Results and prospects on LIV and QG gravity limits with photons from astrophysical sources

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OUTLINE

- LIV in Fundamental Theories
- LIV tests with AGNs & GRBs
- Present outreach
- Future prospects

Summary & Discussion

LIV in Fundamental Theories

- Lorentz Invariance/Symmetry:
  Einstein's/Special Relativity & Quantum Mechanics/Standard Model
  – overall Theoretical Physics

- At scale ~10^{-35} m (10^{19} GeV) nature of space needs to account for microscopic effects
  → Unified Theory: Quantum Gravity (QG)

- Some models of QG lead to Lorentz Symmetry Violation (LIV)
  - D-brane String models with foamy structure of space-time
  - Non-commutative geometry
  - Spontaneous symmetry breaking
  - some LQG

- Lorentz Symmetry is exact in Particle Physics
  here tests at high energies

LIV in Fundamental Theories

- LIV can be tested in different ways:

  - Photon decay, Vacuum Cherenkov Radiation
  - Modified GZK cutoff with UHERCs
  - TeV ɣ-ray spectra of extragalactic sources
  - Vacuum birefringence …

- Dispersion of light in vacuum:

  → modification of velocity of light with photon energy

Tests with un-polarized photons from variable, distant and energetic sources: AGNs, GRBs and (Pulsars)
(e.g. J. Ellis, N. E. Mavromatos, D.V.Nanopoulos 1999, L.J. Garay 1998, G. Amelino-Camelia et al., 2001)

Modifications of the Dispersion Relations

- LIV modifies dispersion relations for photons

$$c^2 p^2 = E^2 (1 + \xi (E/E_{planck}) + \zeta (E/E_{planck})^2 + \ldots)$$

- Leading corrections to the speed of light (c) in vacuum

$$v = \delta E / \delta p = c(1 - \xi (E/E_{planck}) - \zeta (E/E_{planck})^2)$$

Linear term: $\xi = \frac{E_{planck}}{E_{QG}}$ and $\zeta = (\frac{E_{planck}}{E_{QG}})^2$

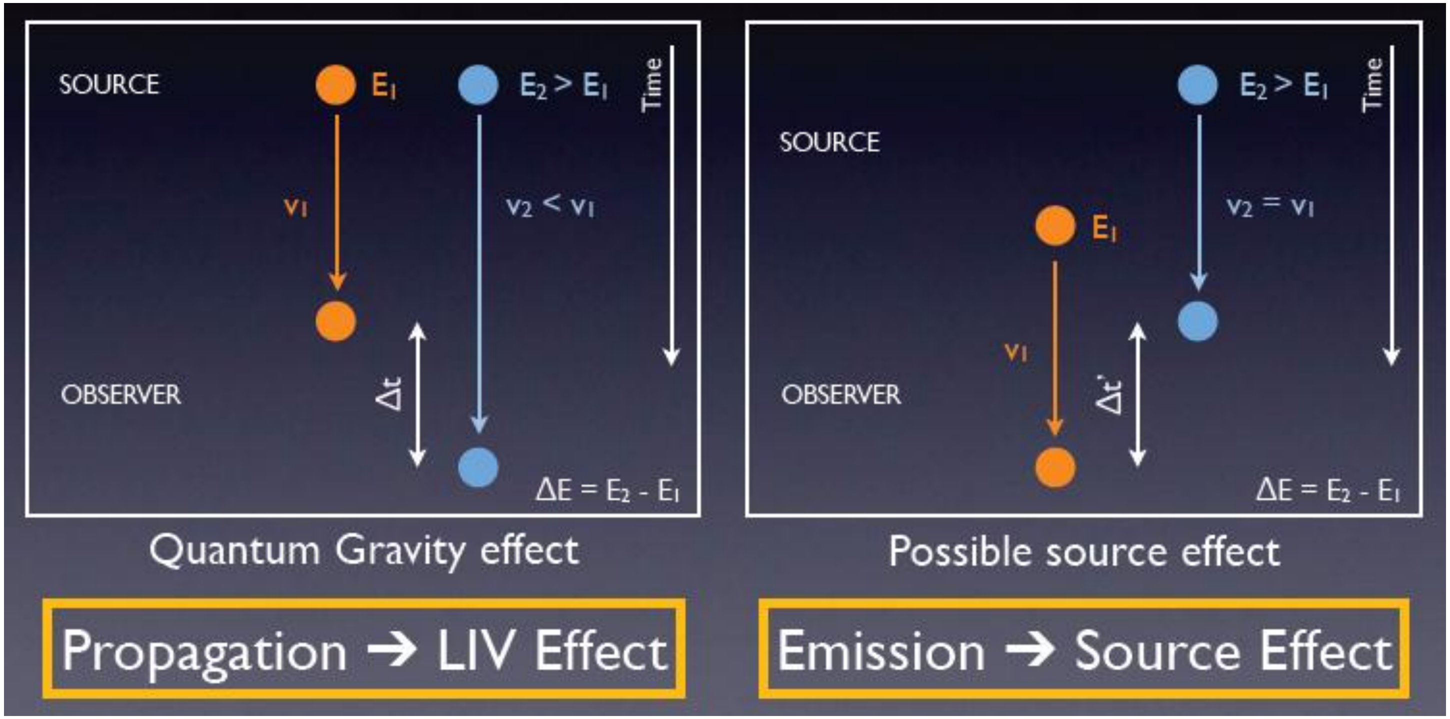
- Figure of Merit for LIV studies with astrophysical sources:

$$\xi \approx \frac{c E_p}{d} \frac{\Delta t}{\Delta E}$$

Energy dependent Time-Lags

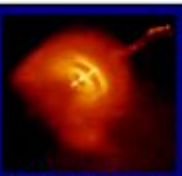
- What do we measure : time-lags as a function of energy and not E_{QG}
- The time-lags can also appear in the emission processes at the source

J. Bolmont



Astrophysical probes of LIV

+ redshift →

	 Pulsar	 Active Galactic Nuclei	 Gamma Ray Burst
Ad.	• Permanent pulsations •Distinguish between LIV/source effects	•Extragalactic • Up to TeV	• Extragalactic •Up to TeV ?
Disad.	• Galactic • Up to 400 GeV(Crab) to be confirmed with H.E.S.S.2	• Source effects • Random transient evts	• Source effects • Obs. based on luck

Time-lags: methods for deriving E_{QG}

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),** **Fermi (GRB)**	best statistical precision
Cost Function/Shannon Pair-View (new)	**Fermi (GRB)**	

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

Time-lag measurement - likelihood

- Strategy adapted from *Martinez & Errando (Astropart.Phys. 31 (2009) 226)*

$$P(E,t)=N\int_0^{\infty} A(E_s)\Gamma(E_s)G(E-E_s,\sigma(E_s))F_s(t_s-\tau_n E_s^n)\,dE_s$$

$A(E_s)$: Acceptance of telescope
$G(E-E_s)$: Energy smearing functon
$\Gamma(E_s)$: Spectrum at source
$F_s(t_s)$: Light curve at source

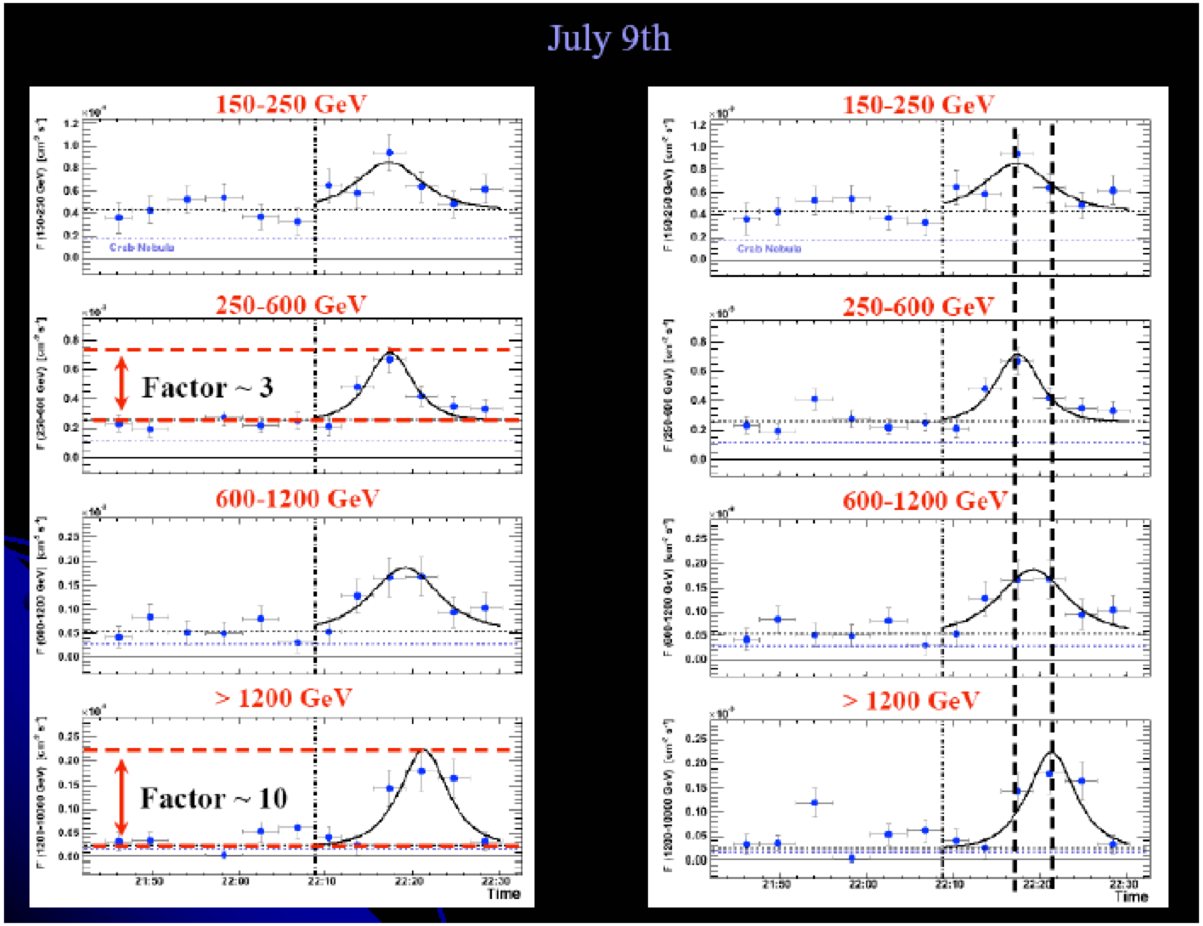
- The time-lag parameter : $\tau_n = \frac{t_2 - t_1}{E_2^n - E_1^n} \simeq s_\pm \frac{(1+n)}{E_{QG}^n H_0} k_n$ with $k_n = \int_0^z \frac{(1+z')^n \, dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$
(s/TeV for n=1)
(s/TeV^2 for n=2)

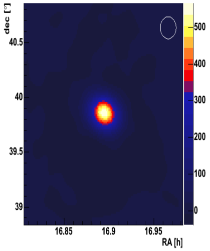
1) Parametrize Template Light curve **$F_s(t_s)$** at low energy and spectrum **$A(E_s)$**
2) Use **Maximum Likelihood** at high energy to estimate the time lag parameter.

- The likelihood is the product of the p.d.f's over all the photons in the fit:

$$L=\prod_i P(E,t)$$

MAGIC: Mrk501 flare – a minute lag ?





Mrk501
z = (0.034)
fast flares

→ Finally: observed lag attributed to the "source" emission

MAGIC: Mrk 501 2005 flare

→ $E_{QG} > 0.3\ 10^{18}$ GeV @ 95% CL

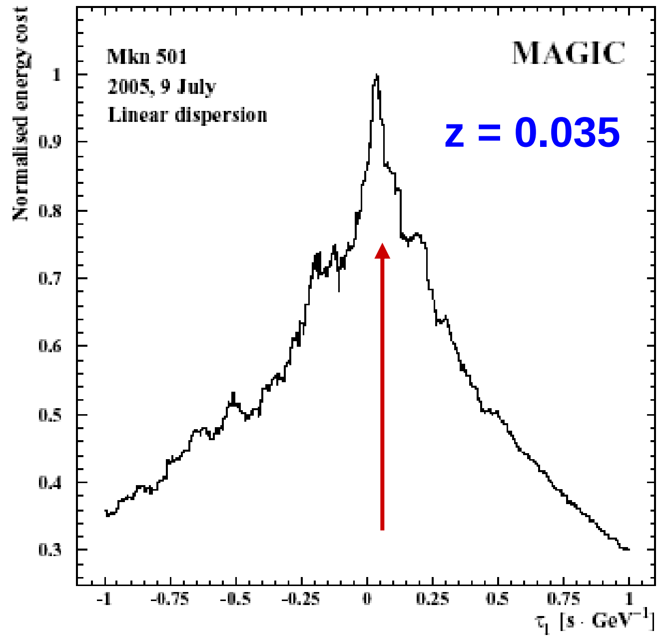
Idea:

- 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

vacuum refractive index linear in energy



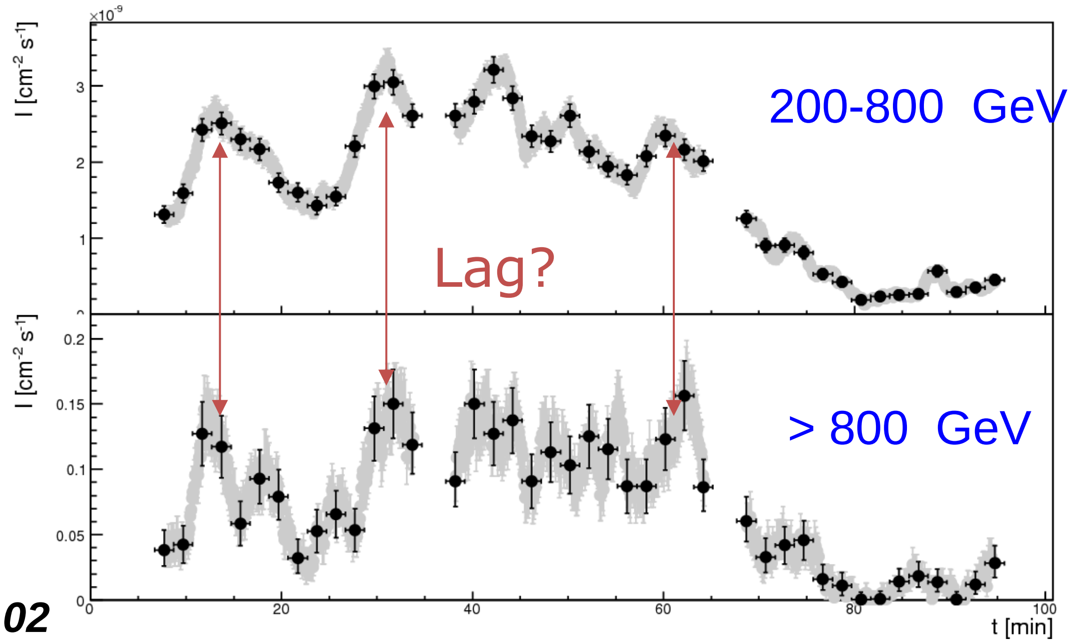
Position of ECF maximum:
value of τ which recovers the signal in the sense of maximizing power

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

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

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

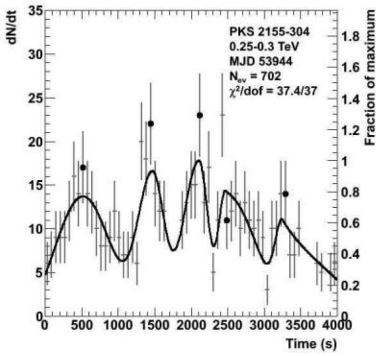
Z = 0.116 ***Aharonian et al., H.E.S.S. PRL 101:170402 (2008)***



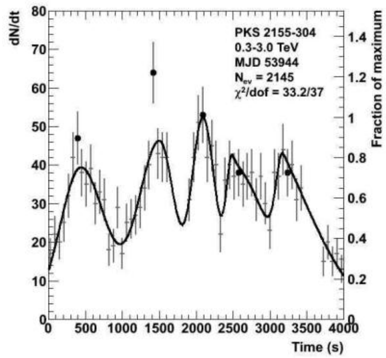
MJD 53944.02

Method 1 (MCCF): $E_{QG} > 0.7\ 10^{18}$ GeV @ 95% CL
Method 2 (CWT) : $E_{QG} > 0.5\ 10^{18}$ GeV @t 95% CL

PKS 2155-304 – constraints with likelihood

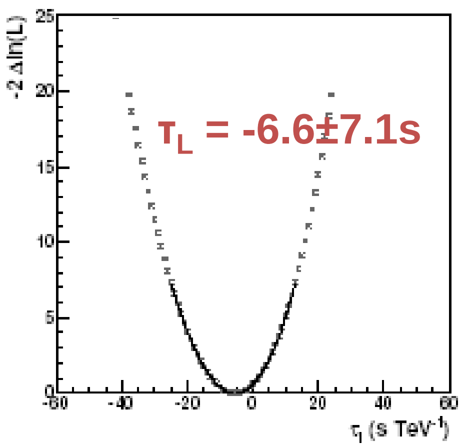


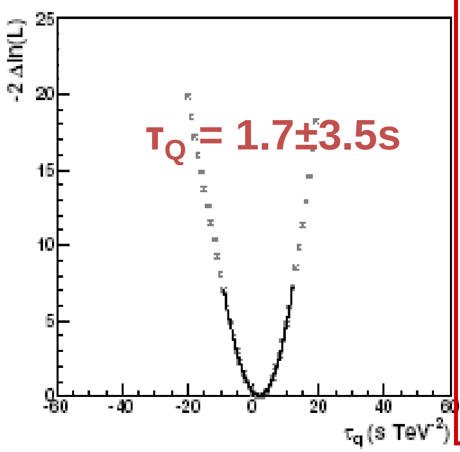
Low energy LC template



High energy LC Likelihood fit

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



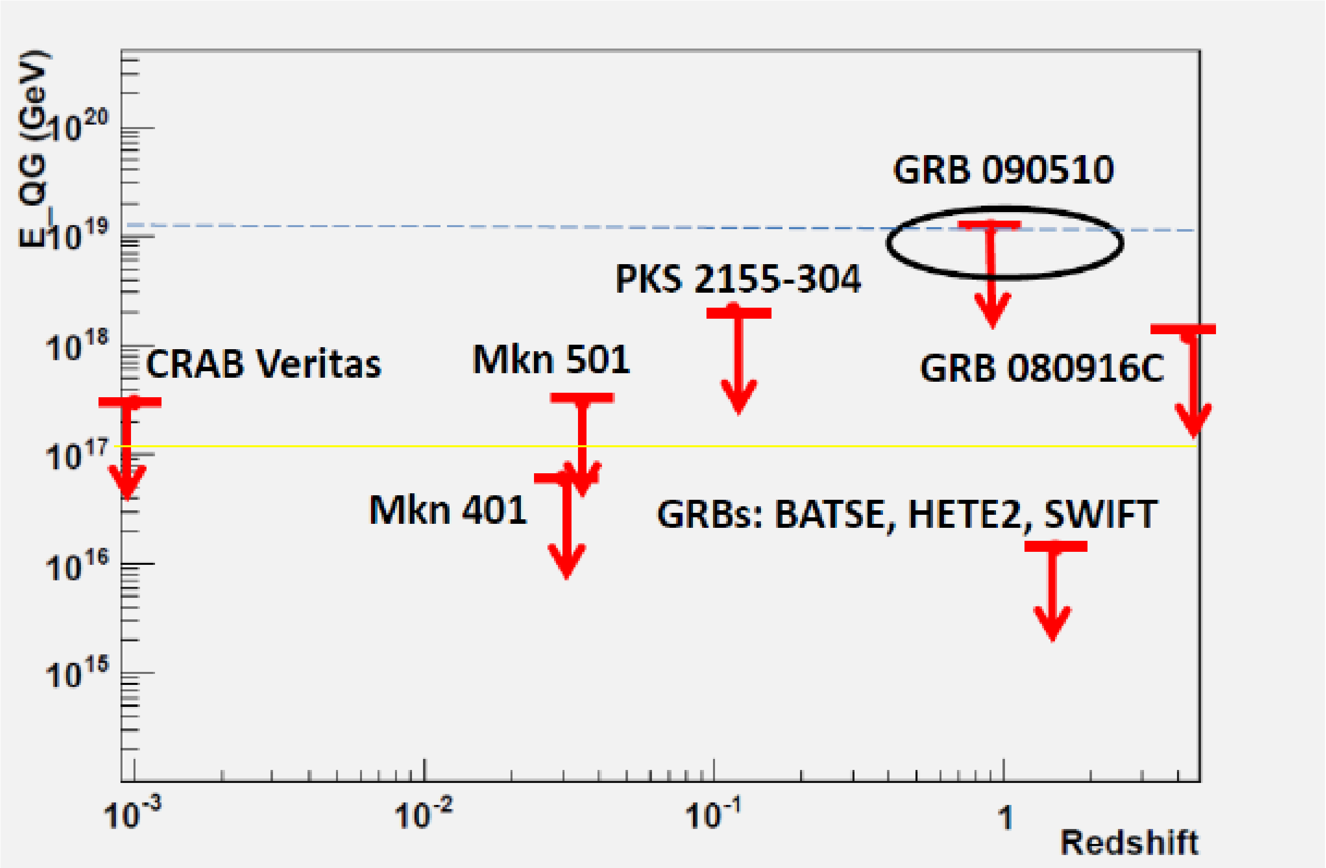


Best constraints on E_{QG} scale with AGNs:

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

Published in Astrop. Phys.

Limits on E_{QG} (linear term) in 2012



→ Best limit with GRB 090510 at E_P disfavors some models with linear dependence of c on energy – QG foam, diffractive index, …

Limits on E_{QG} (linear term) in 2012

- Lot of discussions about the limit with GRB 090510 strongly dependent on highest energy photon of 30 GeV

- Unique result with 1 GRB: use similar methods, no study of systematic effects
  source induced effects ?
  redshift dependence?

- To study Fundamental properties of the Space-Time we need extraordinary efforts as
  "Extraordinary claims require extraordinary evidence"
  (J. Ellis et al., 2009)

→ re-analysis of the 4 "golden GRBs" of Fermi

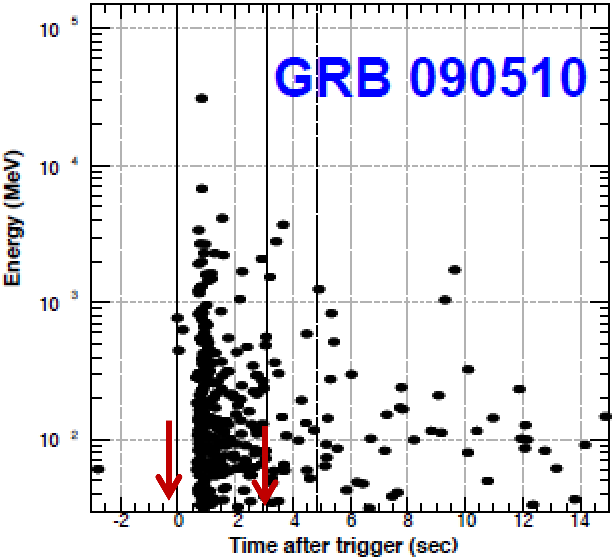
Data of 4 GRBs seen by Fermi-LAT

GRB	Redshift	κ_1	κ_2
080916C	4.35 ± 0.15	4.44	13.50
090510	0.903 ± 0.003	1.03	1.50
090902B	1.822 ± 0.001	2.07	3.96
090926A	2.1071 ± 0.0001	2.37	4.85

Times t_i and energies E_i of photons from 4 Gamma-Ray Bursts observed by *Fermi-LAT*

Notes:

- various redshift z
- energies from 20 MeV to 30 GeV
- timescale from 3s (090510) to 25s

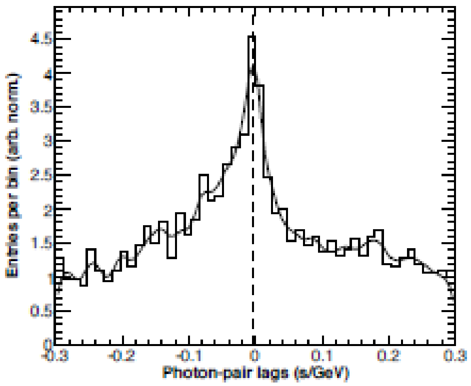


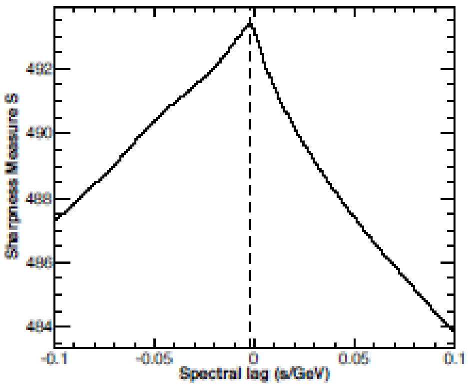
(t_i, E_i) for GRB 090510

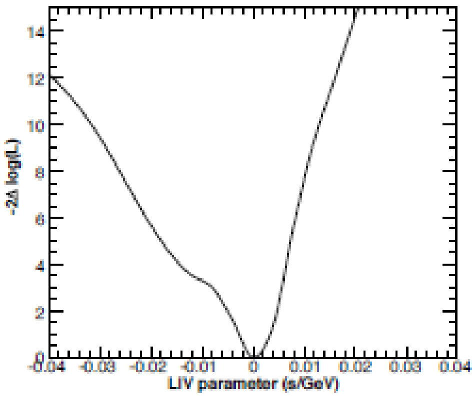
Importance of selected time window – migrations at 0.5 MP scale

Three methods to look for dispersion

PairView (PV)	Sharpness Maximization (SMM)	Maximum likelihood (ML)
1 calculation of $L_{i,j} = \frac{t_i - t_j}{E_i^n - E_j^n}$	**1** For a given τ_n: $S(\tau_n) = \sum_{i=1}^{N-\rho} \log\left(\frac{\rho}{t'_{i+\rho} - t'_i}\right)$	**1** Build a model $P(t,E\|\tau_n) = \frac{1}{N_{pred}}\Lambda(E)f(t-\tau_n E^n)$
2 distribution of $L_{i,j}$	**2** calculation for several τ_n	**2** test it for different τ_n



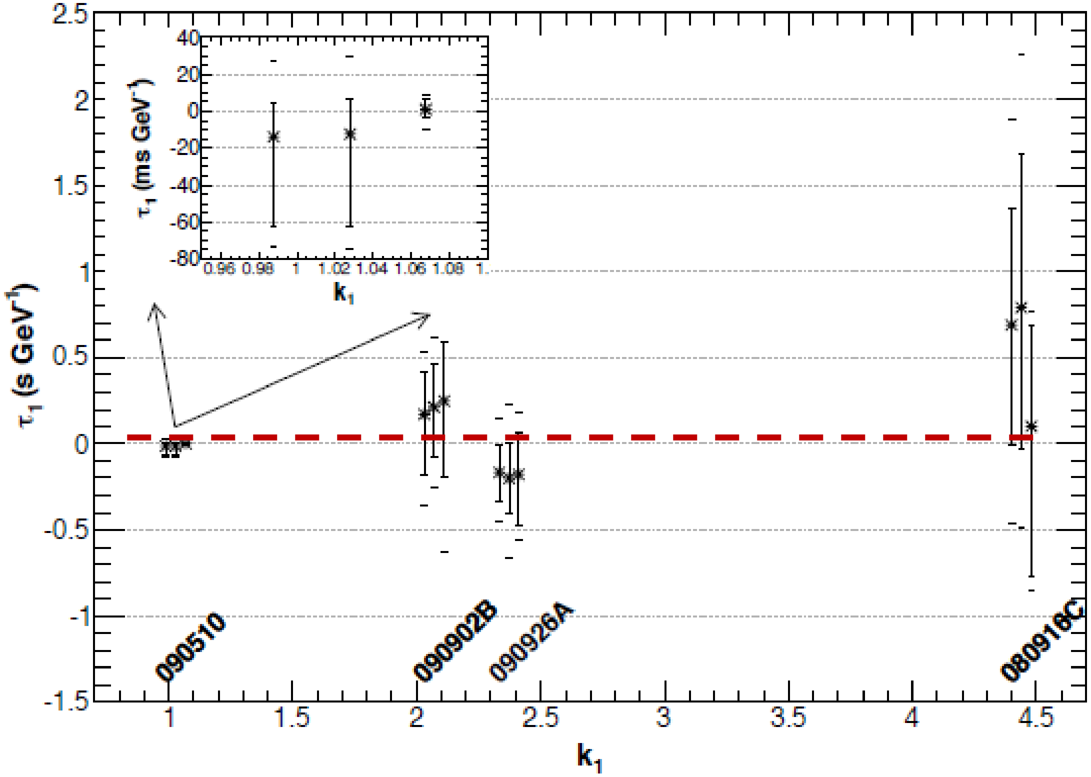




Constraints on the time-lag parameter τ_n

Linear case (n = 1)

$$k_1 = \int_0^z \frac{(1+z')\,dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

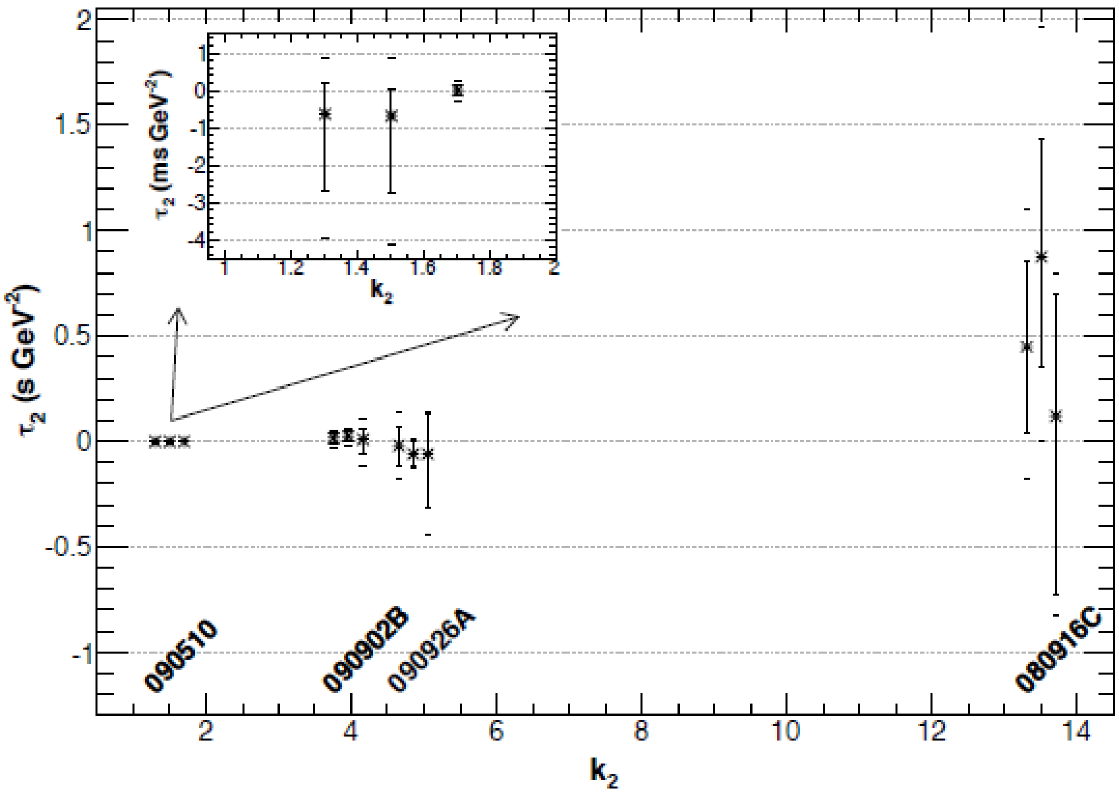


→ No significant "linear" time-lag measured with 4 GRBs

Constraints on the time-lag parameter τ_n

Quadratic case (n = 2)

$$k_2 = \int_0^z \frac{(1+z')^2\, dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$



→ No significant "quadratic" time-lag measured with 4 GRBs

Accounting for GRB intrinsic dispersions

$$\tau_n = \tau_{\mathrm{LIV}} + \tau_{\mathrm{intrinsic}}$$

(data) (LIV effect) (source)

Modelization of τ_{int}, assuming observations are dominated by source effects:

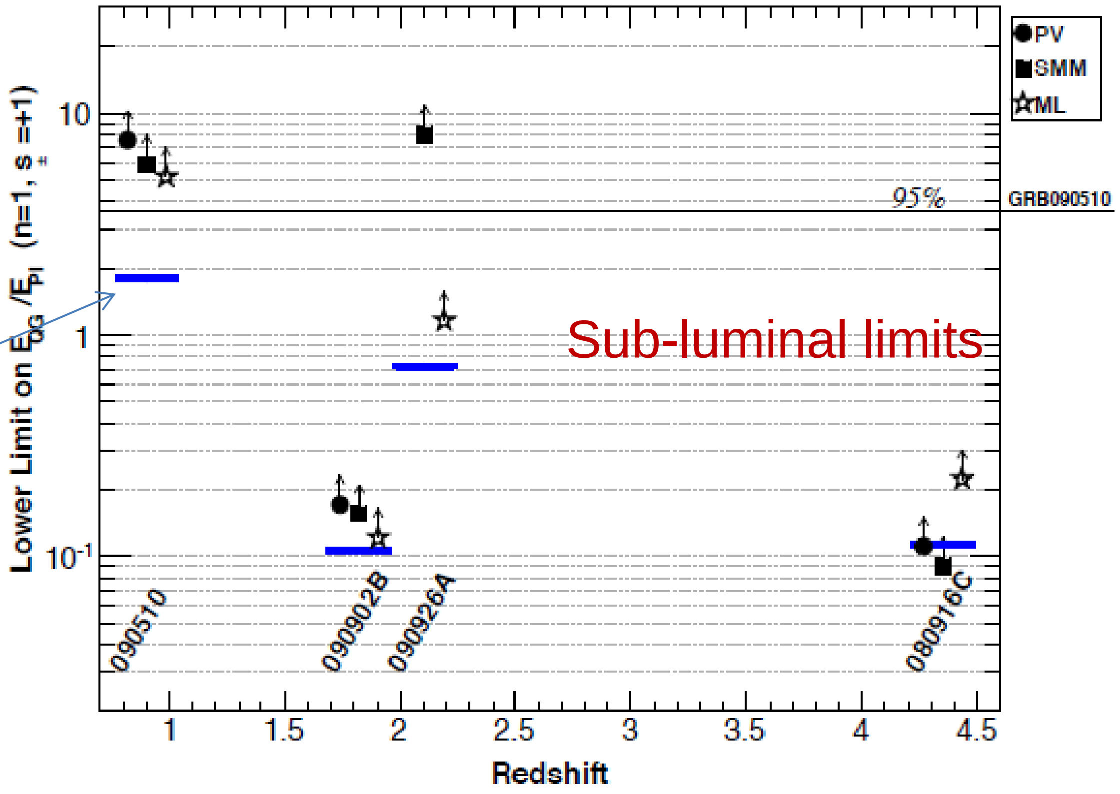
- width(τ_{int}) = width(τ_n) and $\langle\tau_{\mathrm{int}}\rangle = \langle\tau_n\rangle = 0$
- PDF of τ_{int} set to match distribution of possibilities for τ_n
  $\rightarrow$ symmetric confidence intervals on τ_{LIV}
- worst case scenario
  $\rightarrow$ most conservative limits

the Systematic error were set to be ~ Statistical error

95% CL lower limits on E_{QG}

Linear case (n = 1)

$$\tau_1 = \frac{\Delta t}{\Delta E} \simeq \frac{2}{E_{QG} H_0} k_1(z)$$

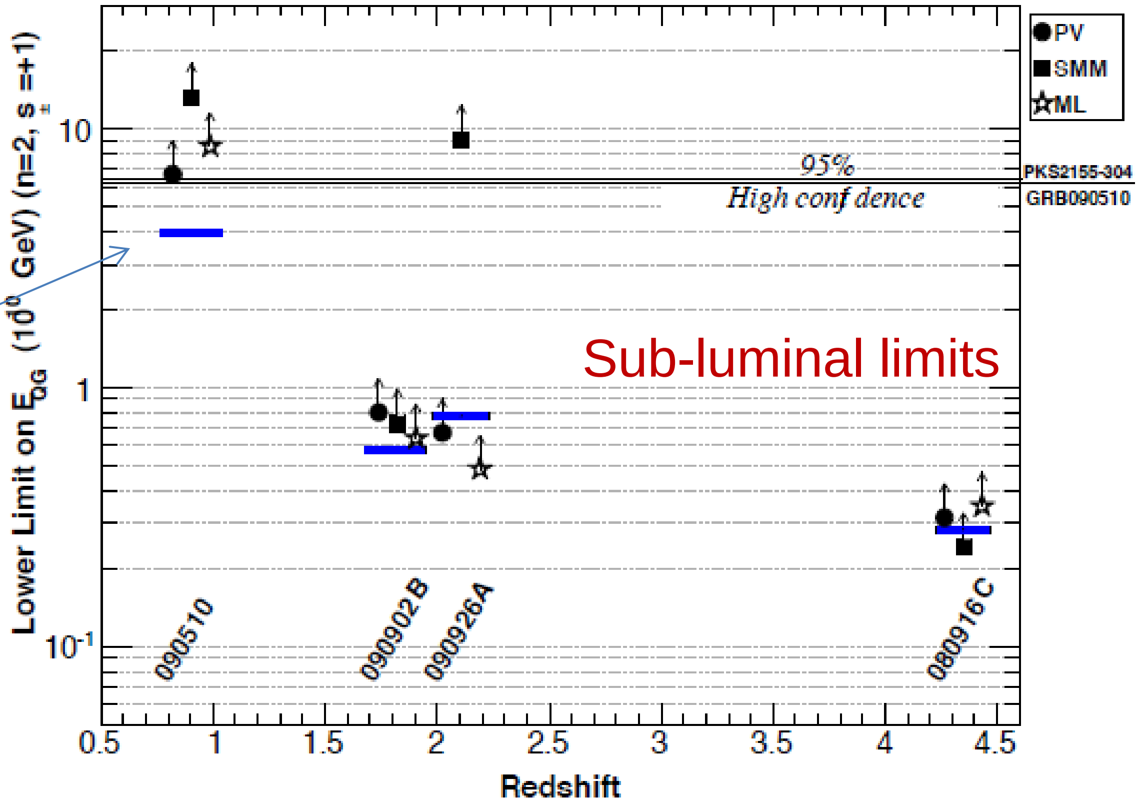


with systematics
(source effects)

95% CL lower limits on E_{QG}

Quadratic case (n = 2)

$$\tau_2 = \frac{\Delta t}{\Delta E^2} \simeq \frac{3}{E_{QG}^2 H_0} k_2(z)$$



with systematics
(source effects)

Conclusions : latest Fermi results

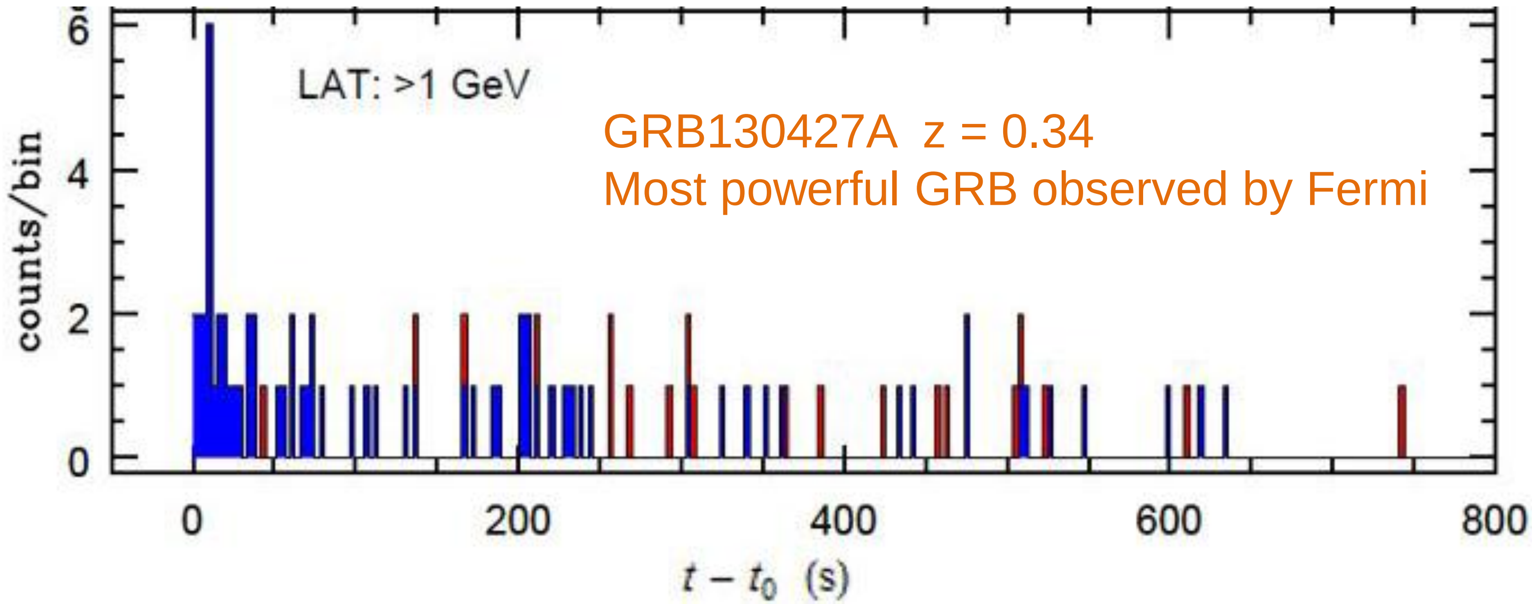
- Paper published: Phys. Rev. D 87, 122001 (2013) [arXiv:1305.3463]
  Detailed description of methods and procedures (30 pages)

- 4 bright GRBs with measured redshift analyzed
  with 3 different methods :

$E_{QG}^{1} > 7.6\ E_{P}$
$E_{QG}^{2} > 1.3\ 10^{11}$ GeV

→ the most stringent, complete and robust results on linear and quadratic term
→ Linear LIV constraint has reached the Planck scale boundary
even taking account intrinsic potential time-lags
disfavors some classes of QG models *but still with only one measurement*
→ Quadratic LIV needs to be improved

Next studies: GRB130427A



Amelino-Camelia, et al. (arXiv: 1305.2626) :

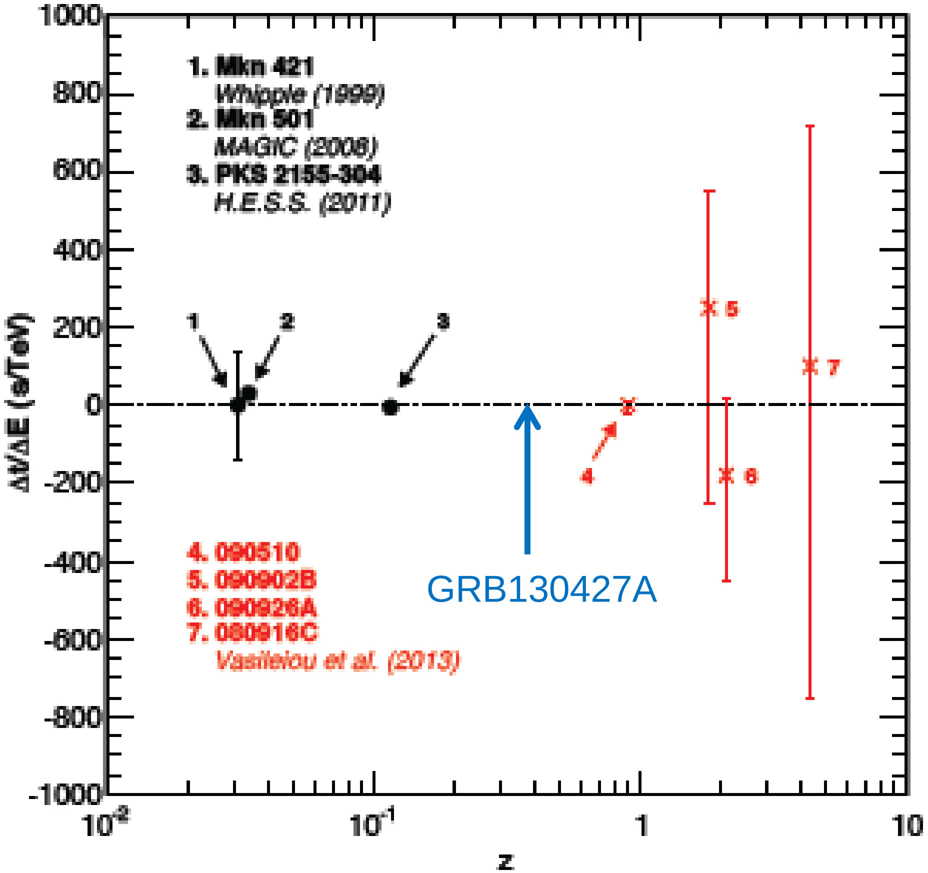
Study of correlations time-energy-redshift, minibursts

→ unusual results at a given scale and redshift

$E_{QG} \sim M_P/25$?

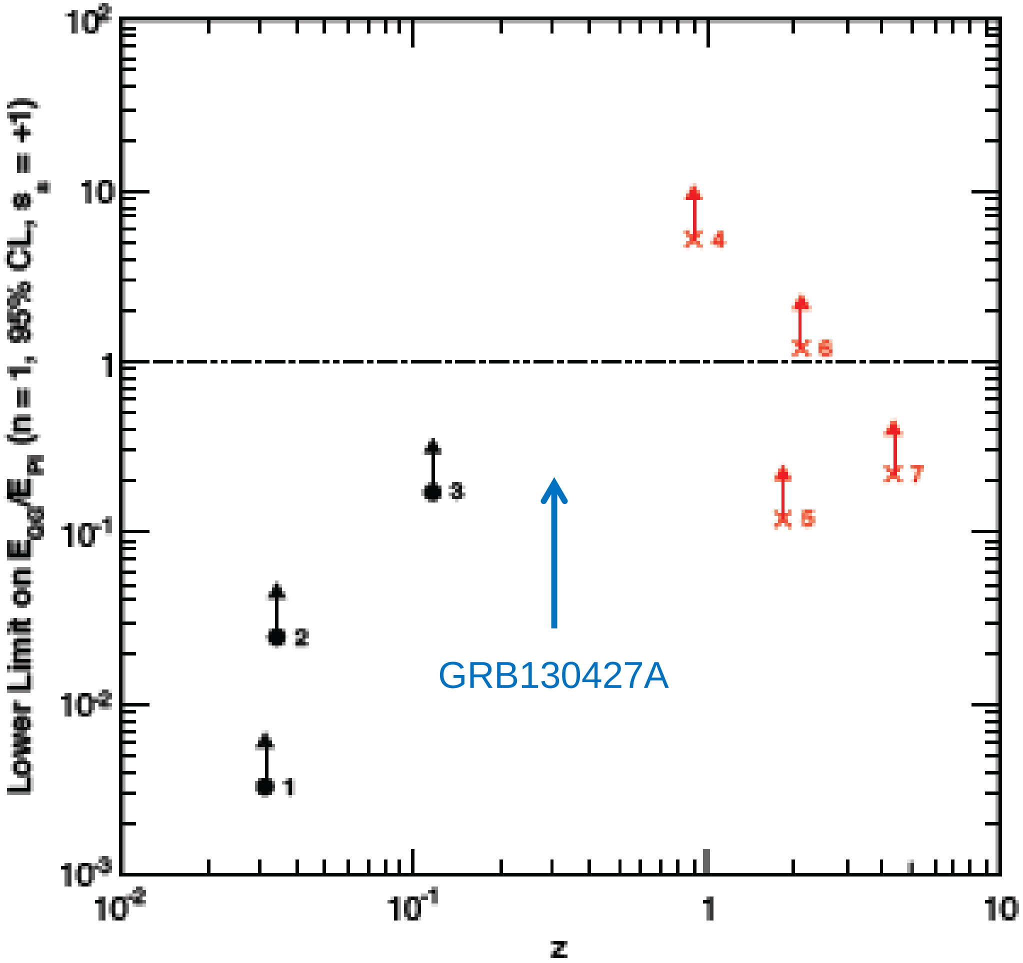
→ importance of continuity in probing all z ranges

Synergy between GRBs & AGNs



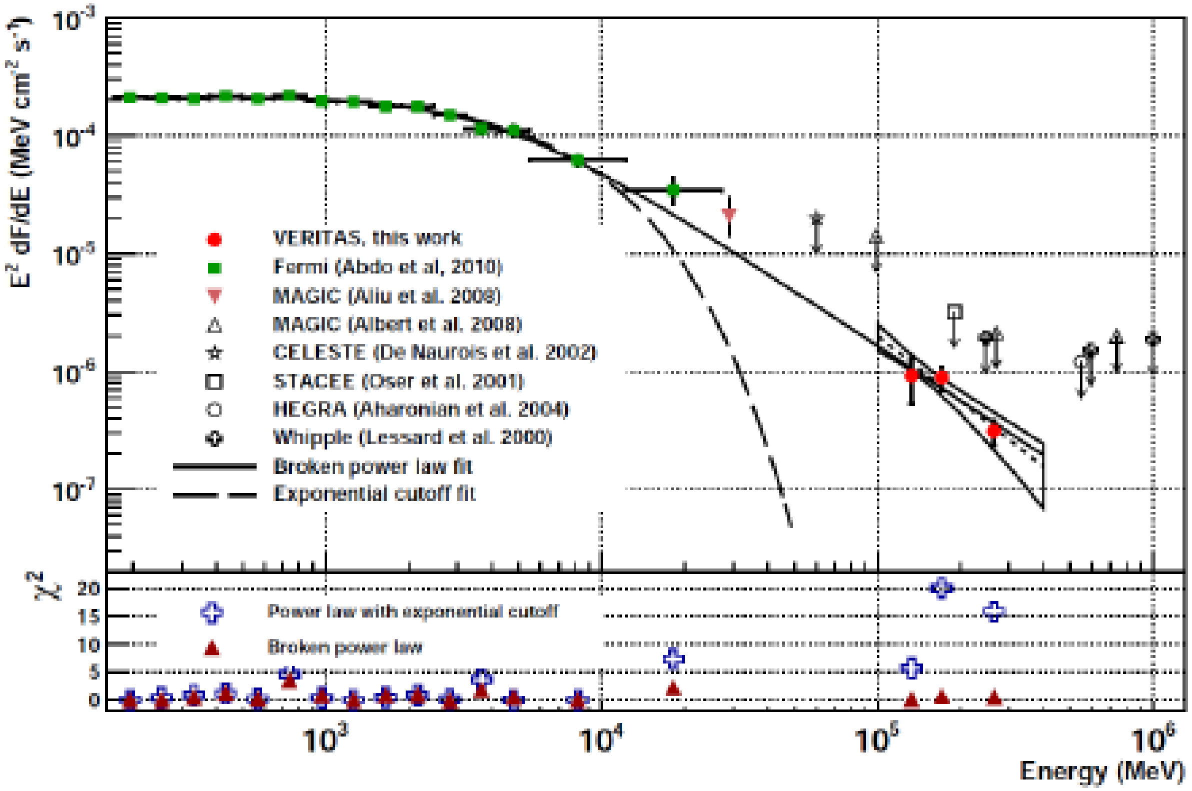
- Measured time-lags as a function of energy : → *no significant deviation from zero value*
- Large errors from GRBs at high z : low stats and long GRBs

E_{QG} with GRBs & AGNs



- z < 0.9 :
  limits below M_P
- z = 0.9
  very short GRB
  limit dependent on
  highest energy γ
- Stacking 3 long GRBs :
  ~ 0.7 M_P

VERITAS: CRAB pulsar



$E_{QG,1} > 1.9\ 10^{17}$ GeV

DisCan method - arXiv:1337.8382

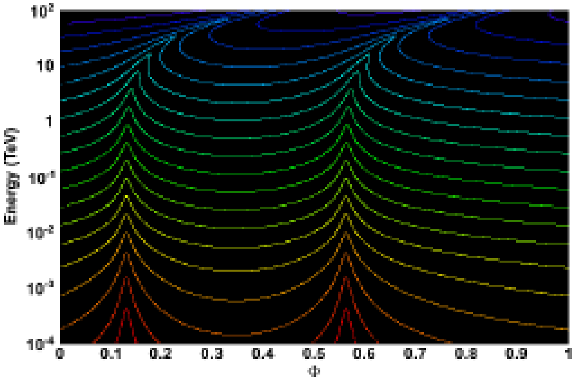
Pulsars: phase-lag parameter

- Time delay due to LIV:

→ phase delay between photons of ≠ energies in the reconstructed phasogram.

- Define a phase-lag parameter : $\varphi_n = \frac{\tau_n}{P(t)}$
  (TeV^{-1} for n=1)
  (TeV^{-2} for n=2)

$P(t) \approx P + \dot{P}t$ For short time scale: $P(t) \approx P$



- Parametrize Template Phasogram $\mathbf{F_s}$ at low energy and spectrum $\mathbf{A(E_s)}$

$$F_s(t_s - \tau_n E_s^n) \rightarrow F_s(\Phi_s - \varphi_n E_s^n)$$

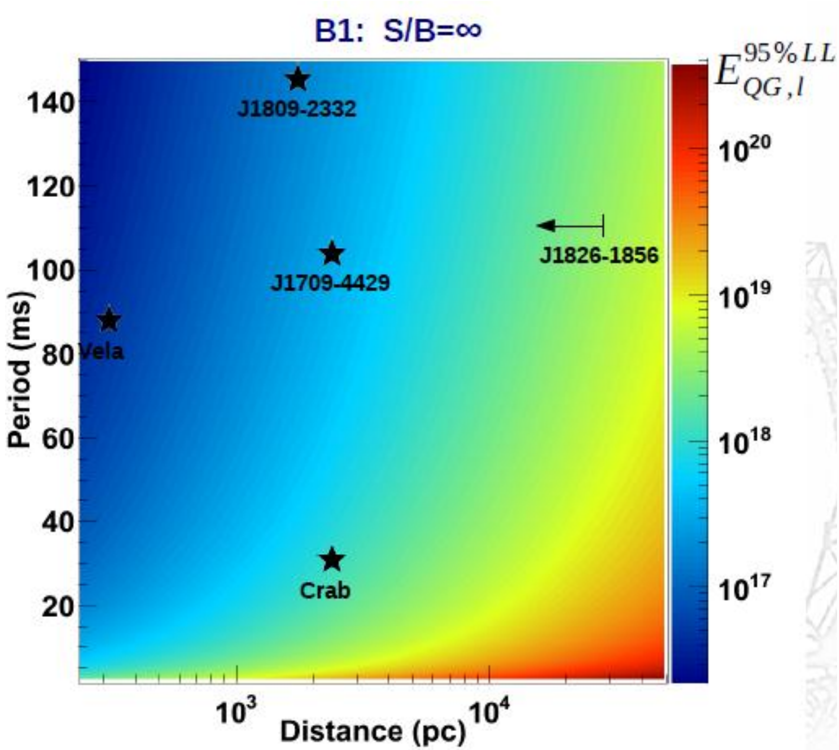
$$P(E,t) \rightarrow P(E,\Phi)$$

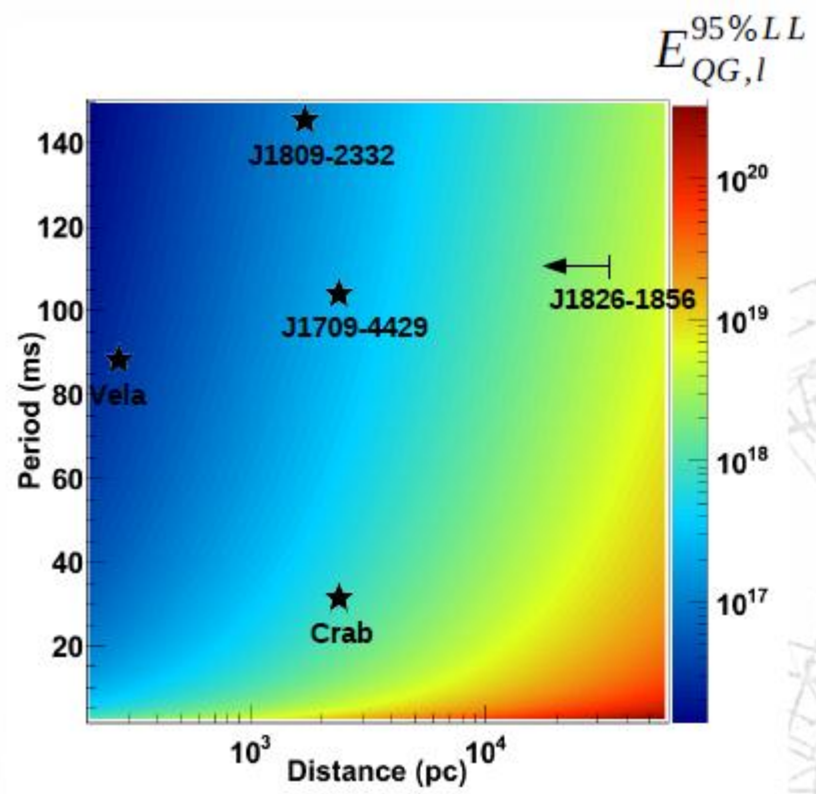
- **Maximum Likelihood** at high energy gives estimate on the phase-lag parameter.

$$L = \prod_i P(E,\Phi)$$

Simulations for H.E.S.S. II

Sensitivity to linear term: 2 background models





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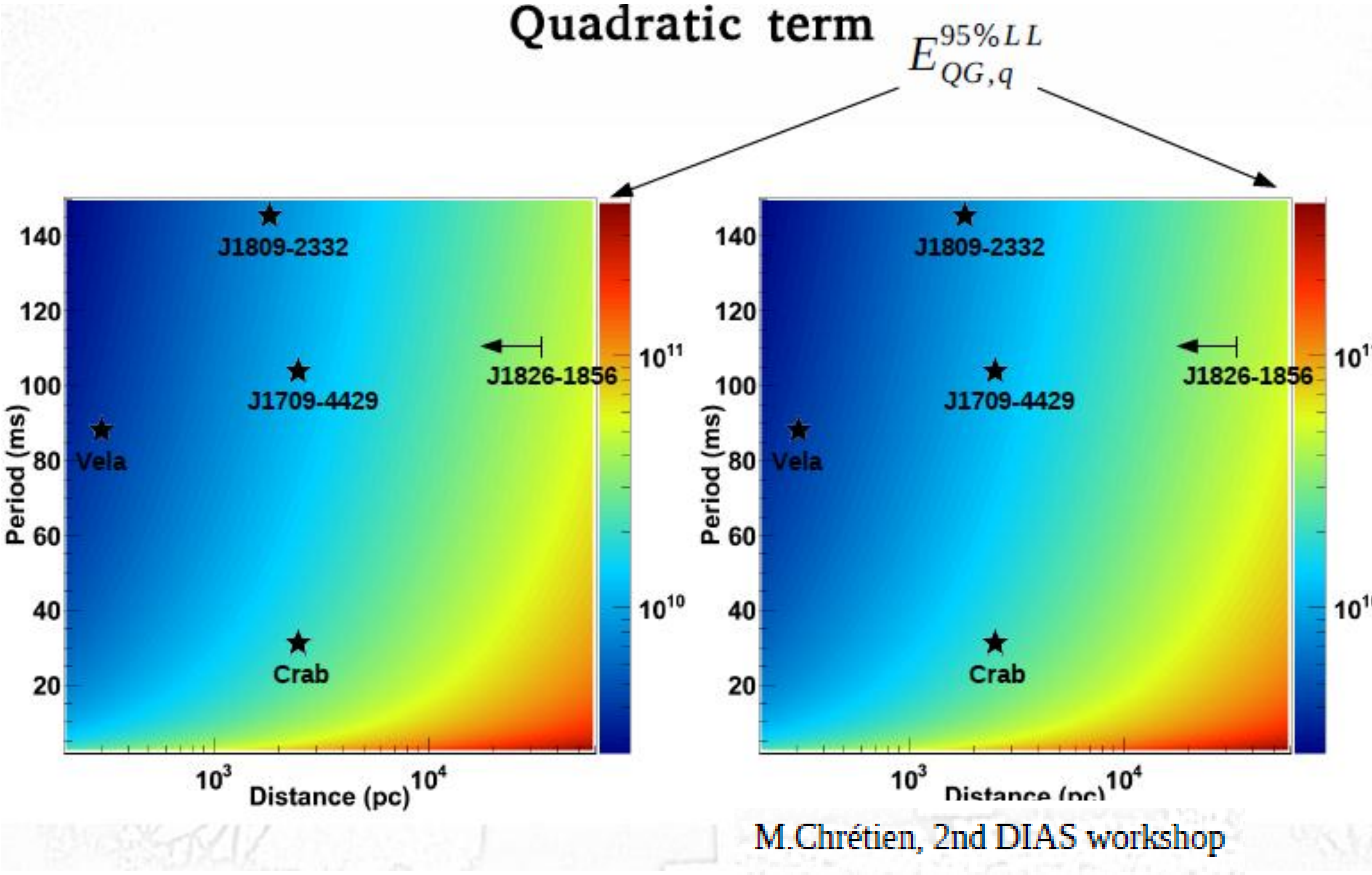
Simulations for H.E.S.S. II



Simulations for H.E.S.S. II

$E_{QG}^{95\% LL}$ (GeV) for H.E.S.S.2 pulsar candidates	Linear		Quadratic	
	S/B=∞	S/B=1	S/B=∞	S/B=1
Crab	1.04×10^{18}	5.47×10^{17}	1.74×10^{10}	1.48×10^{10}
PSR J1826-1256*	$< 3.18 \times 10^{18}$	$< 1.83 \times 10^{18}$	$< 3.19 \times 10^{10}$	$< 2.72 \times 10^{10}$
PSR J1709-4429	3.19×10^{17}	1.84×10^{17}	1.01×10^{10}	8.63×10^{9}
PSR J1809-2332	1.64×10^{17}	9.5×10^{16}	7.25×10^{9}	6.20×10^{9}
Vela	4.69×10^{16}	2.71×10^{16}	3.87×10^{9}	3.31×10^{9}

* *from published upper limit on distance (Fermi 2nd year catalog)*

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Discussion & OUTLOOK

- LIV is not a necessary feature in Quantum Gravity Theory however LIV at Planck scale provides observational window of QG effects
  → study of LIV at ~ E_P energy may provide a signature of QG phenomena

- Present data : Pulsars, AGNs and GRBs allow to approach E_P as a QG scale and even exceed E_P for at least 1 case
  → disfavor models with $E_{QG} < E_P$

- Studies with 3 types of sources are mandatory – coherence of results?

- Measurements with redshift important for Physics and Systematic source effects
  Theory does not exclude different effects at different redshifts and energy ranges

- New results are expected with H.E.S.S. II: Pulsars, AGNs at higher z other short GRBs in Fermi-LAT
  Real Progress : Population studies in future CTA observatory