Planck scale exclusion limits on Lorentz invariance violation from H.E.S.S. spectral analysis of the blazar Mrk 501

Matthias Lorentz & Pierre Brun
for the H.E.S.S. Collaboration

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H.E.S.S.

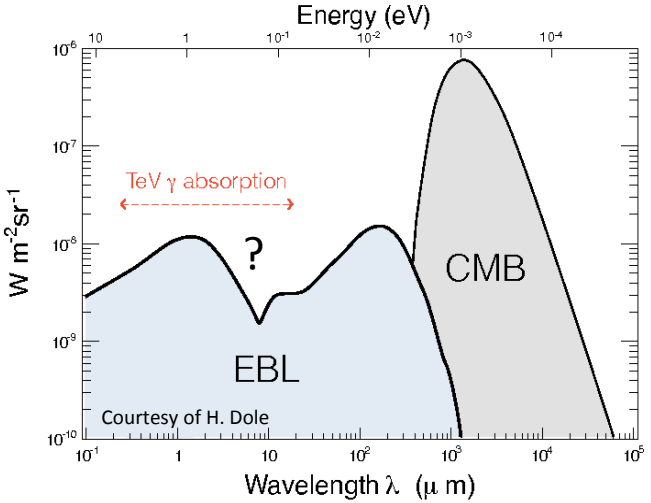
Irfu - CEA Saclay
Institut de recherche
sur les lois fondamentales
de l'Univers

Outline

- **Absorption of γ rays on the Extragalactic Background Light (EBL)**
  - Standard EBL opacity
  - Opacity modifications due to Lorentz Invariance violation (LIV)
- **H.E.S.S. observations of Mrk 501 during the 2014 flare**
  - The H.E.S.S. experiment
  - Mrk 501 exceptional flare in 2014
- **Strong constraints on the LIV energy scale**
  - Linear case
  - Quadratic case

H.E.S.S.

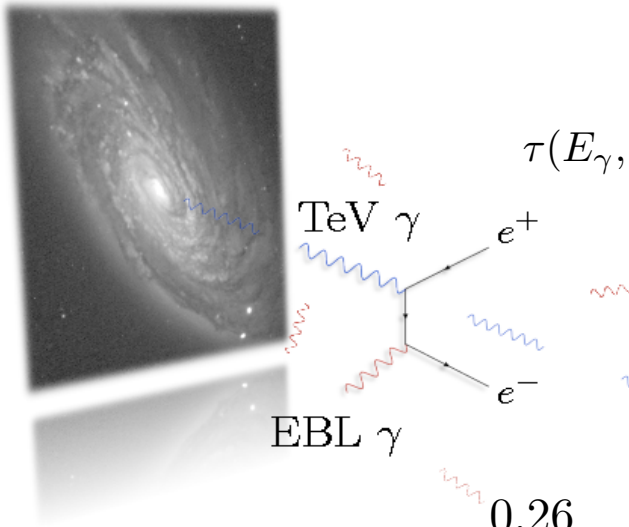
Extragalactic background light and γ-ray absorption



- **What is the EBL ?**
  Background photon field (IR to UV) originating from starlight and dust re-emission.
  Direct measurements are difficult

- **EBL absorbs γ rays by e^+e^- pair creation**
  Universe not transparent to γ rays over extragalactic distances : **optical depth τ**

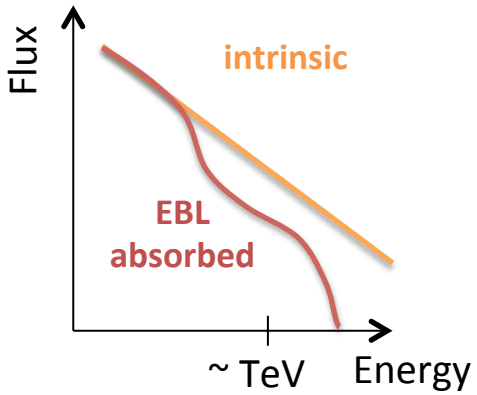
  Attenuation pattern in the VHE spectra of AGNs



$$\tau(E_\gamma, z_s) = c \int_0^{z_s} dz \frac{dt}{dz} \int_0^2 d\mu \frac{\mu}{2} \int_{\epsilon_{thr}}^{\infty} d\epsilon \frac{dn_{EBL}(\epsilon, z)}{d\epsilon} \sigma_{\gamma\gamma}\left(E_\gamma(1+z), \epsilon, \mu\right)$$

$$\Phi_{obs}(E_\gamma) = \Phi_{int}(E_\gamma) e^{-\tau(E_\gamma, z_s)}$$

$$\epsilon_{thr}\ (\mathrm{eV}) \simeq \frac{0.26}{(1+z)^2 E_\gamma(\mathrm{TeV})}$$



Local EBL energy distribution

Upper limits

Lower limits

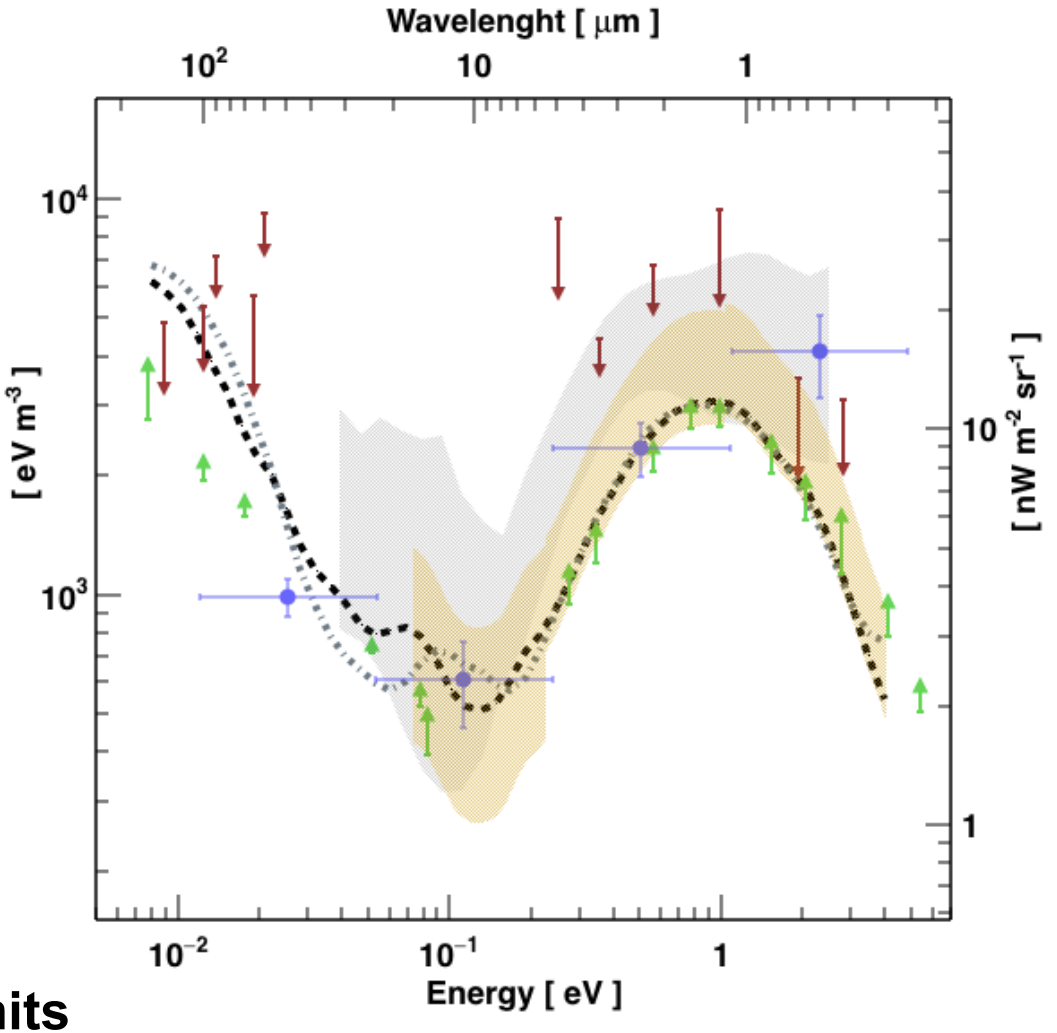
Franceschini et al. 2008 (Fr08)

Dominguez et al. 2011 (Dom11)

H.E.S.S. 2013
Model dependent : $1.27^{+0.18}_{-0.15} \pm 0.25$ x Fr08

H.E.S.S. preliminary
Model independent (ML et al. ICRC 2015)

Biteau & Williams 2015, γ rays only



General agreement between models and γ-ray constraints, in between upper and lower limits

Lorentz invariance violation and γ-ray absorption

- Effective parameterization of LIV with modified dispersion relation

$$E_\gamma^2 = p_\gamma^2 \pm E_\gamma^2 \left(\frac{E_\gamma}{E_{\mathrm{LIV}}} \right)^n$$

Symmetry breaking around Planck energy in some quantum gravity models

$$E_{\mathrm{LIV}}^n / \xi_n = E_{\mathrm{Planck}} = \sqrt{\hbar c^5 / G} \simeq 1.22 \times 10^{28} eV$$

- Affects **center of mass energy** and **pair creation threshold**

$$s \rightarrow s \pm \frac{E_\gamma^{n+2}}{E_{\mathrm{LIV}}^n} \qquad \epsilon_{\mathrm{thr}} \rightarrow \epsilon_{\mathrm{thr}} \mp \frac{1}{4} \frac{E_\gamma^{n+1}}{E_{\mathrm{LIV}}^n}$$

$\Rightarrow$ Propagates into EBL optical depth

Jacob, U., & Piran, T. (2008). Phys. Rev D, arxiv 0810.1318
Fairbairn, M., Nilsson, A., Ellis, J., Hinton, J., & White, R. (2014) JCAP

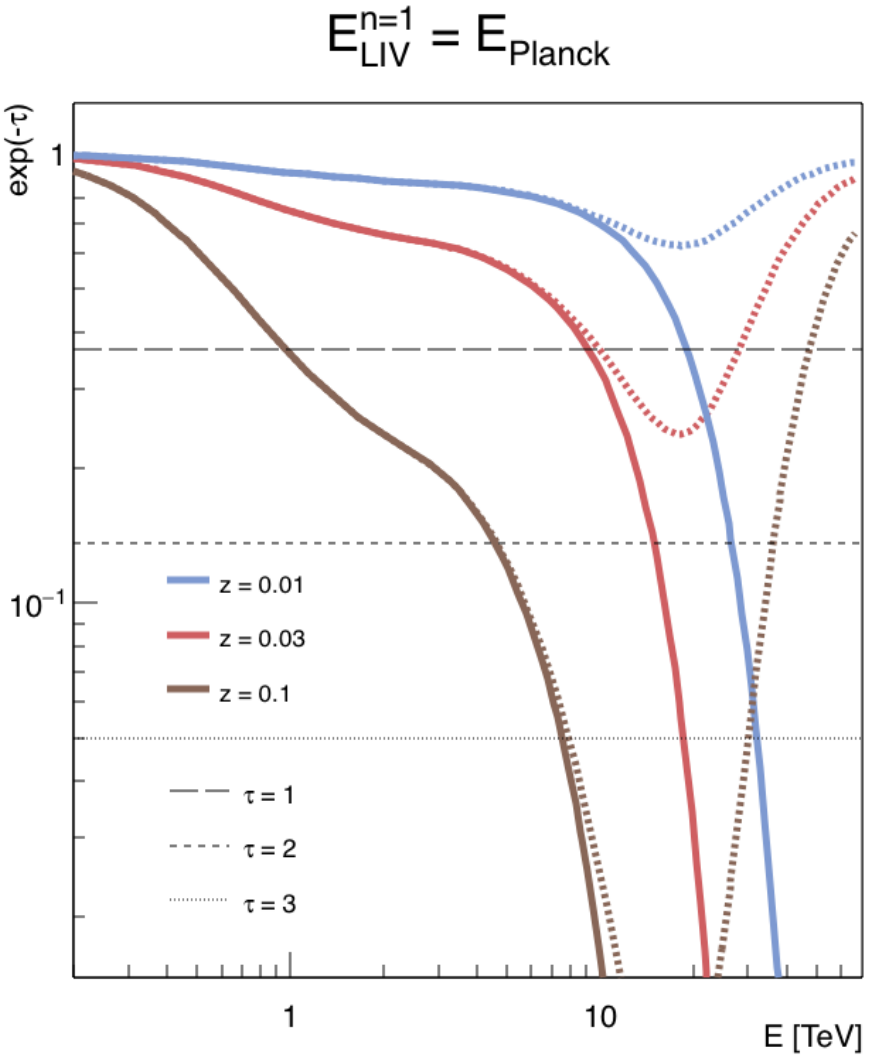
LIV - modified EBL absorption

This study :
- Francheschini et al. (2008) EBL model
- Subluminal LIV
- LIV only affecting photons

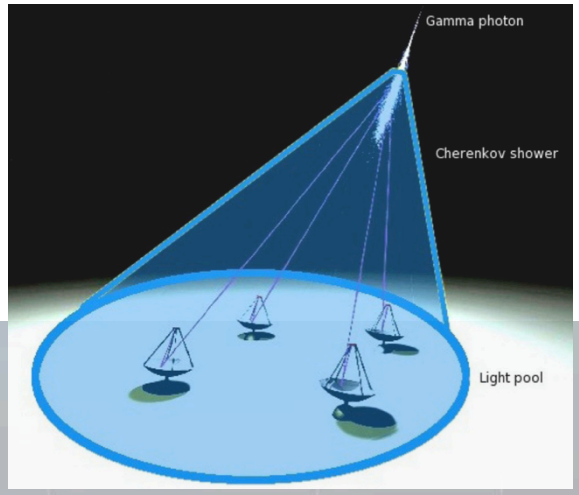
Planck scale linear LIV can naturally be tested with an EBL - affected spectrum extending > 10 TeV

➔ Need for a bright & nearby extragalactic source

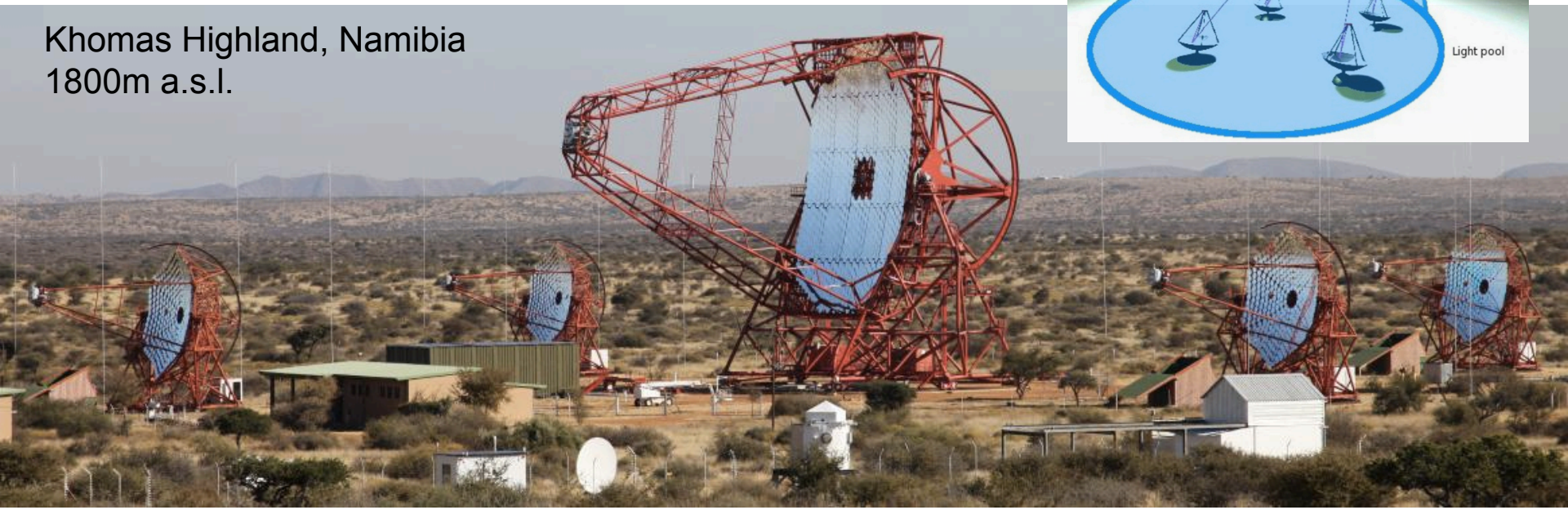
Mrk 501 known as an promising source, e.g. :
Fairbairn et al. (2014), JCAP
Tavecchio & Bonnoli (2016), A&A
Biteau & Williams (2015), ApJ



The H.E.S.S. array of Cherenkov telescopes



Khomas Highland, Namibia
1800m a.s.l.



- 5 telescopes : 4 x 107 m^2 + 1 x 615 m^2
- Field of view 5° (3.5°), PSF 0.1°
- Energy range : ~50 GeV to ~50 TeV, 10% resolution

H.E.S.S.

H.E.S.S. observations of Mrk 501 during the 2014 flare

- **Mrk 501**
  - Well known blazar at redshift z = 0.034
  - Very bright and strongly variable at all energies

- **June 2014 flare (reported at ICRC 2015)**
  - Observations triggered as ToO, mean zenith angle ~ 63°
  - Very significant detection ~ 67σ in 2h (H.E.S.S. phase I analysis)
  - Highest fluxes ever recorded by H.E.S.S. on Mrk 501
  - **Spectrum extending very significantly above 10 TeV**

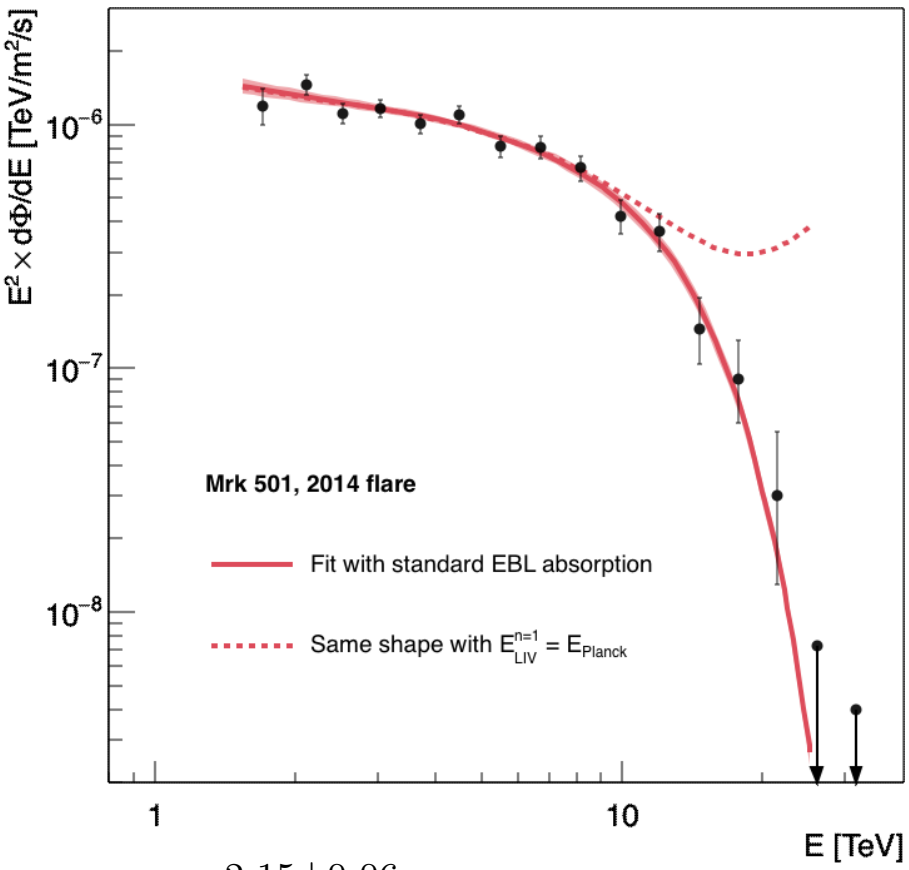
Mrk 501, 2014 flare : VHE spectrum

H.E.S.S. phase I analysis
G. Cologna et al. (ICRC 2015)

Well fitted by an EBL- absorbed power law, up to ~ 20 TeV

No sign of intrinsic curvature

- Probe ~ 10^{-2} eV EBL region
- **Ideal to test LIV at E_{Planck}**



$$\frac{d\Phi_{\rm int}}{dE} = (1.68 \pm 0.16) \times 10^{-6} \left(\frac{E}{1\ \rm TeV}\right)^{-2.15\pm0.06} \ \rm m^{-2}\ s^{-1}\ TeV^{-1}$$

LIV exclusion limits : linear case

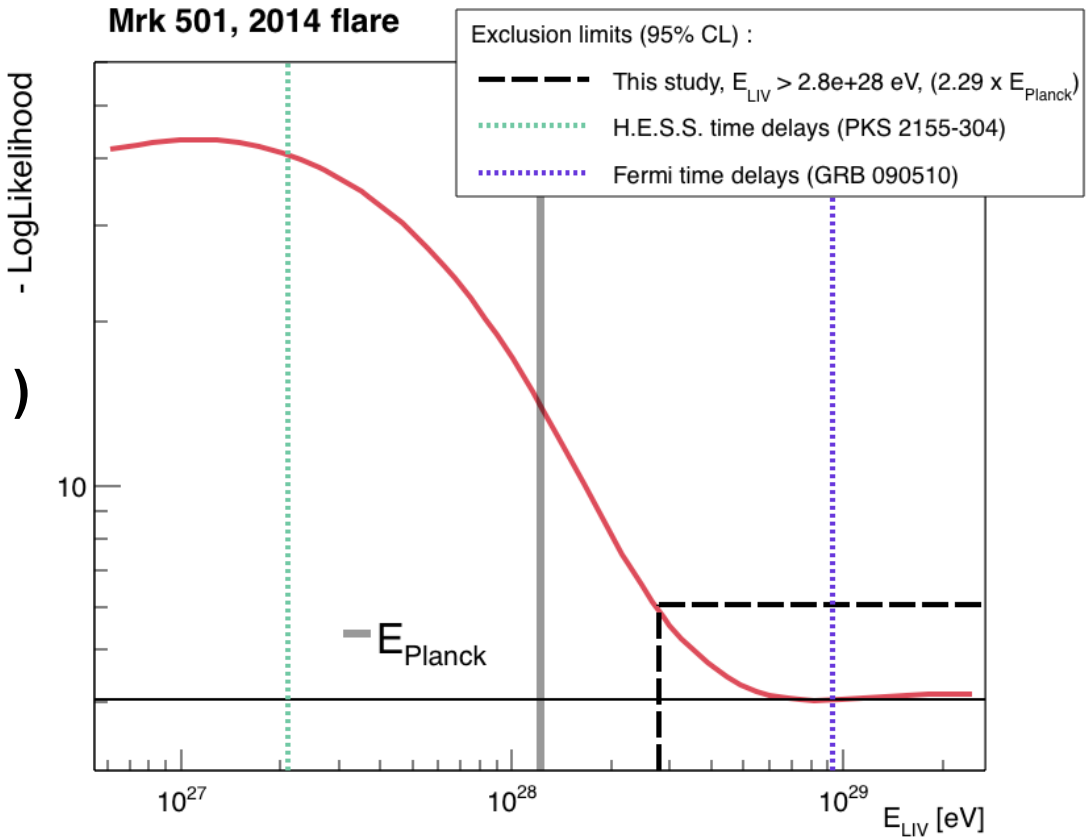
Scanning E_{LIV} values with spectral parameters free in the fit

Fit reaches plateau

➔ Standard case

$E^{n=1}_{LIV} > 2.29\ E_{Planck}$ (95% CL)

E_{Planck} excluded at 4.5 σ



LIV exclusion limits : quadratic case

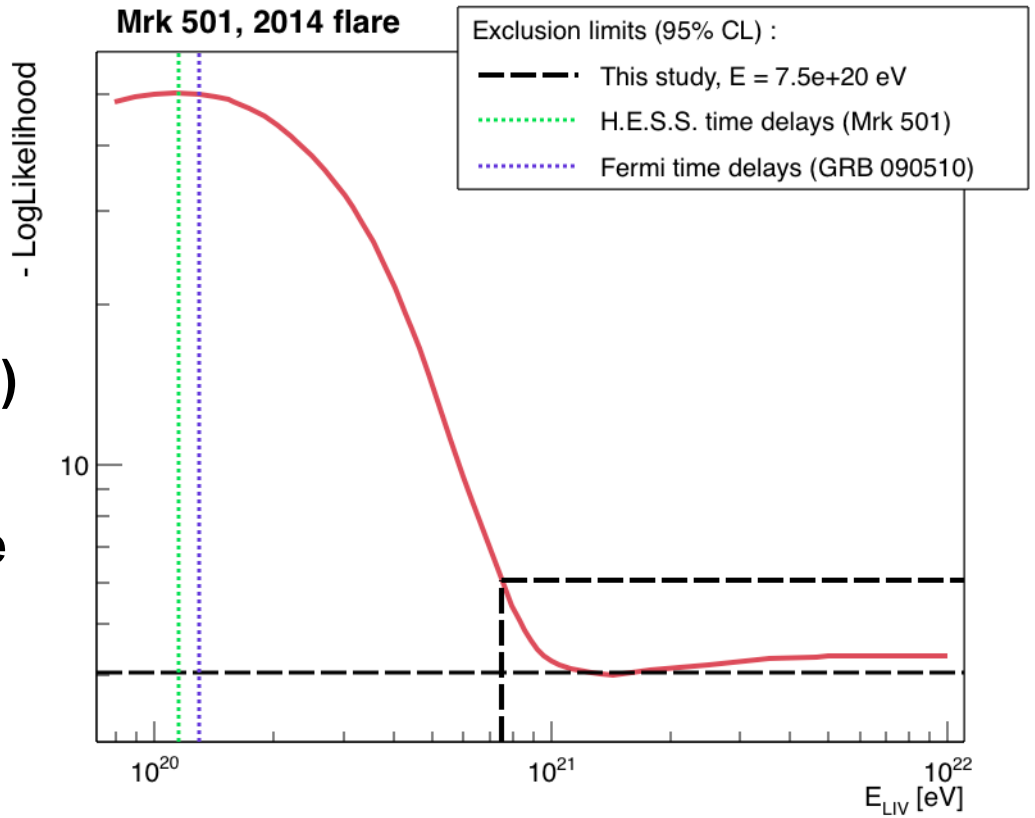
Scanning E_{LIV} values with spectral parameters free in the fit

Fit reaches plateau

➔ Standard case

$E^{n=2}_{LIV}$ > 7.5 x 10^{20} eV (95% CL)

Currently the best limits in the quadratic case



Summary

- Severe bounds on LIV energy scale using the VHE spectrum of Mrk 501 during the 2014 flare :

Best limits obtained with AGNs

	$2\,\sigma$	$3\,\sigma$	$5\,\sigma$
n=1	2.8×10^{28} eV ($2.29 \times E_{Planck}$)	1.9×10^{28} eV ($1.6 \times E_{Planck}$)	1.04×10^{28} eV ($0.86 \times E_{Planck}$)
n=2	7.5×10^{20} eV	6.4×10^{20} eV	4.7×10^{20} eV

- Confirms GRB 090510 limit for the linear scenario
- Pushes higher the current limit for the quadratic scenario

Extra slides

Probed EBL range

Threshold :

$$E_{EBL}\ (\mathrm{eV}) \simeq \frac{0.26}{(1+z)^2 E_\gamma(\mathrm{TeV})}$$

(~4.77 microns)

Peak :

$$E_{EBL}\ (\mathrm{eV}) \simeq \frac{1.04}{(1+z)^2 E_\gamma(\mathrm{TeV})}$$

(~1.187 microns)

LIV also affecting electrons ?

If LIV affects electrons **equally**
⇒ Limits on E_{LIV} ~ divided by 2

But : strong constraints on the LIV scale for electrons from Crab synchrotron :

$$\mathbf{E_{LIV,\ electrons}^{n=1} > 10^{7}\ E_{Planck}}$$

Jacobson, T., Liberati, S., & Mattingly, D. (2003). A strong astrophysical constraint on the violation of special relativity by quantum gravity. Nature, 424(6952), 1019-1021.