LIV searches with H.E.S.S.

LINK workshop, RAL UK

Agnieszka Jacholkowska, 12/11/2010

OUTLINE

Introduction

- LIV searches with Active Galaxies

- Methods used in analyses

- Results on Lorentz Symmetry breaking and Quantum Gravity scale

Discussion and Prospects

Motivation

- Fundamental Symmetries at high energies

Strong theoretical interest in possible high energy violation of local Lorentz Invariance (LI)
→ local LI may be not exact symmetry of the vacuum

- Quantum Gravity scale

  - LI violation (LIV) is <u>not a necessary</u> feature of Quantum Gravity (QG) however, LIV effects at Planck scale provide observational window of QG effects
  → Study of LIV at ~ E_P energy (breakdown of "standard" physics laws) provides a signature of QG phenomena

  - absence of LIV provides constraints on viable QG theories
  → Discard models which predict LIV phenomena

Modified Dispersion relations

→ Modification of speed of light (c) in vacuum
→ T-o-F studies with photons

Un-polarized Photons with energy E and momentum p:

$$c^2p^2 = E^2 (1 + \xi (E/E_P) + \zeta (E/E_P)^2 + \ldots)$$

predicted by some models of String theory and Loop QG

speed of light in vacuum:

$$v = \delta E / \delta \vec{p} = c(1 - \xi (E/E_P) + \zeta (E/E_P)^2)$$

Detect LIV → measure parameters ξ, ζ (> 0 or < 0)

Tests of LIV & Astrophysics

- Astrophysical messengers

Photons: simple modeling, limited in ΔE

Electrons: synchrotron radiation of pulsars
UHECRs: model dependent formalism
for threshold modifications of the GZK limit
Neutrino: limited in statistics, not seen from sources
Gravitons: not seen yet

- Astrophysical experiments with Photons

- Space missions: excellent space detectors for violent event detection
Pulsars, GRBs, AGNs – past BATSE, HETE2, present SWIFT, Fermi, future SVOM, …
- Ground based telescopes: highest ΔE, limited variability of the AGN flares - H.E.S.S., MAGIC, VERITAS, and future CTA

Dispersion measurements

(G. Amelino-Camelia, J. Ellis, S. Sarkar, et al., Nature 395, 1998)

→ Active Galaxies and Gamma-Ray Bursts are well suited :

- **Transient sources**
- **Bright**
- **At cosmological distances**
- **Wide energy range emission (0.1 MeV – TeV)**

• **Figure of Merit of a source:**

$$\Delta t = \xi \frac{L}{\mathrm{c}} \frac{\Delta E}{\mathrm{E_{QG}}}$$

L distance of the source, ΔE energy lever-arm, E_{QG} scale if $\xi = \pm 1$

<u>Caveat:</u> intrinsic time lags

Energy dependent time-lags of 2 origins: emission + propagation (redshift dependence !)

• **Light propagation from distant astrophysical sources is affected by expansion of the Universe**

$$h(z) = \sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}$$

$$\Delta t = \mathrm{H}_0^{-1} \frac{\Delta E}{\mathrm{E_{QG}}} \int_0^z \frac{(1+z)dz}{h(z)}$$

Active Galaxies

Blazars - variable AGNs

- extra-galactic sources producing γ-rays via gravitational potential energy release of matter from an accretion disk surrounding Super Massive Black Hole (SMBH)

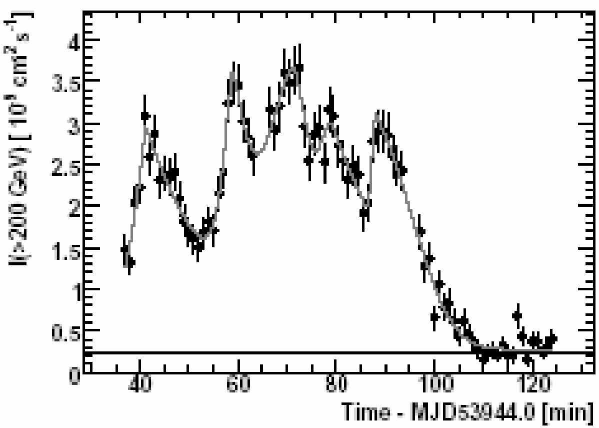
- TeV regime: redshift values 0.03 – 0.4
  energy spectrum subject to EBL effects

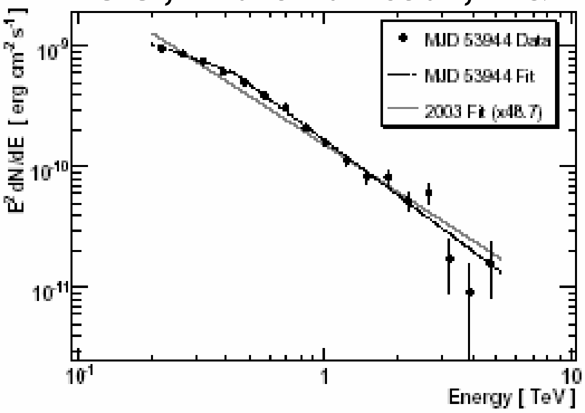
- beamed emission, large inferred luminosities, relativistic plasma jets pointing to the observer and flux variations by factors > 10 over time scales < 1hour (flares)

Active Galaxies: flares

PKS 2155-304 “Big Flare” (H.E.S.S. July 2006)

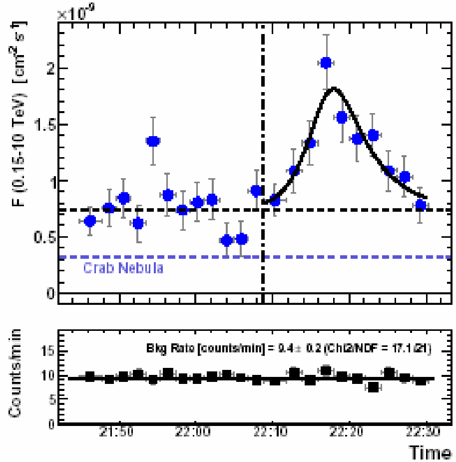
H.E.S.S., Aharonian et al., A & A 457,899 (2006)

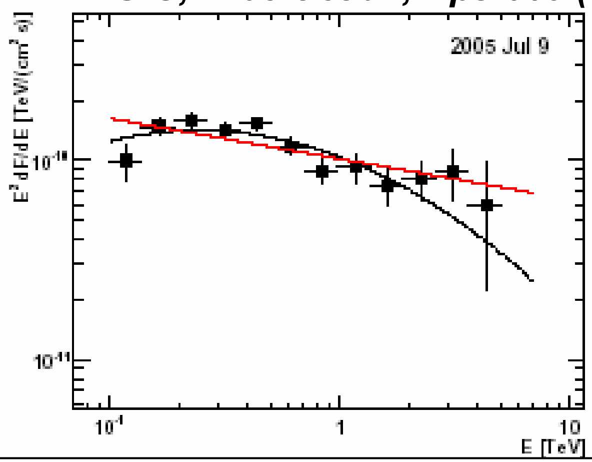




Mrk 501 Flare (MAGIC July 2005)

MAGIC, Albert et al., ApJ 669 (2007)





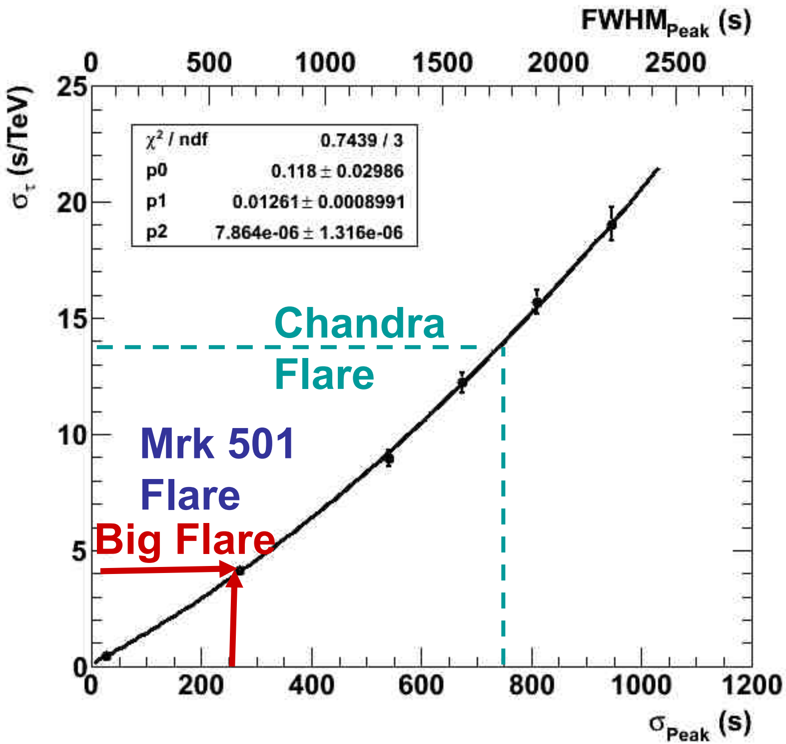
Methods and Procedures

Cross Correlation Function (MCCF)	**H.E.S.S. (AGN)** **BATSE (GRB)**	low systematic effects
Energy Cost Function (ECF)	**MAGIC (AGN)**	
Wavelet Transforms (CWT)	**H.E.S.S., (AGN)** **BATSE, HETE2, SWIFT (GRB)**	driven by LC binning
Likelihood fit	**MAGIC, H.E.S.S. (AGN)** **INTEGRAL (GRB)**	best statistical precision
Cost Function/Shannon	**Fermi (GRB)**	

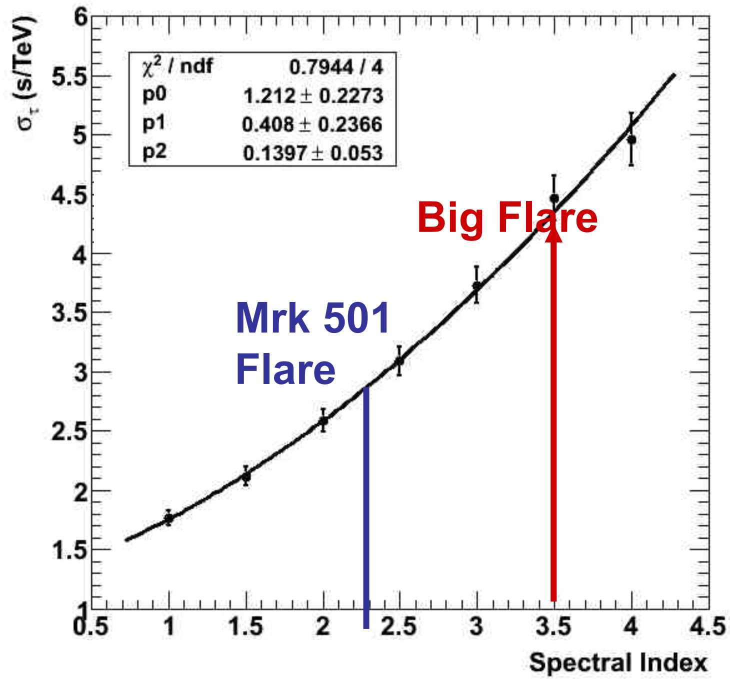
→ Precision studies require: evaluation of systematic effects and error calibrations

Methods and Procedures

→ Precision depends on pulse width and spectral index
example : Likelihood fit for a 1 gaussian LC



Pulse width (σ)

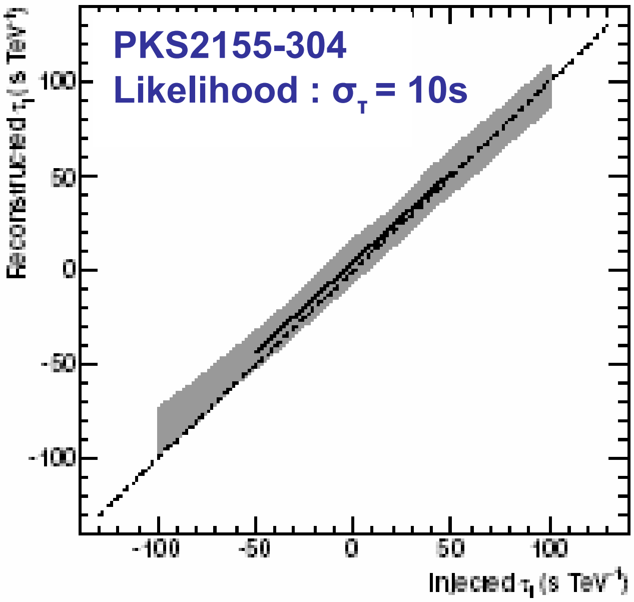


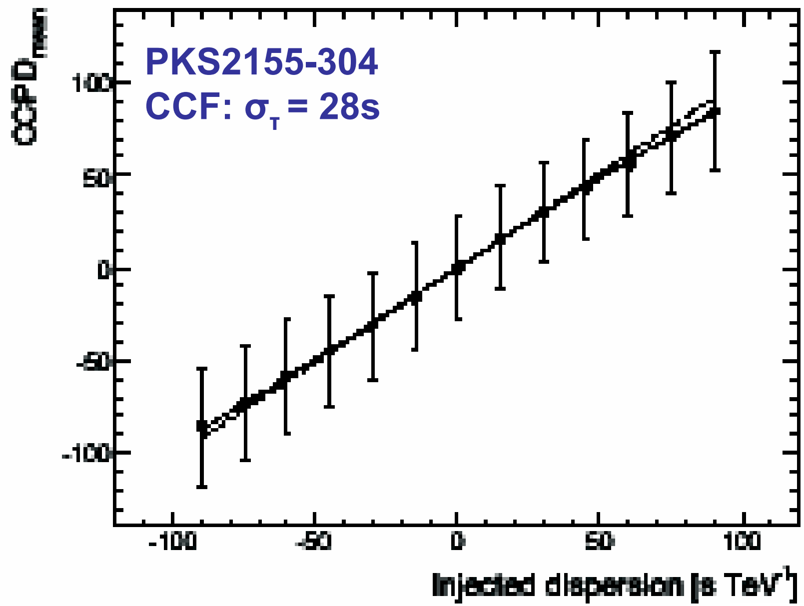
Spectral index (Γ)

Methods and Procedures

→ For robust results:

- use of at least 2 methods (probe different aspects of the Light Curve)
- need of error calibration by Light Curve simulations
- increase of precision → need of systematic effect evaluation





H.E.S.S. - PKS2155-304 “Big” flare

→ Exceptional flare in 2006: 7 x CRAB flux

- Statistics after cuts ~ 10000 photons in 1.5 hrs
- Energy spectrum: broken power-law
  No strong indication of spectral variability
- Light Curve presents several well resolved bursts described by fast rise, slow decay similar to GRBs
- Fourrier power spectrum analysis shows variability < 600 s

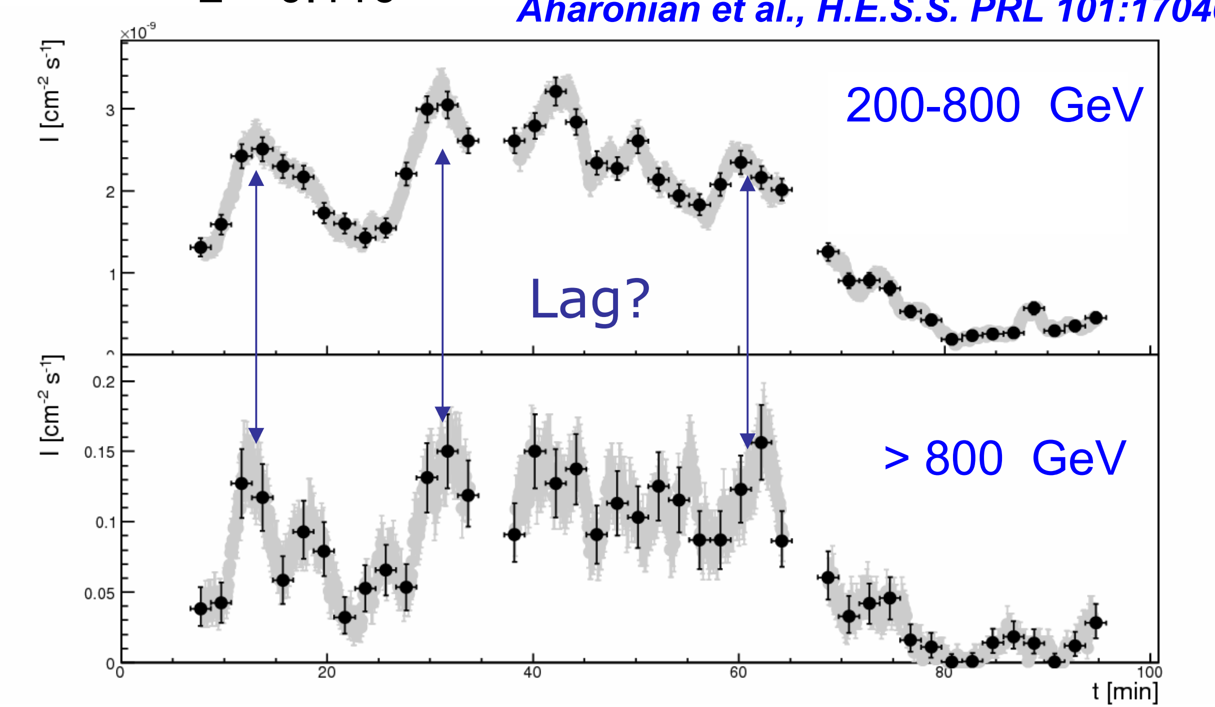
Here: search for time-delays between Light Curves of different energies to quantify a possible energy dispersion with 3 methods

H.E.S.S. - PKS 2155-304 Big flare

→ Find a time-lag with Light Curves in 2 different energy ranges

z = 0.116

Aharonian et al., H.E.S.S. PRL 101:170402 (2008)



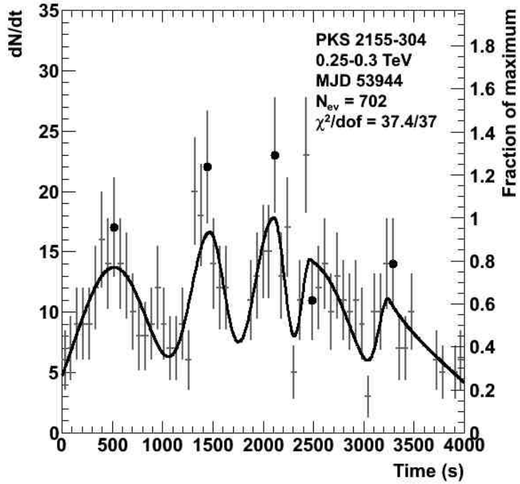
MJD 53944.02

MCCF: $E_{QG} > 0.7\ 10^{18}$ GeV at 95% CL

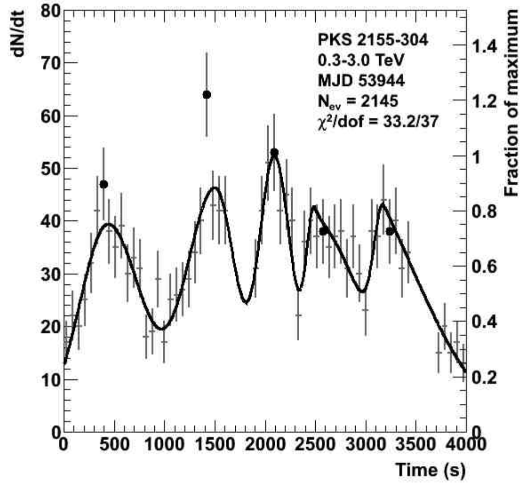
CWT : $E_{QG} > 0.5\ 10^{18}$ GeV at 95% CL

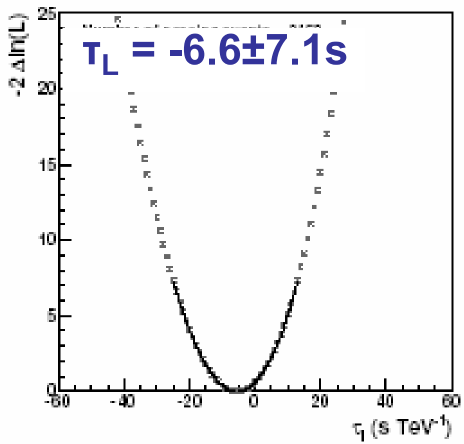
H.E.S.S. constraints with Likelihood

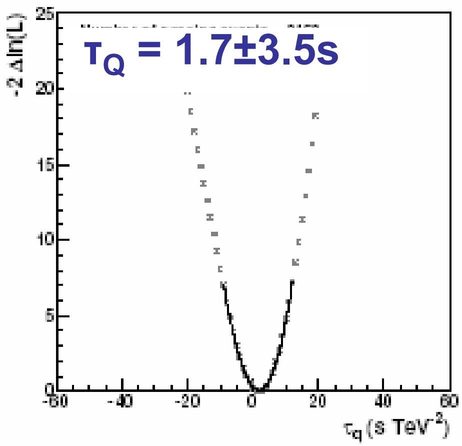
Low energy LC template



High energy LC Likelihood fit







Method:
Martinez & Errando, Astrp. Phys. 31, 2009

H.E.S.S. constraints with Likelihood

→ Event-by-event Likelihood fit with a template (model) light curve
→ No significant time-lag detected in PKS2155-304 Big Flare data > 2σ in Δt

	Estimated error	Change in estimated τ_l (s TeV^{-1})	Change in estimated τ_q s TeV^{-2}
Selection cuts		< 5	< 5
Background contribution	1%	< 1	< 1
Acceptance factors	2%	< 1	< 1
Energy resolution	1%	< 1	< 1
Energy calibration	10%	< 2	< 2
Spectral index	1%	< 1	< 1
Calibration systematics (constant, shift)	10%	< 5	< 1
$F_S(t)$ parameterization		≈ 7	≈ 3
Total		< 10.3	< 6.6

Best constraints on Quantum Gravity scale with AGNs:

Linear term: $E_{QG} > 2.1\ 10^{18}$ at 95% CL
Quadratic term: $E_{QG} > 0.5\ 10^{11}$ at 95% CL

Submitted to Astrop. Phys.

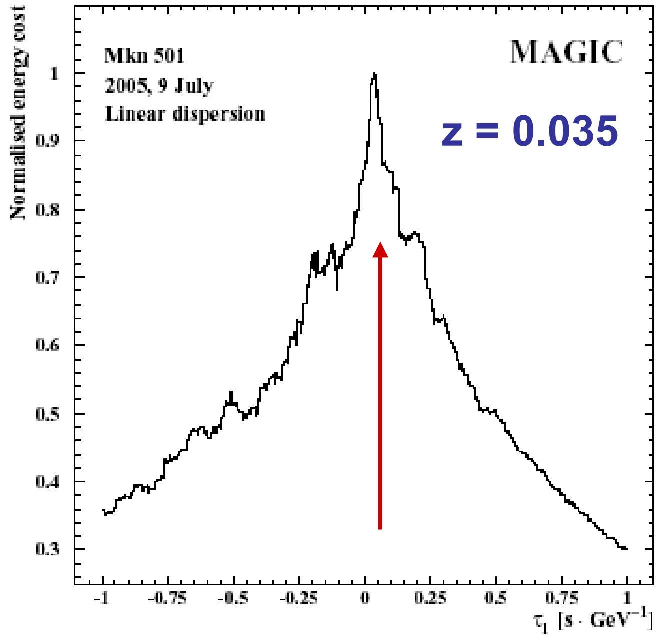
MAGIC: Mrk 501 2005 flare

→ $E_{QG} > 0.3\ 10^{18}$ GeV at 95% CL (linear model)

MAGIC + J. Ellis et al., Phys.Lett.B, 2009

Idea:

- apparent duration of the pulse is increased by the dispersion
- the energy/unit t decreases with distance from the source
- so dispersion can be extracted by maximizing the energy emitted by the source

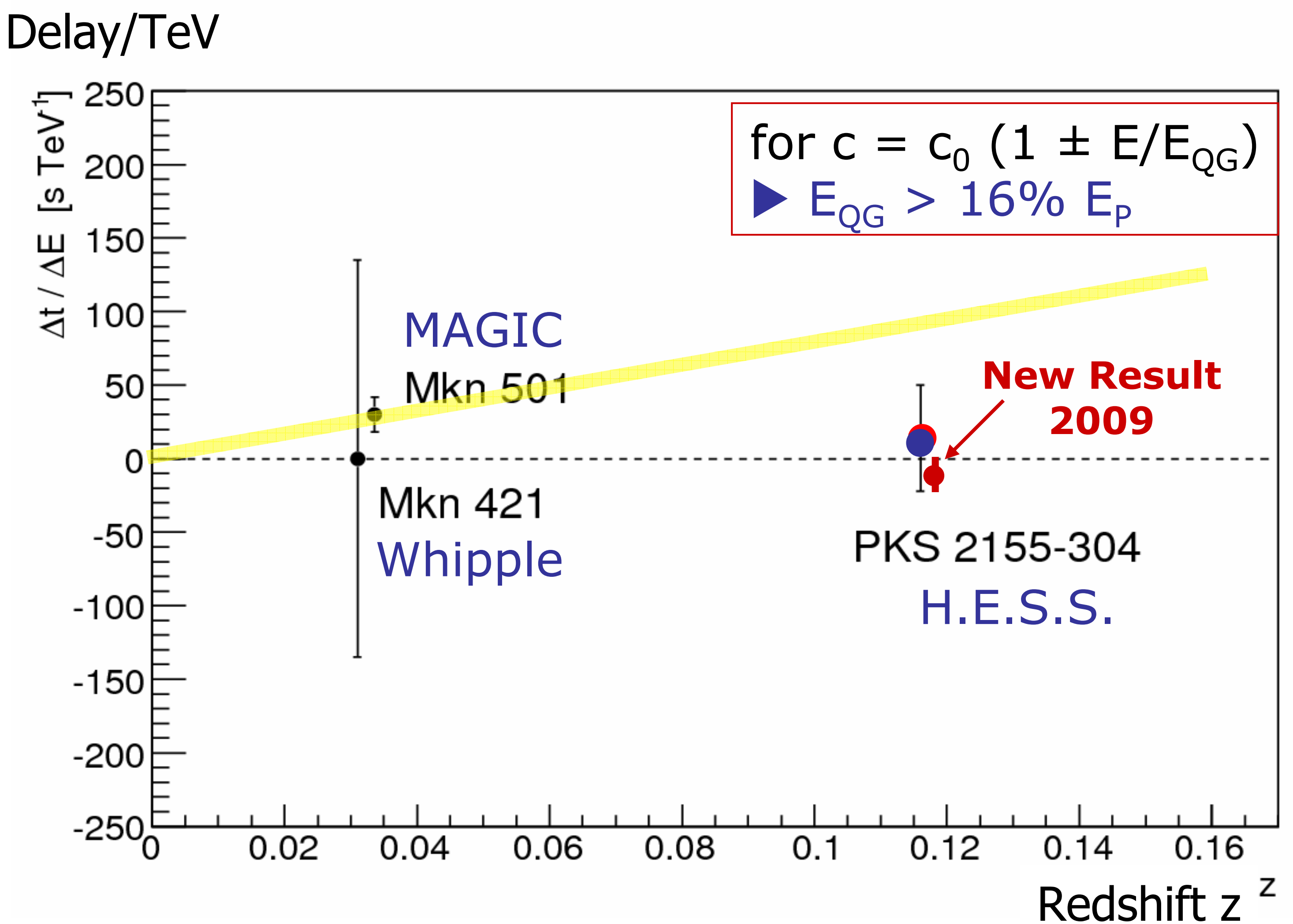


$ECF_L = \Sigma_{\tau 1<t<\tau 2} E(i)$
the transformation is repeated for many values of τ

Position of ECF maximum:
value of τ which recovers the signal in the sense of maximizing power

vacuum refractive index linear in energy

AGN limits on LI Violation mass scales



Present results from T-o-F studies

Source	Experiment	Method	Results linear, quadratic (GeV)
Mrk 421	Whipple	Likelihood	$E_{QG} > 0.6 \times 10^{17}$
Mrk 501	MAGIC	ECF + Likelihood	$E_{QG} > 0.3 \times 10^{18}$, $> 0.3\ 10^{11}$
PKS 2155-304	H.E.S.S.	MCCF + Wavelets + Likelihood	**$E_{QG} > 2.1 \times 10^{18}$, $> 0.5\ 10^{11}$**
GRB 021206	RHESSI	Fit + Mean arrival time in a spike	$E_{QG} > 1.5 \times 10^{17}$
GRB 080916C	Fermi GBM + LAT	Δt = t(Photon with highest E) – t_0	$E_{QG} > 1.5 \times 10^{18}$
GRB 090510	Fermi GBM + LAT	CCF, cost function/Shannon	**$E_{QG} > 1.2 \times 10^{19}$, $> 0.5\ 10^{11}$**
9 GRBs	BATSE + OSSE	Wavelets	$E_{QG} > 0.6 \times 10^{16}$
15 GRBs	HETE-2	Wavelets	$E_{QG} > 0.4 \times 10^{16}$
17 GRBs	INTEGRAL	Likelihood	$E_{QG} > 0.4 \times 10^{11}$
35 GRBs	BATSE + HETE-2 + SWIFT	Wavelets	$E_{QG} > 1.4 \times 10^{16}$
CRAB pulsar	EGRET	Δt of photons > 2 GeV	$E_{QG} > 0.2 \times 10^{16}$

Discussion

- Present results

  - interesting constraints on LIV with limited number of fast AGN flares
  - various methods tested and used
  - need of a factor of ~5 in sensitivity: $E_{QG} > 16\% E_P$
  - in future: improve constraints on the "quadratic" term
  - source effects cannot be excluded

- Outreach for Theory

- present limits on Lorentz Invariance and Quantum Gravity with AGNs approach Planck scale in case of "Linear" models
  → the limit on the Quadratic term does not exclude any theoretical model
- importance of LIV searches with different type of sources, redshift values, energy ranges

Prospects

- Prospects in Physics

  - studies of dependencies with redshift
    procedure to be developed: different experimental conditions
  - study effects of "Fuzziness" on Pulse shape
  - absorption of TeV photons: threshold modifications
  - synergy with GRBs in Fermi

- Prospects for experiments
  - new phases: MAGIC2 & H.E.S.S.2 !

  - CTA: follow-up of AGNs: more rapid AGN flares will be detected
    increase in A_{eff} and E_{min} & E_{max}: increase in photon statistics
    energy lever-arm
    access to higher redshift
  - possible long GRB detection will open new domain !

Prospects : absorption in the spectra of AGNs

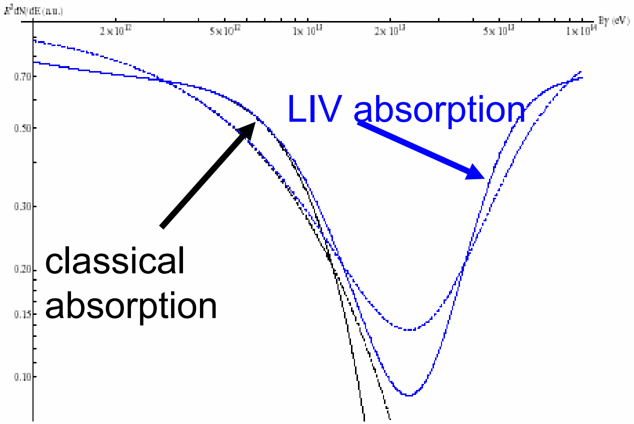
Jacob & Piran, 2008

- Principle: study of cosmological interaction between γ-rays and infra-red background photons
- Deformed pair-production threshold due to LIV effects

$$\epsilon_{thr} = m_e^2/E_\gamma + \frac{1}{4}\left(\frac{E_\gamma}{\xi_n E_{pl}}\right)^n E_\gamma,$$

→ testing LIV effects at Planck scale

Blazar spectrum (z=0.03) with LIV at E_P



- In practice: Investigate absorption in TeV spectra of AGNs

→ exponential cutoff due to EBL in presence of LIV: re-emergence of photons above threshold energy E*

- Warning: the break in the spectrum should result from EBL attenuation and *not to be* an intrinsic feature of the source

CTA target sensitivity

M. Raue, 2010