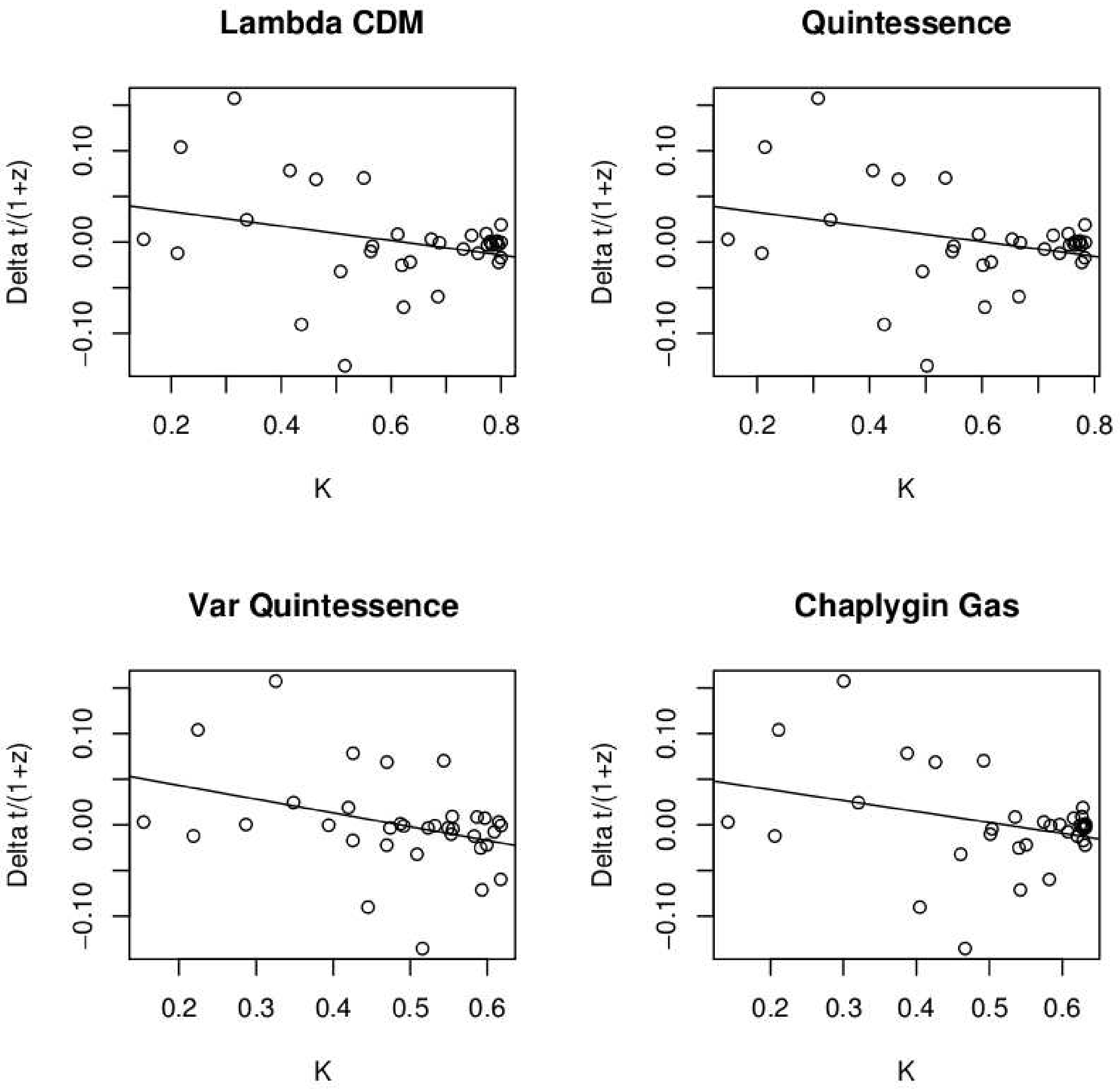
$$K = \frac{1}{1+z} \int_0^z \frac{(1+z')dz'}{\mathbf{H}(\mathbf{z}')}$$

$$a_{LIV} = \frac{\Delta E}{E_{QG}}$$

we performed fits in five already used cosmological models
(using the same sample of 35 GRBs as Ellis for better comparison)

  - **Marek Biesiada and Aleksandra Piórkowska**
    submitted to Class. Quantum Grav.

The background cosmology impact



The background cosmology impact

Regression coefficients (with 1σ ranges):

Cosmological model	**Regression coefficient $\mathbf{a_{LIV}}$**	**Intercept b**
ΛCDM	$a_{LIV} = -0.0794 \pm 0.0447$	$b = 0.0494 \pm 0.0288$
Quintessence	$a_{LIV} = -0.0806 \pm 0.0460$	$b = 0.0489 \pm 0.0288$
Var Quintessence	$\mathbf{a_{LIV} = -0.1510 \pm 0.0683}$	$\mathbf{b = 0.0735 \pm 0.0340}$
Chaplygin Gas	$a_{LIV} = -0.1201 \pm 0.0618$	$b = 0.0627 \pm 0.0330$
Braneworld	$a_{LIV} = -0.0866 \pm 0.0493$	$b = 0.0501 \pm 0.0294$

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Chaplygin Gas	$a_{LIV} = -0.1201 \pm 0.0618$	$b = 0.0627 \pm 0.0330$
Braneworld	$a_{LIV} = -0.0866 \pm 0.0493$	$b = 0.0501 \pm 0.0294$

- Contrary to our expectations the effect does not get smaller in the alternative models
- The highest effect occurs in the quintessence model

The background cosmology impact

Values of AIC, Akaike differences, Akaike weights w_i

(in Bayesian language equivalent to posterior model probabilities)

and odds against the model (with respect to the best fitted one):

Model	**AIC**	Δ_i	w_i	**Odds against**
ΛCDM	1.645	1.645	0.152	2.276
Quintessence	1.712	1.712	0.147	2.354
Var Quintessence	**179.645**	**0.**	**0.347**	**1.**
Chaplygin Gas	183.072	1.042	0.206	1.684
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- the quintessence model with varying equation of state seems to be the best fitted . . .

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- **Time delays between images of gravitationally lensed quasars should not depend on cosmology and intrinsic time-lags - THIS IDEA LOOKS VERY INTERESTING, BUT AT PRESENT SEEMS TO BE EXPERIMENTALLY UNREALISTIC . . .**