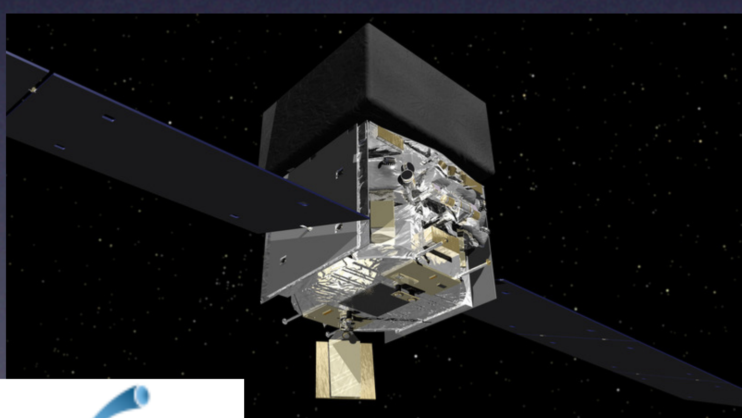
Lorentz Invariance Violation: The latest Fermi results and the GRB/AGN complementarity

J. Bolmont
LPNHE - Université Pierre & Marie Curie



RICAP 2013
May 22-24, 2013 - Roma

Content

- Introduction
  - The formalism in use
  - Propagation vs. intrinsic lags
- The latest Fermi results
  - The three methods in use
  - Acounting for intrinsic lags
  - Results
- Conclusions and prospects
  - GRB/AGN complementarity
  - Future developments

Introduction

The formalism in use

- QG related effects should appear at E ~ O(E_P = 1.2x10^{19} GeV)
- These effects include deformation or violation of Lorentz Invarience
- For E << E_P, a series expansion is expected to be possible, giving:

$$c' = c\left(1 \pm \xi \frac{E}{E_{\mathrm{P}}} \pm \zeta^2 \frac{E^2}{E_{\mathrm{P}}^2}\right)$$ at the 2nd order

- Depending on their energies, photons travel at different speeds
- Tiny modifications can add-up over very large propagation distances and lead to measurable delays
➔ use of variable and distant sources (GRBs, AGN flares)
- We consider two photons with energie E_1 and E_2 emitted at the same time and detected at times t_1 and t_2.
  - At the first order : $$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_{\mathrm{P}} H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$
  - At the second order: $$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2E_{\mathrm{P}}^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$\Delta t = t_1 - t_2 \qquad \Delta E = E_1 - E_2 \qquad \Delta E^2 = E_1^2 - E_2^2 \qquad \Omega_\Lambda = 0.7 \qquad \Omega_m = 0.3$$

The formalism in use

- QG related effects should appear at $E \sim O(E_P = 1.2 \times 10^{19}$ GeV)
- These effects include deformation or violation of Lorentz Invarience
- For $E \ll E_P$, a series expansion is expected to be possible, giving:

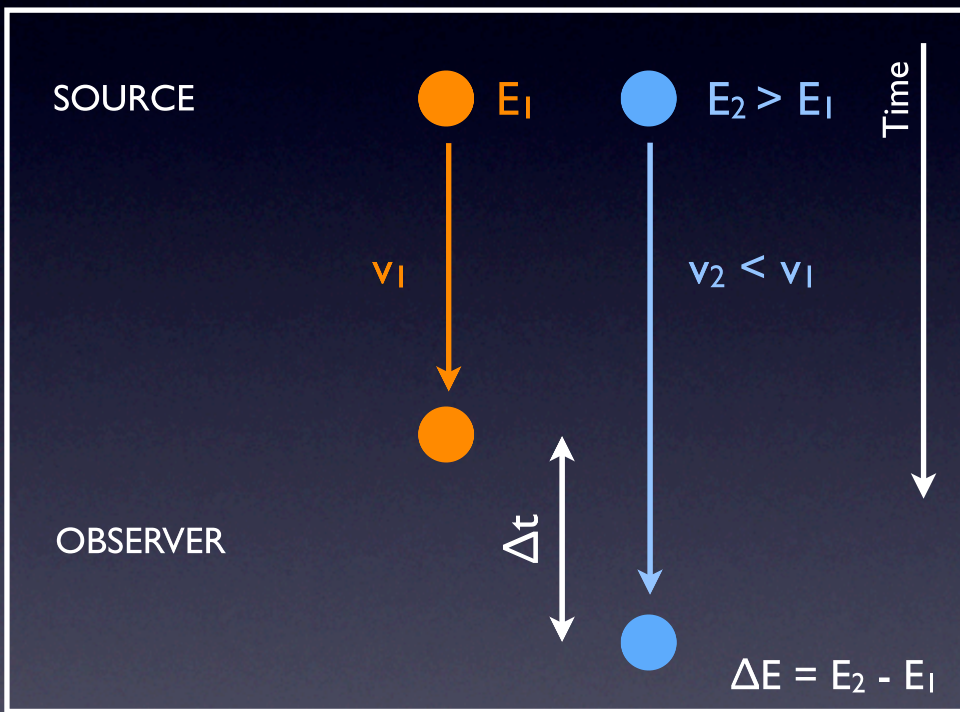
$$c' = c\left(1 \pm \xi \frac{E}{E_{\mathrm{P}}} \pm \zeta^2 \frac{E^2}{E_{\mathrm{P}}^2}\right)$$ at the 2nd order

- Depending on their energies, photons travel at different speeds
- Tiny modifications can add-up over very large propagation distances and lead to measurable delays
  ➔ use of variable and distant sources (GRBs, AGN flares)
- We consider two photons with energie E_1 and E_2 emitted at the same time and detected at times t_1 and t_2.
  - At the first order : $$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_{\mathrm{P}} H_0} \boxed{\int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}}$$ k_1
  - At the second order: $$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2 E_{\mathrm{P}}^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

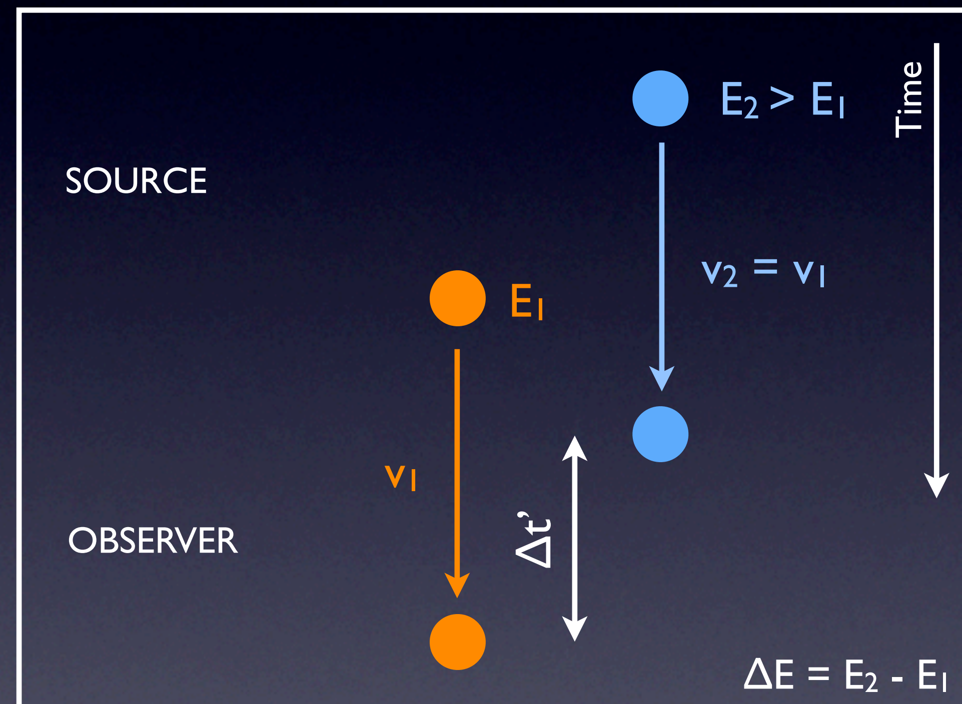
$$\Delta t = t_1 - t_2 \qquad \Delta E = E_1 - E_2 \qquad \Delta E^2 = E_1^2 - E_2^2 \qquad \Omega_\Lambda = 0.7 \qquad \Omega_m = 0.3$$

QG Effects vs. Source Effects

- BUT : Emission processes or the structure of the source can introduce a time lag too !
- It is necessary to separate the two effects ➔ population studies



Quantum Gravity effect



Possible source effect

Propagation ➔ LIV Effect

Emission ➔ Source Effect

The latest Fermi results

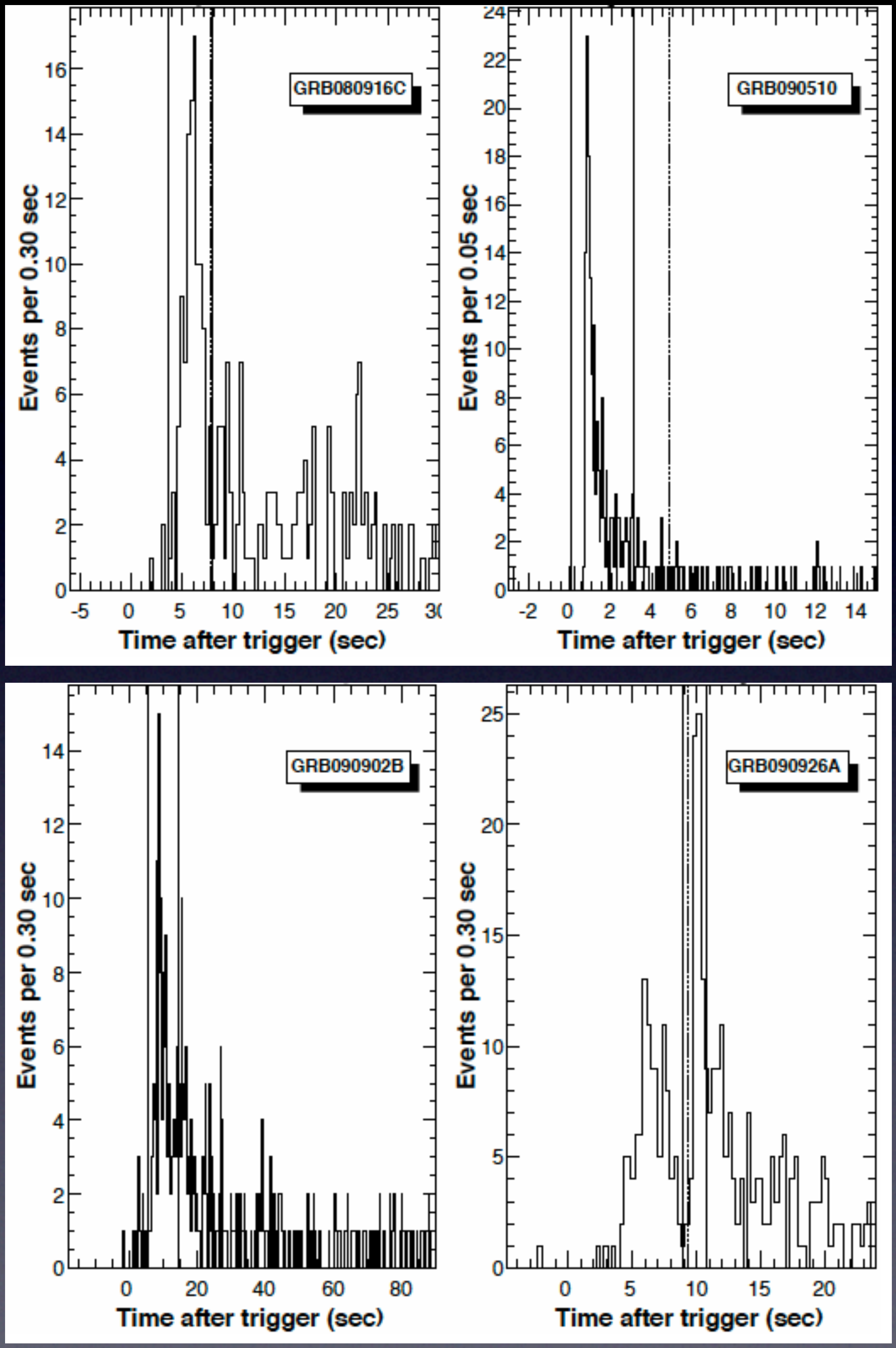
«Constraints on Lorentz Invariance Violation with Fermi-LAT observations of GRBs»

- V. Vasileiou, F. Piron, J. Cohen-Tanugi (LUPM Montpellier)
- A. Jacholkowska, JB, C. Couturier (LPNHE Paris)
- J. Granot (Open Univ. of Israel)
- F. Stecker (NASA GSFC)
- F. Longo (INFN Trieste)

Accepted for publication by PRD
arXiv:1305.1553

Overview

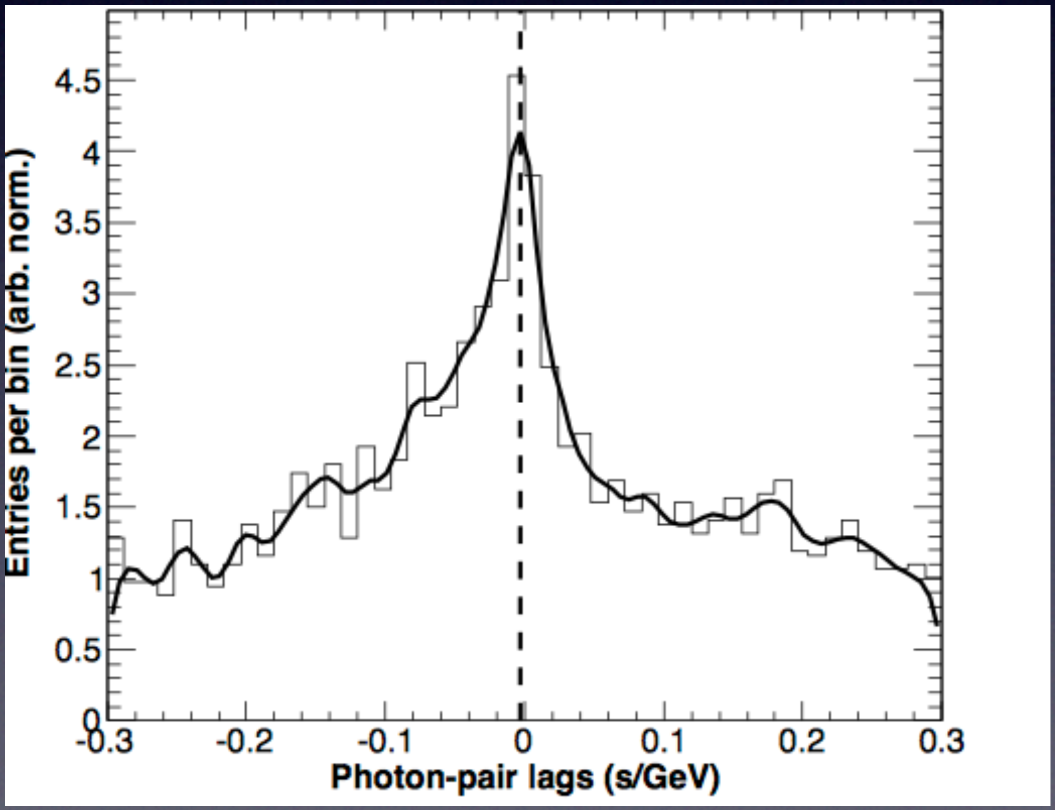
- Use of LAT data
  - 20 MeV - 300 GeV
  - High effective area
  - Low background
  - Good energy recontruction accuracy (~10 % at 10 GeV)
- 4 GRBs are analyzed
  - 090510, 090902B, 090926A, 080916C
  - Known redshifts (from 0.9 up to 4.3)
  - Variability time scale down to tens of ms
  - Maximum energy detected: 31 GeV
  - ~100 events/GRB above 100 MeV
- 3 analysis methods ➔ «PairView», «Sharpness Maximization Technique», «Maximum Likelihood»
  - Complementarity in sensitivity
  - Reliability of the results



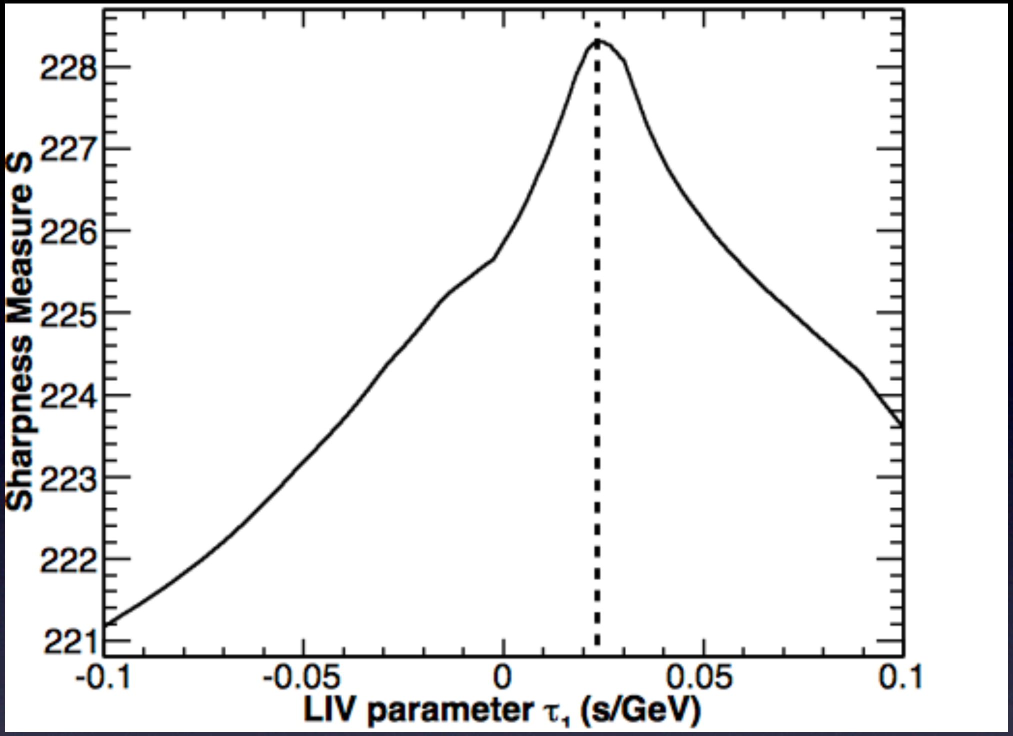
Method #1: PairView

$$l_{i,j} \equiv \frac{t_i - t_j}{E_i^n - E_j^n}$$

- Calculate the spectral lags $l_{i,j}$ between all pairs of photons i and j in a dataset
- The distribution of $l_{i,j}$ values peaks approximatly at the true value of τ.
  - ➡ Histogram
- The peak position is determined using a Kernel Density Estimate of the distribution.
  - ➡ Smooth curve
- The KDE peak gives the estimate for τ.
  - ➡ Dashed line



Method #2: Sharpness Maximization Technique



- LIV spectral dispersion smears light-curve structure and decrease sharpness
- Apply an inverse dispersion to the data to maximize the sharpness

  ➡ Smooth curve
- The sharpness peak gives the estimate for τ.

  ➡ Dashed line
- The sharpness S is defined by the formula on the right, where t'_i is the modified detection time of the i^{th} photon and ρ is a parameter selected using simulations

$$S(\tau_n) = \sum_{i=1}^{N-\rho} \log\left(\frac{\rho}{t'_{i+\rho} - t'_i}\right)$$

Method #3: likelihood fit

- Study of the correlation between the arrival time and the energy of the photons
- Method used by Lamon *et al.* for INTEGRAL, by Martinez and Errando for MAGIC and by Abramowski et al. for H.E.S.S.
- We use the following form for the probability density function:

$$P(t,E) = N \int_0^{\infty} A(E_S)\,\Gamma(E_S)\,G(E-E_S,\sigma(E_S))\,F_S(t-\tau E_S)\,dE_S$$

where $\Gamma(E_S)$ is the emitted spectrum, $G(E-E_S, \sigma(E_S))$ is the smearing function in energy, $A(E_S)$ is the acceptance of the detector and F_S is the emission time distribution at the source

- Here we assume linear and quadratic effects with a time-lag parameter τ expressed in s/GeV (s/GeV^2)
- The likelihood function is then given by the product

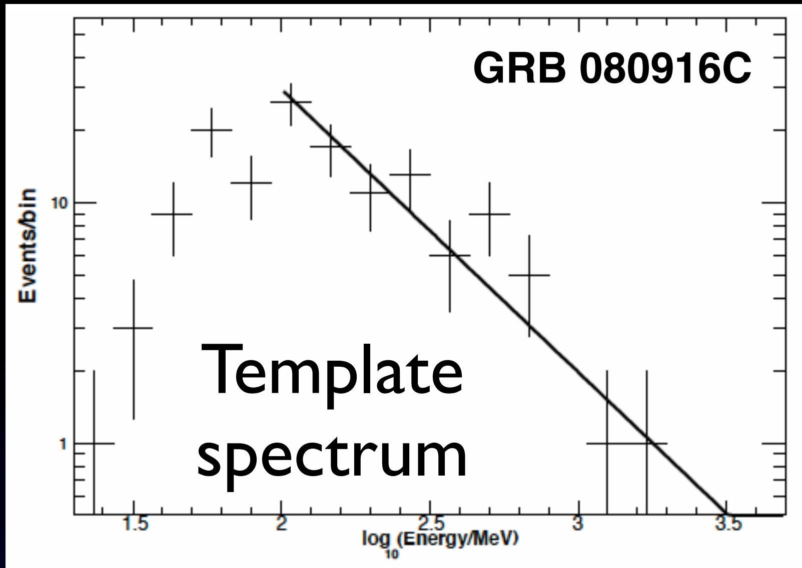
$$L = \prod_i P_i(t,E)$$

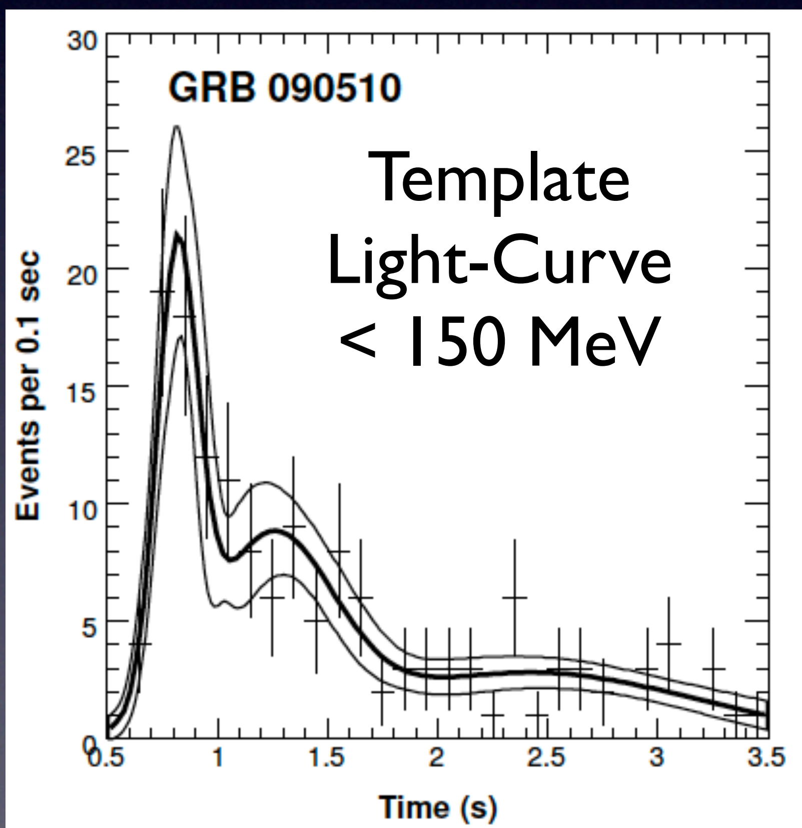
over all photons in the studied sample

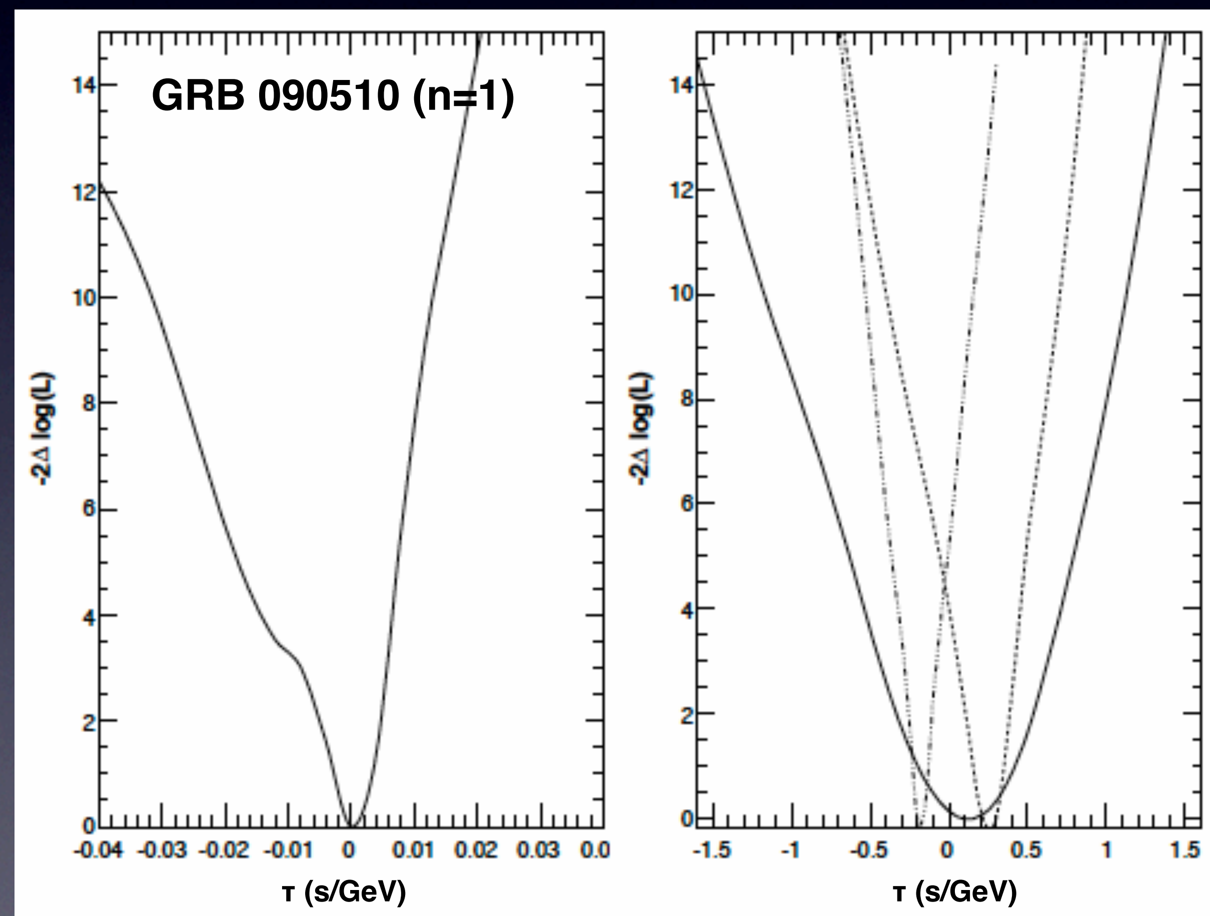
- The maximum of the likelihood gives the time-lag τ_l (τ_q) in s/GeV (s/GeV^2)

Method #3: Example

- The minimum of the curve gives the best estimate of τ: on the right plot, 080916C (full line), 090902B (dotted line) and 090926A (dashed double-dotted line)





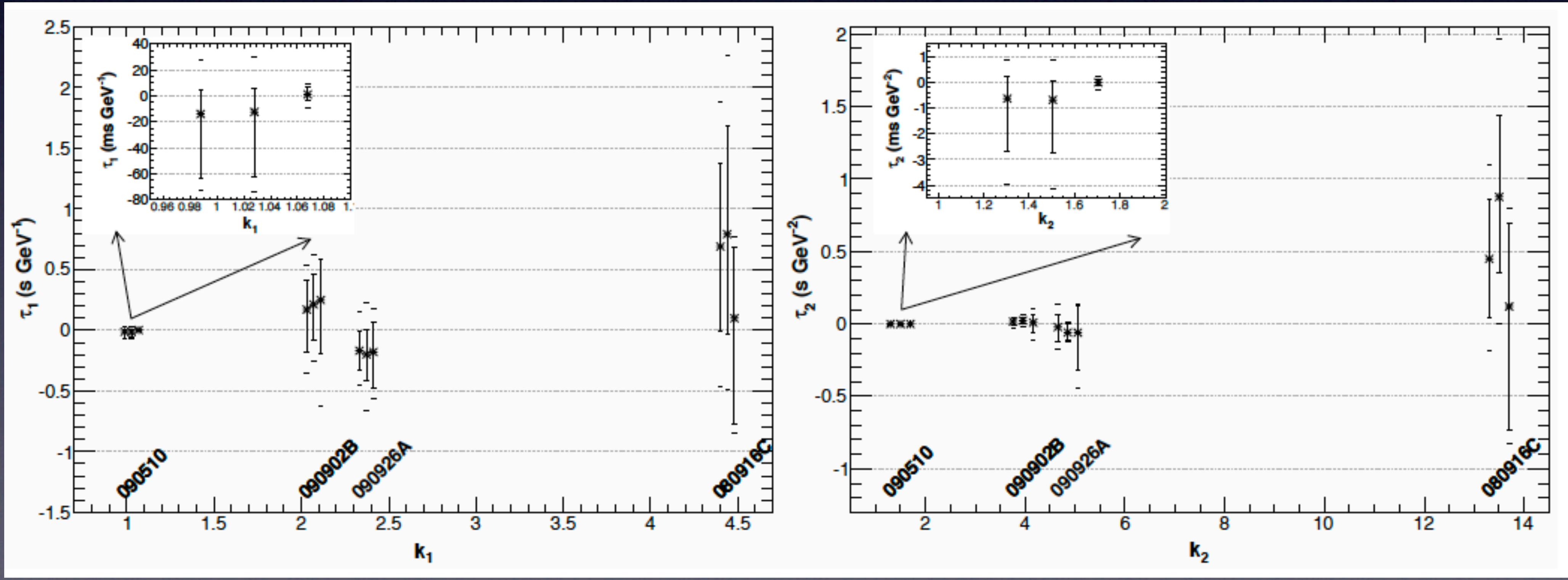


Results

- Three methods ➔ three points for each GRB
- Markers ➔ best estimate of τ
- 90% (99%) CL intervals

All confidence intervals are compatible with 0 dispersion

Constraints with the 3 methods are in good agreement



Accounting for Source-Intrinsic Effects

- It is probable the measured lag has two components:

$$\tau = \tau_{INT} + \tau_{LIV}$$

where τ_{INT} is the intrinsic dispersion (due to the source) and τ_{LIV} is the LIV-induced dispersion

- There is no good model available to predict the value of τ_{INT}.

  ➡ A conservative modelization of τ_{INT} is used.

- We assume the observations are dominated by source effects
  - The PDF of τ_{INT} is chosen to match τ allowed by the data
    - Average of 0
    - Width matching the width of τ
  - τ_{INT} is modelled to reproduce the allowed range of possibilities for τ

    ➡ Worst case scenario

    ➡ Less stringent limits on τ_{LIV}

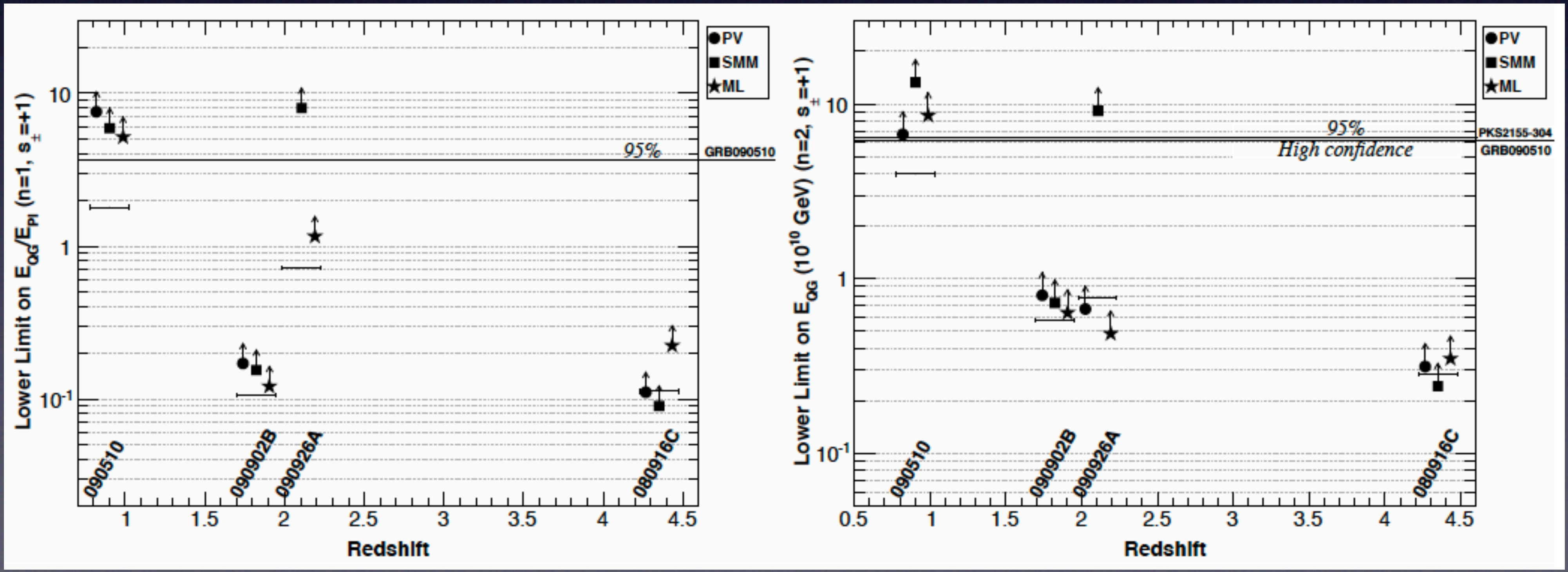
$$\boxed{\text{Most conservative limits on } \tau_{LIV}}$$

95% CL lower limits on E_{QG}

- Subluminal case, Left: linear LIV, Right: quadratic LIV
- Horizontal lines: previous published limits: Fermi (Abdo et al. 2009), H.E.S.S. (Abramowski et al. 2011)
- Bars: average constraint accounting for GRB-intrinsic effects
- Current limits improved by a factor 2-4

➡ $E_{QG} \gtrsim 8\ E_{Pl}$ for n=1

➡ $E_{QG} \gtrsim 1.3\times10^{11}$ GeV for n=2



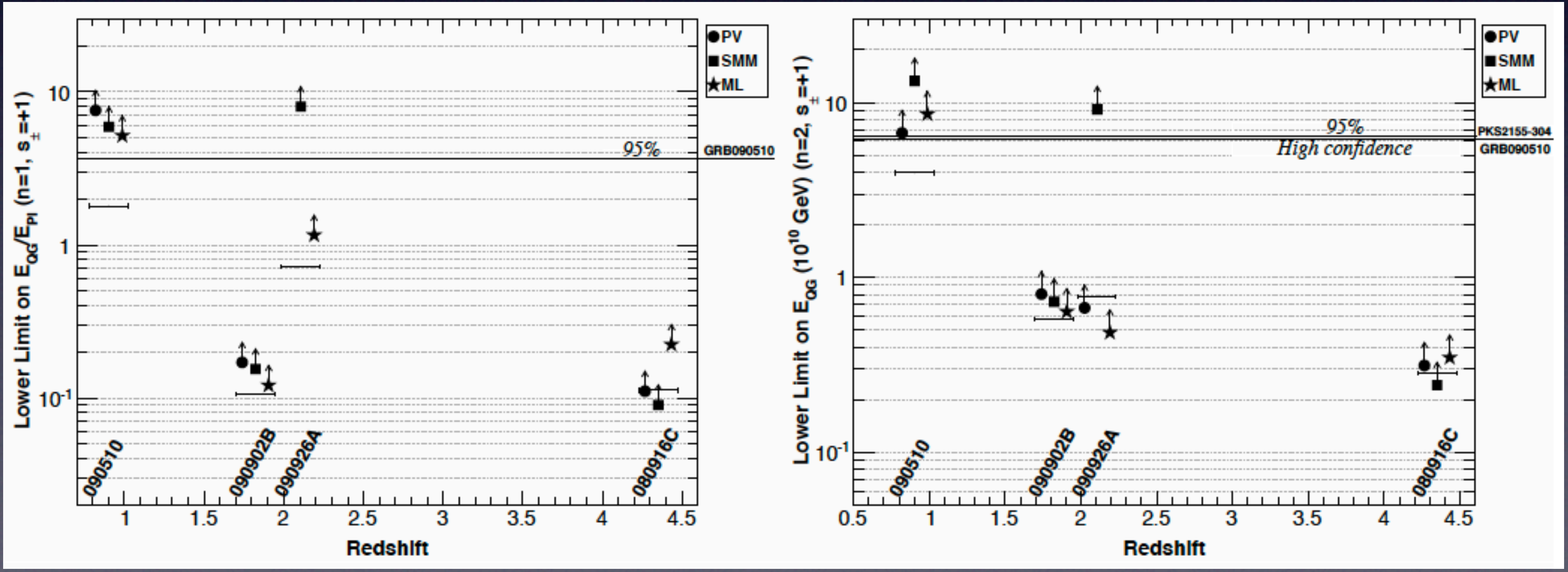
95% CL lower limits on E_{QG}

- Subluminal case, Left: linear LIV, Right: quadratic LIV
- Horizontal lines: previous published limits: Fermi (Abdo et al. 2009), H.E.S.S. (Abramowski et al. 2011)
- Bars: average constraint accounting for GRB-intrinsic effects
- Current limits improved by a factor 2-4

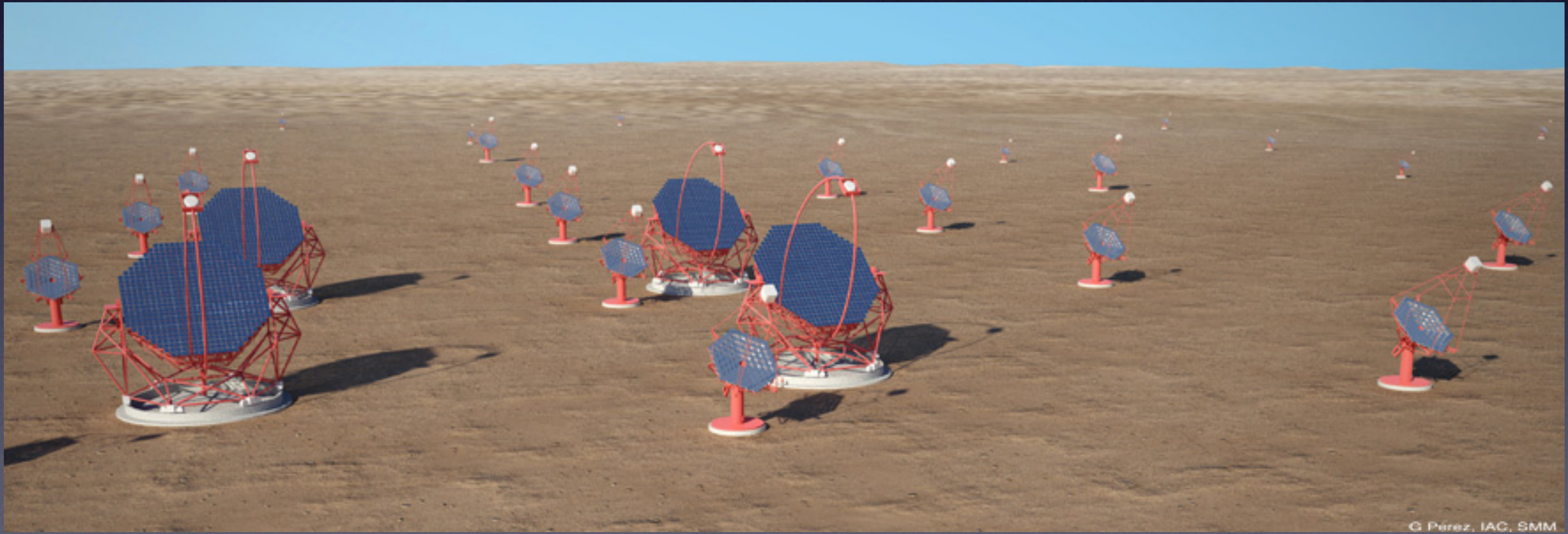
➡ $E_{QG} \gtrsim 8\ E_{Pl}$ for n=1

➡ $E_{QG} \gtrsim 1.3\times10^{11}$ GeV for n=2

Over the Planck scale for 090510, even accounting for intrinsic effects



Conclusions and prospects



Summary of the last Fermi results

- Paper available: arXiv/1305.3463
  - 30 pages
  - Detailed description of procedures, systematics, verification tests
  - Accepted by PRD

- 4 bright GRBs analysed
- 3 different methods used

$$\boxed{\begin{array}{l} E_{QG,1} > 7.6\ E_{Pl} \\ E_{QG,2} > 1.3\times10^{11}\ \mathrm{GeV} \end{array}}$$

➡ The most stringent and robust constraints for linear and quadratic LIV so far

➡ Linear LIV has reached the Planck scale boundary

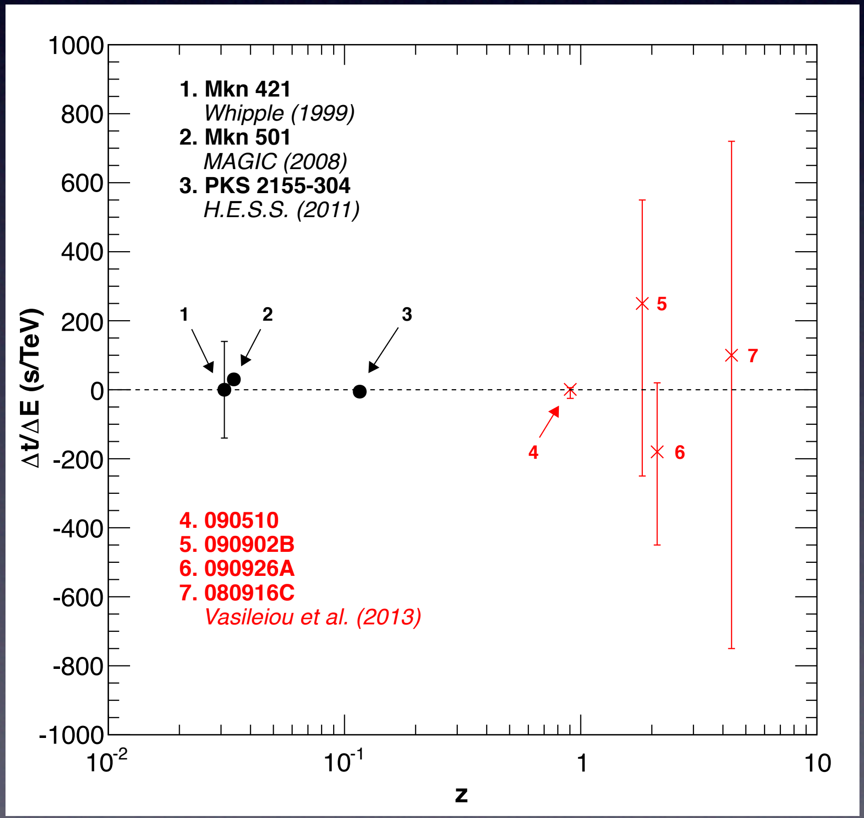
➡ Quadratic LIV still need to be improved

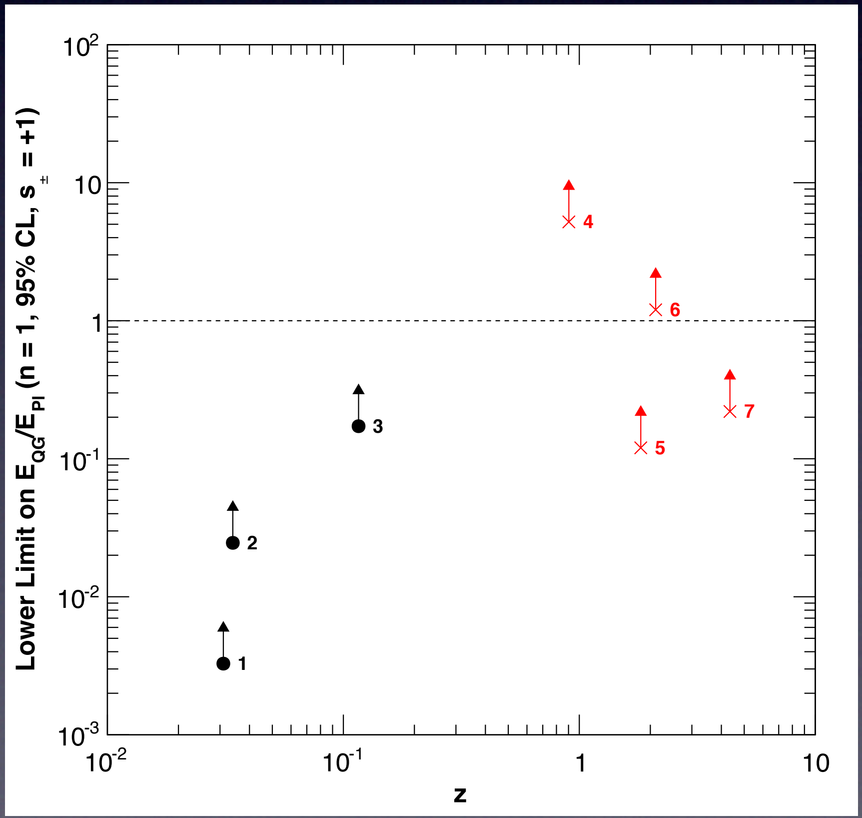
GRB/AGN Complementarity

- Comparison between Vasileiou et al. results (ML) and previous results obtained with AGNs
- AGNs ➔ high statistics with ground-based instruments BUT low redshift (EBL) and low statistics with satellites
- GRBs ➔ high statistics with space instruments BUT lower energies and no detection from the ground

High energies, low distance

Low energies, large distance





What's next ?

- CTA
  - Start around 2018
  - Large energy range coverage (~10 GeV - 100 TeV) with different sizes of telescopes
    - ➡ Overlap with satellites
  - Sensitivity increased by a factor 10
    - ➡ More sources discovered
  - Dedicated pointing strategy for transient source discoveries
    - ➡ More sources discovered that can be used for LIV searches

- Linear LIV has reached the physicaly meaningful bound of the Planck scale
- In the future, the effort should be put on constraining the quadratic LIV !
  - ➡ Ground-based detectors and satellites will need to work together to make the energy range as large as possible (GeV - TeV)
  - ➡ Necessary work on source effects

Grazie mille !