Searches for Lorentz Invariance Violation with Gamma-Ray Observatories and Latest Results from Fermi-LAT

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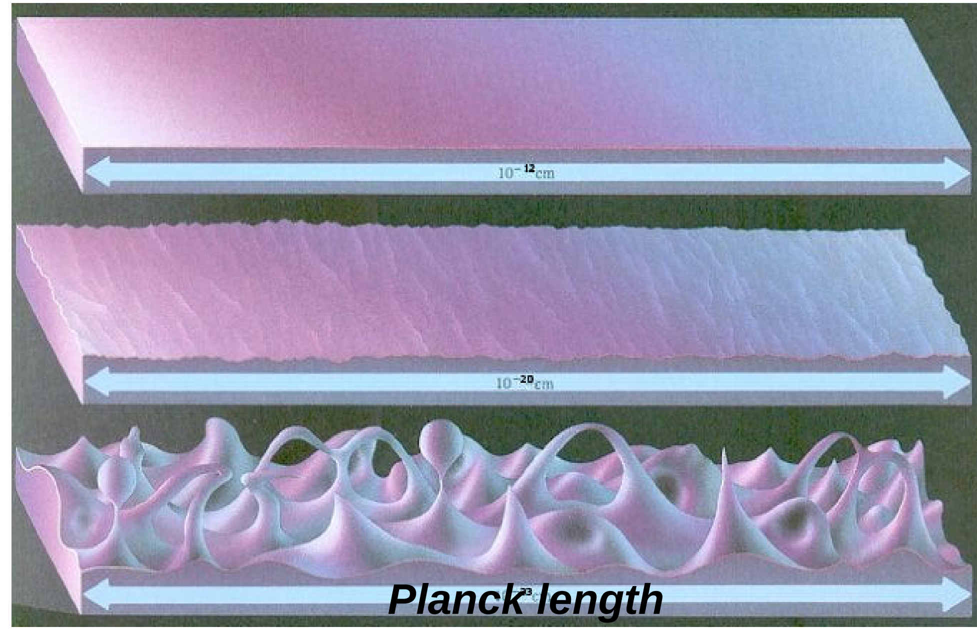
Lorentz Invariance Violation

- Nature of space-time at scales small enough for quantum effects to become important (i.e., Planck length 10^{-35} m) is unknown.
- Several QG scenarios/models hypothesizing on this nature:
  - *Stochastic space-time foam* ♦ *loop quantum gravity* ♦ *Non-commutative geometry* ♦ *string-inspired models (D branes)* ♦ warped brane worlds ♦ emergent gravity ♦ *etc.*



- "Quantum Gravity Phenomenology" – associated with variety of phenomena:
  - Quantum decoherence and state collapse ♦ QG imprint on initial cosmological perturbations ♦ Cosmological variation of couplings ♦ Violation of discrete symmetries, and
  - **Violation of space-time symmetries** → **Violation of Lorentz Invariance**

↑ *Focus of this talk*

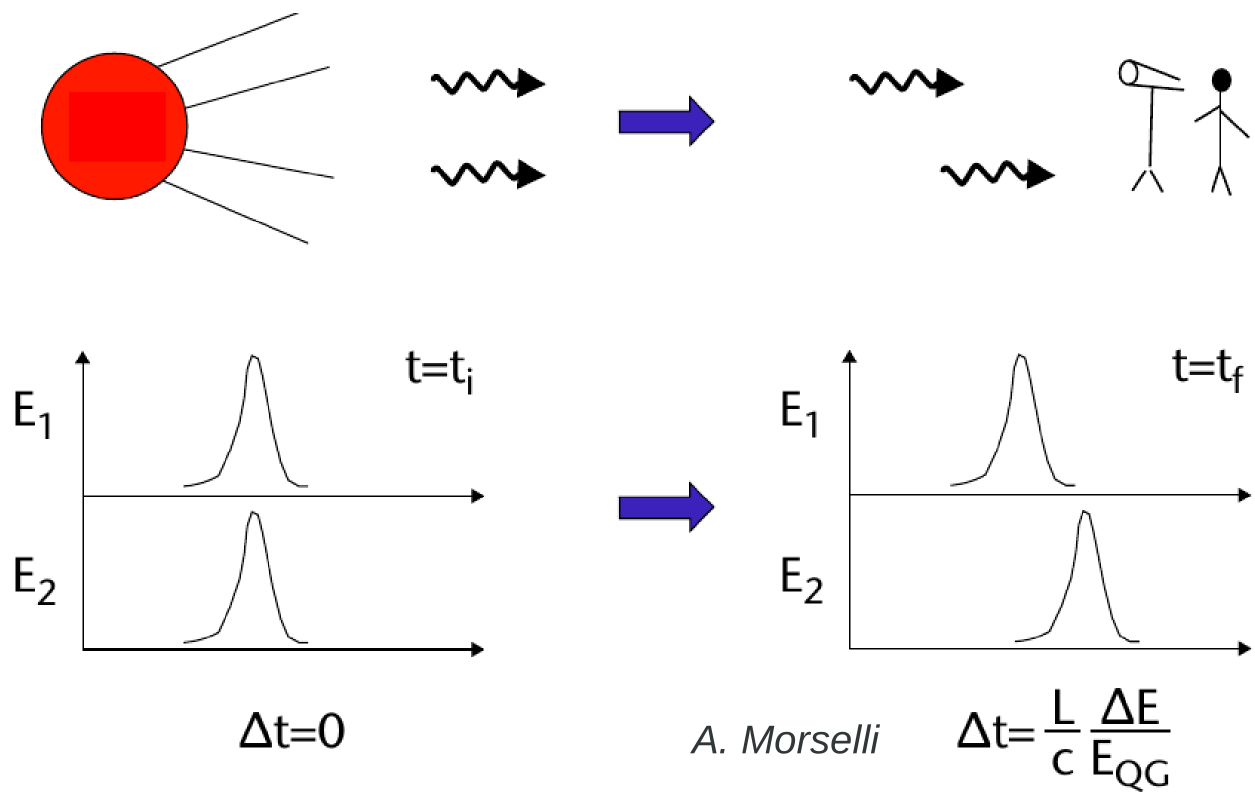
- *For a review see Liberati & Maccione '09, Mattingly '05, Stecker '09.*

Lorentz Invariance Violation

- Violation of Lorentz Invariance (LIV) can manifest in various ways, e.g.:
  - Presence of a Maximum Allowable Velocity of a particle ≠ c
    - *Vacuum Cherenkov Radiation (by superluminal electrons in vacuum)*
  - Modification of energy thresholds of reactions
    - *GZK cutoff of UHECR spectra (UHECR + CMB)*
    - *Cutoffs of γ-ray spectra of extra-galactic sources (γ+EBL)*
  - Allowance of particle interactions/decays kinetically forbidden by LI (*e.g., photon decay*)
  - Suppression of particle interactions or decays
  - Modified dispersion relations
    - Vacuum birefringence ← *See next talk by G. Gubitosi*
    - **Vacuum dispersion** ← *Focus of this talk*
- *For a review see Mattingly '05*

Vacuum Dispersion

- If speed of light (in vacuum) is energy dependent then
  - two photons of energies $E_h > E_l$ emitted together from a distant source will arrive with a time delay $\Delta\tau$.
- Using the observables $\Delta\tau$, E_h, E_l, the distance of the source, and some assumptions on the emission properties we can constrain LIV.



Series Expansion Framework

- LIV effect is described as a series of powers of the photon energy E_γ divided by the **Quantum Gravity energy scale $E_{QG,n}$,**

$$u(E_\gamma) = \partial E/\partial p \simeq c[1 - s_\pm \times (E_\gamma/E_{QG,1}) - s_\pm \times (E_\gamma/E_{QG,2})^2 + ..]$$

Energy dependent speed of light ($u(E_\gamma)$)

Speed of light at limit of zero E_γ. (c)

Perturbation due to LIV ($- s_\pm \times (E_\gamma/E_{QG,1}) - s_\pm \times (E_\gamma/E_{QG,2})^2 + ..$)

- $E_{QG,n}$: energy scale that the QG effects causing LIV become important
  - Quantity that we want to constrain
  - Expected to be close to the Planck Energy (E_{Pl} =1.2 x 10^{19} GeV) and likely smaller

    ➔ Piece of information that can be used to exclude/disfavor QG models
- Since $E_\gamma << E_{QG,n}$ → sum dominated by lowest term allowed by theory: n = 1 or 2
- $s_{\pm}$: theory-dependent parameter equal to (+,-)1 for (subluminal, superluminal) LIV

Series-Expansion Framework

- We define the "LIV parameter" τ_n that describes the *observed degree of dispersion*
- *Measured in s/GeV^n*

$$k_n \equiv \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_\Lambda + \Omega_\mathrm{M}(1+z')^3}} dz'$$

2. Calculate κ_n using source's distance.

$$\tau_n \equiv \frac{\Delta t}{(E_h^n - E_l^n)} \simeq s_\pm \frac{(1+n)}{2H_0} \frac{1}{E_{QG}^n} \times k_n$$

1. Directly constrain from data

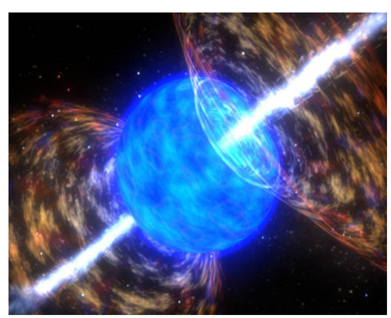
3. Constrain E_{QG}

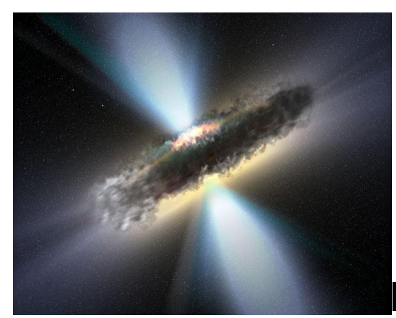
– H_0 is the Hubble constant, n and $s_\pm$ depend on the LIV model we are constraining.

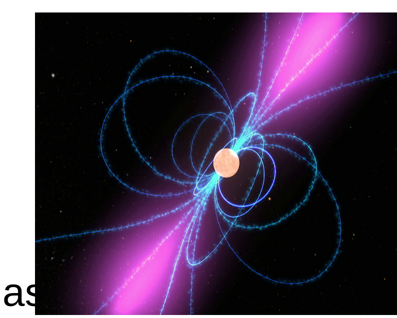
Sources for Constraining LIV-Induced Vacuum Dispersion

Property	Better constraints with	Gamma Ray Bursts	Active Galactic Nuclei	Pulsars
Distance	larger	Extragalactic	Extragalactic	Galactic
Energy range of emission	higher extend	up to tens of GeV	up to TeV	up to 400 GeV (Crab)
Relevant time scales	narrower	down to few tens ms	minutes	~100µs Crab w. VERITAS
Number of (useful) sources	larger	few	few	1
Knowledge of intrinsic effects	better	uncertain	moderate	better
Example sources		090510 (Fermi)	PKS 2155-304 (H.E.S.S.)	Crab pulsar (VERITAS/Fermi)
Relative strength of results		Best for linear ~best for quadratic	Good for linear ~best for quadratic	Ok for linear weak f. quadratic

Great, Good , OK

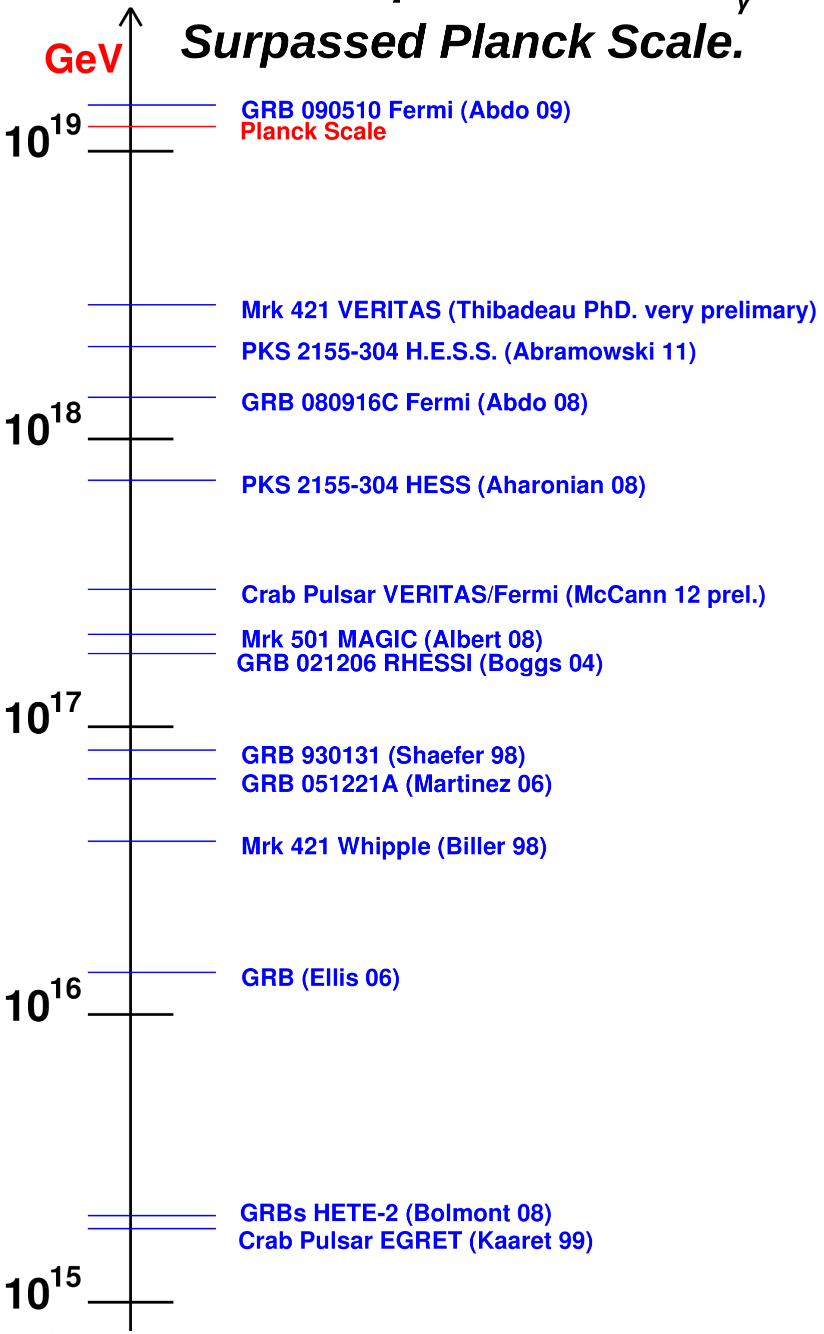




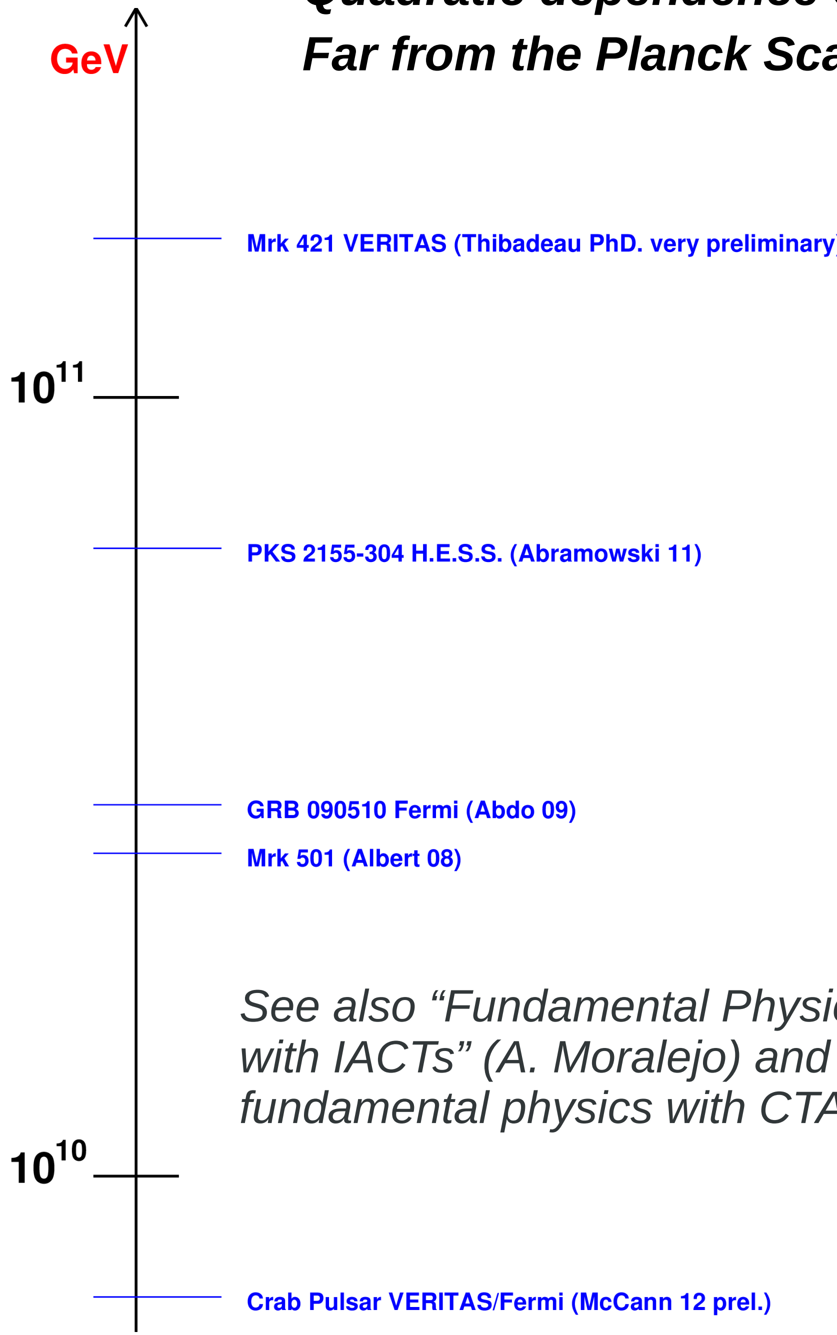


Current Lower Limits on E_{QG} (subluminal LIV)

Linear dependence on E_γ
Surpassed Planck Scale.



Quadratic dependence on E_γ
Far from the Planck Scale.



See also "Fundamental Physics with IACTs" (A. Moralejo) and "Dark matter and fundamental physics with CTA" (E. Moulin).

Latest Fermi-LAT Constraints on LIV

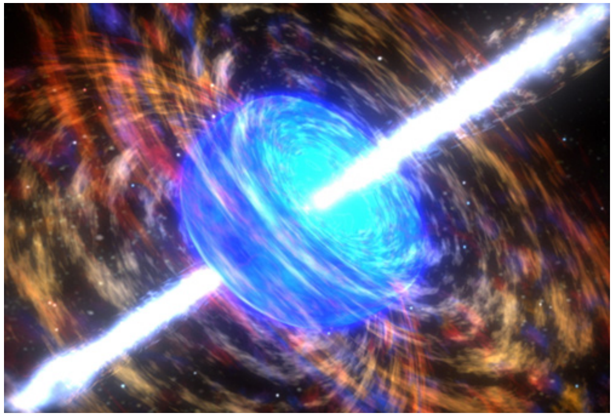
"*Constraints on Lorentz Invariance Violation with Fermi LAT Observations of GRBs*"

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

Analysis Overview

- **Large Area Telescope**
  - 20MeV - >300GeV, space-born Gamma-Ray Observatory, high effective area, low background, good energy reconstruction accuracy (~10% at 10GeV)
  - *See Eric Nuss talk for details on Fermi-LAT (later today)*

- **Data**
  - We use LAT observations of Gamma Ray Bursts
    - Redshifts up to z=4.3
    - Variability time scale down to tens of ms
    - Detected energies up to 31 GeV
    - Adequate statistics (~100 events/GRB E>100 MeV)
  - GRBs 090510, 080916C, 090926A, 090902B



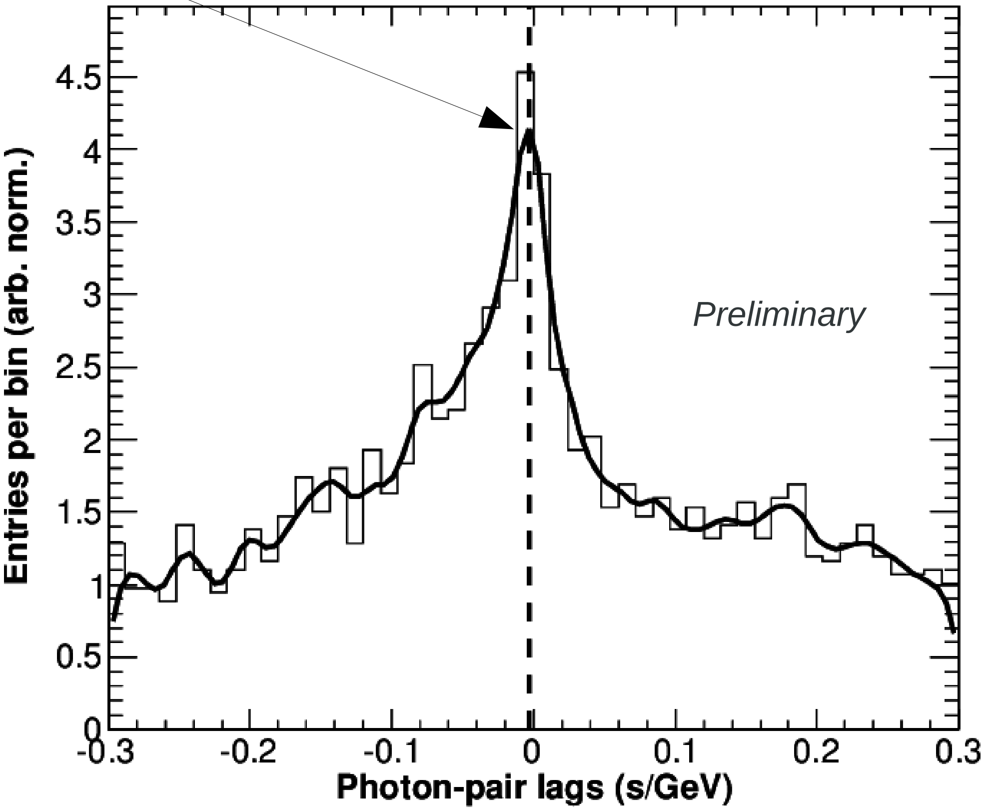
- **Three Analysis Methods → complementarity in sensitivity + reliability of results**
  - "PairView" (PV),
  - "Sharpness Maximization Technique" (SMM)
  - "Maximum Likelihood Analysis" (ML)

Method #1. PairView

1. Calculate the spectral lags $l_{i,j}$ between all pairs of photons in a dataset
   – distribution of $l_{i,j}$ contains a peak approximately centered at the true value τ_n.
2. Identify the most prominent value of $l_{i,j}$ as the best estimate of the LIV parameter, $\hat{\tau}_n$

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

- From application on GRB 090510 for n=1.
- **Histogram:** distribution of photon-pair spectral lags $l_{i,j}$.
- **Thick curve**: Kernel Density Estimate (KDE) of $l_{i,j}$
- **Vertical dashed line:** location of the peak of the KDE used as our $\hat{\tau}_n$.



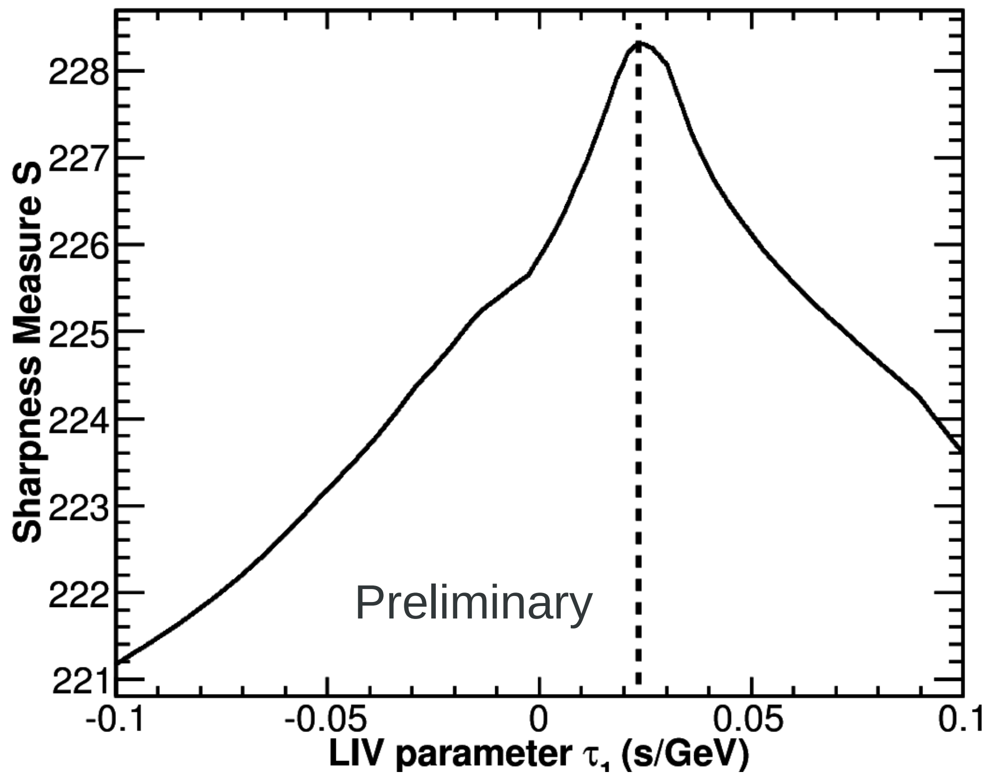
$$\tau_n \equiv \frac{\Delta t}{(E_h^n - E_l^n)} \simeq s_\pm \frac{(1+n)}{2H_0} \frac{1}{E_{QG}^n} \times k_n$$

Method #2. Sharpness Maximization Technique

- LIV spectral dispersion smears light-curve structure → decreases sharpness.
- Search for the degree of dispersion that when it is inversely applied on the data it restores its sharpness, and use it as $\hat{\tau}_n$.
- There are multiple approaches to estimate the sharpness of the light curve:
  - DisCan (Scargle et al. 2008), Energy Cost Function (Albert et al. 2008), Minimal Dispersion Method (Ellis et al. 2008)
- Our measure of the sharpness is:

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

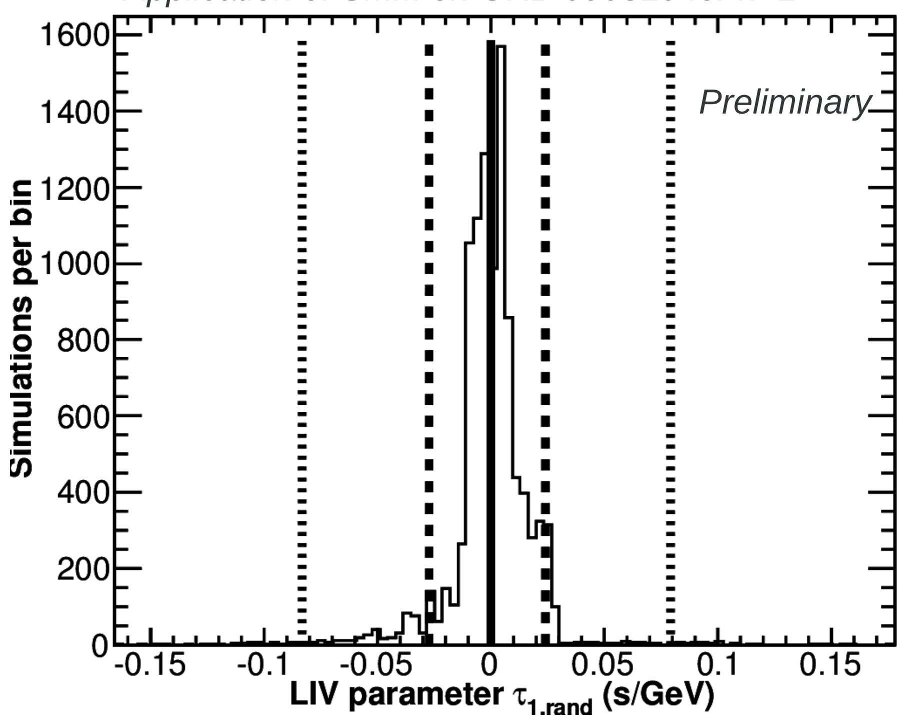
  - where t'_i is the (modified) detection time of the i^{th} photon and ρ is a configurable parameter of our method (selected using simulations).



Confidence Interval Calculation for PV and SMM

- Showed how *a best estimate of* t_n is obtained by PV/SMM.
- How do we construct a confidence interval for t_n?
  1. Apply the methods on a large number of data sets, derived from the actual set by randomizing the associations between event times and energies.
  2. For each randomized data set we produce a $\hat{\tau}_{n,rand}$.
  3. The distribution f_r of $\hat{\tau}_{n,rand}$ is used to approximate the PDF of the error $\epsilon \equiv \hat{\tau}_n - \tau_n$.
  4. From the quantiles of f_r we calculate a confidence interval for τ_n.

Application of SMM on GRB 090510 for n=1



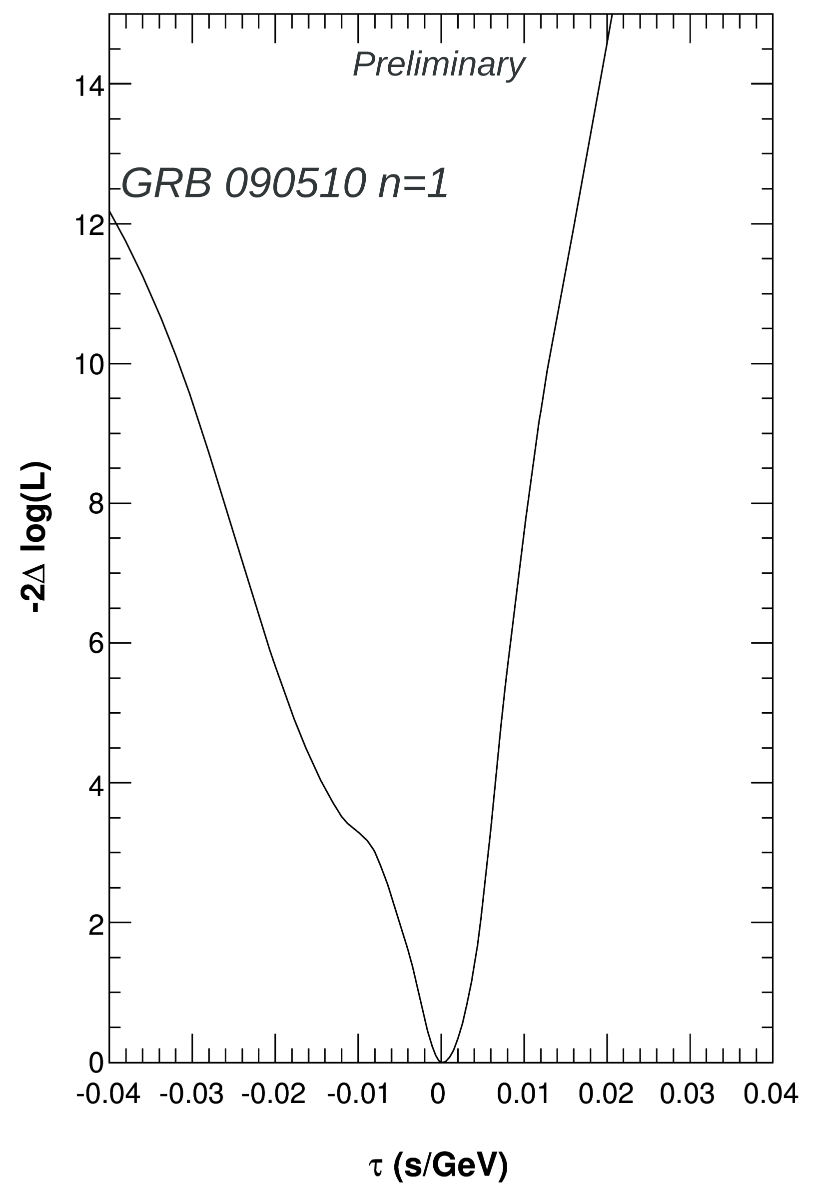
$$
\begin{aligned}
CL &= Pr(q_{(1-CL)/2} < \epsilon < q_{(1+CL)/2}) \\
&= Pr(q_{(1-CL)/2} < \hat{\tau}_n - \tau_n < q_{(1+CL)/2}) \\
&= Pr(\hat{\tau}_n - q_{(1+CL)/2} < \tau_n < \hat{\tau}_n - q_{(1-CL)/2}) \\
&= Pr(LL < \tau_n < UL),
\end{aligned}
$$

Maximum Likelihood Analysis

- Existing method previously applied on LIV studies using AGN
  - *Martinez & Errando 2009, Abramowksi et al. 2011*.

1. Derive a model of GRB data for case of zero LIV.
   a) Light-curve template → obtained from subset of data at low-enough energies for negligible LIV.
   b) Spectral template → obtained from data as is, assuming that LIV does not distort spectrum to a statistically-significant degree.
2. Calculate likelihood of detecting each of the photons in the data given our model and a trial τ_n.
3. Maximize the likelihood to produce best estimate $\hat{\tau}_n$.

- Confidence intervals on τ_n produced by applying method on simulated data sets.

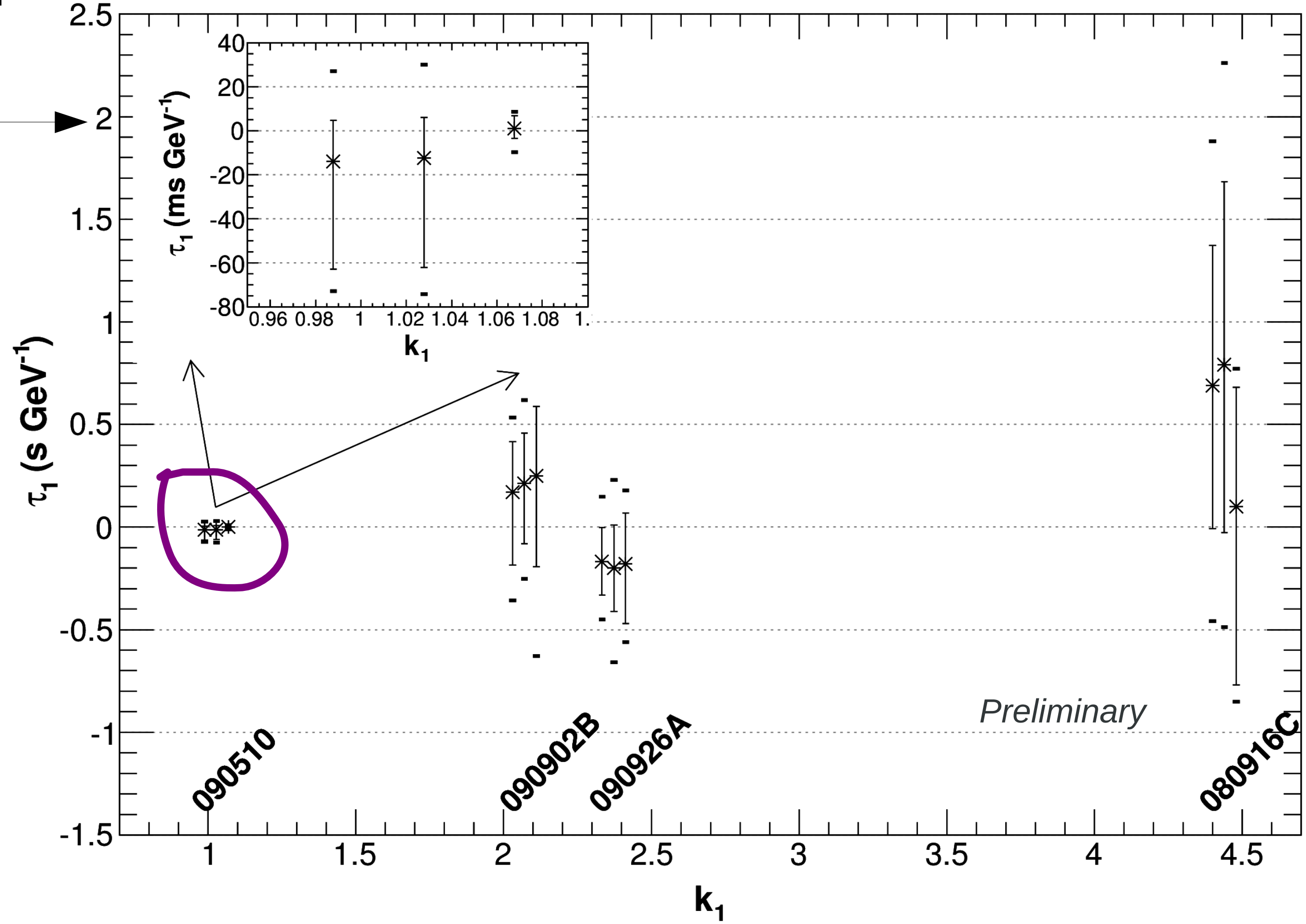


Constraints on τ_1 (linear-in-energy total dispersion)

Best limits from short hard GRB 090510 (tens of ms/GeV)

All confidence intervals compatible with zero dispersion (at 99% CL).

Constraints from the three methods on each GRB are in agreement (overlapping).



- Each triplet → one GRB (left to right : 090510, 090902B, 090926A, 080916C)
- Inside each triplet → our methods (left to right: PV, SMM, ML)
- Markers → best estimate of τ_1.
- Solid-line / external-marker intervals → 90% (99%) two-sided CL confidence intervals
- *Degree of LIV dispersion expected by theory to be proportional to distance parameter k_n*

Accounting for GRB-intrinsic dispersions

- What about GRB-Intrinsic effects?

$$\tau_n = \tau_{GRB} + \tau_{LIV}$$

Methods constrain total degree of dispersion (→ τ_n)

Intrinsic dispersion (nuisance parameter) (→ τ_{GRB})

LIV-induced dispersion (more appropriate to use for producing E_{QG} constraints. (→ τ_{LIV})

- Need to model GRB effects (τ_{GRB}) first → No good models available yet.
  - ➢ We instead choose to model τ_{GRB} conservatively.
- Assume observations dominated by GRB-intrinsic effects
  - – PDF of τ_{GRB} chosen to match possibilities for τ_n allowed by our data.
  - – Are our data compatible with a (say) large positive dispersion?
    - Model τ_{GRB} so that it can reproduce this possibility
- This choice of model for τ_{GRB} produces
  - Symmetric CIs on τ_{LIV}, that correspond to the worst case (yet reasonable) scenario for GRB-intrinsic effects
  - Most conservative (least stringent) overall limits on τ_{LIV} .

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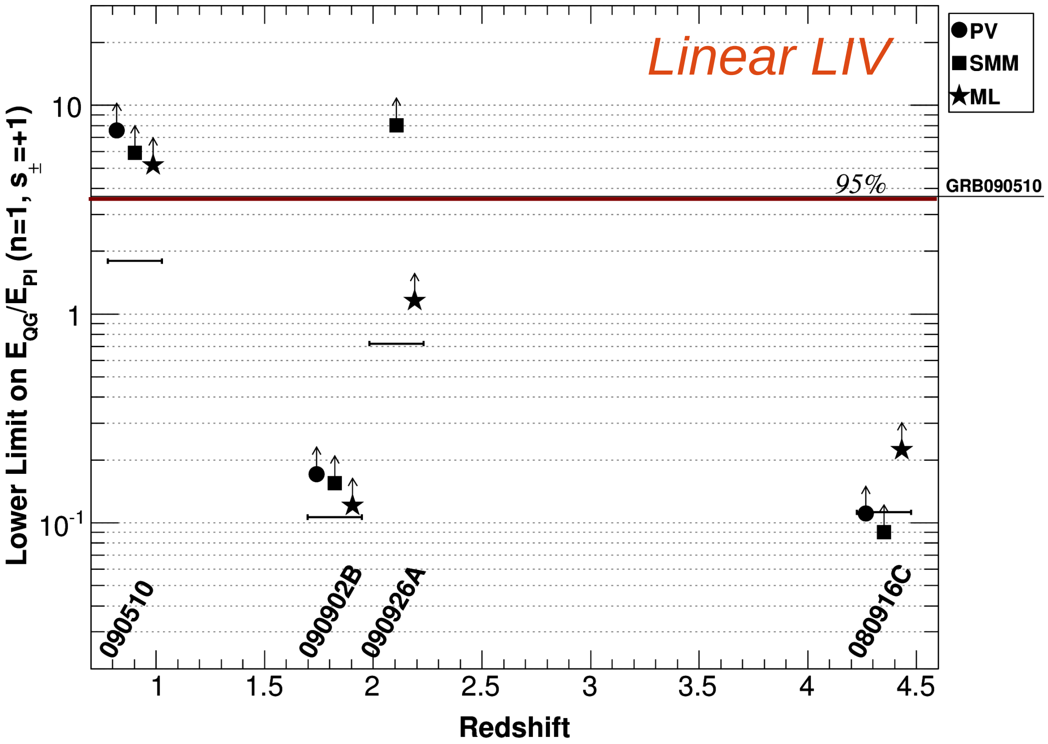
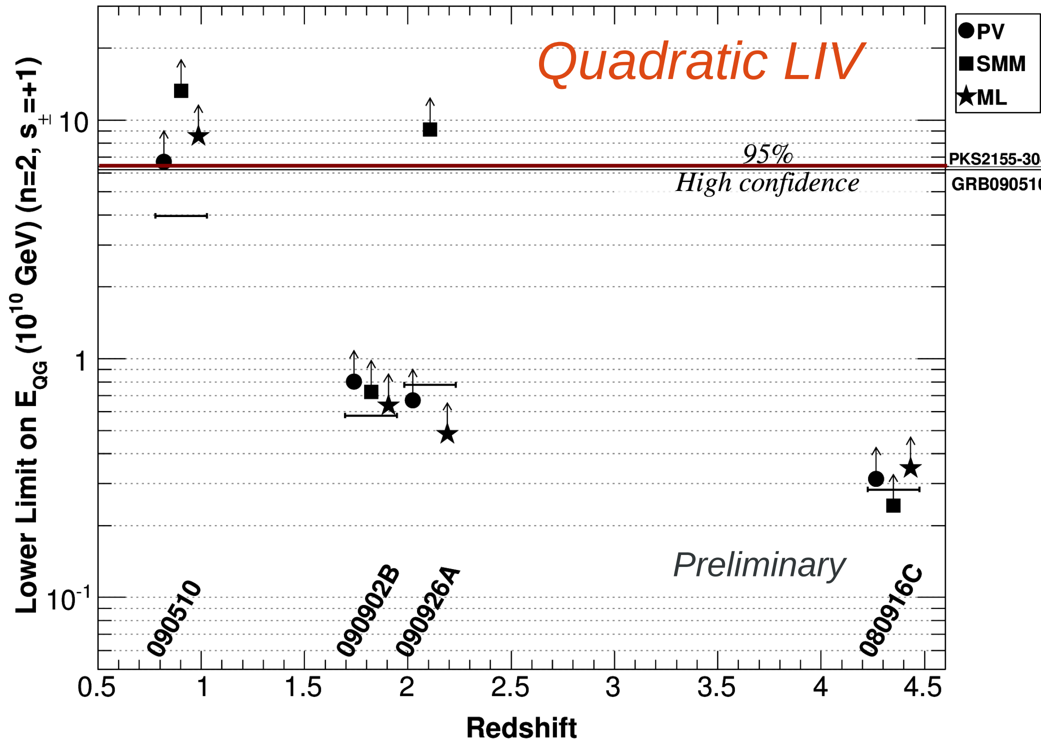
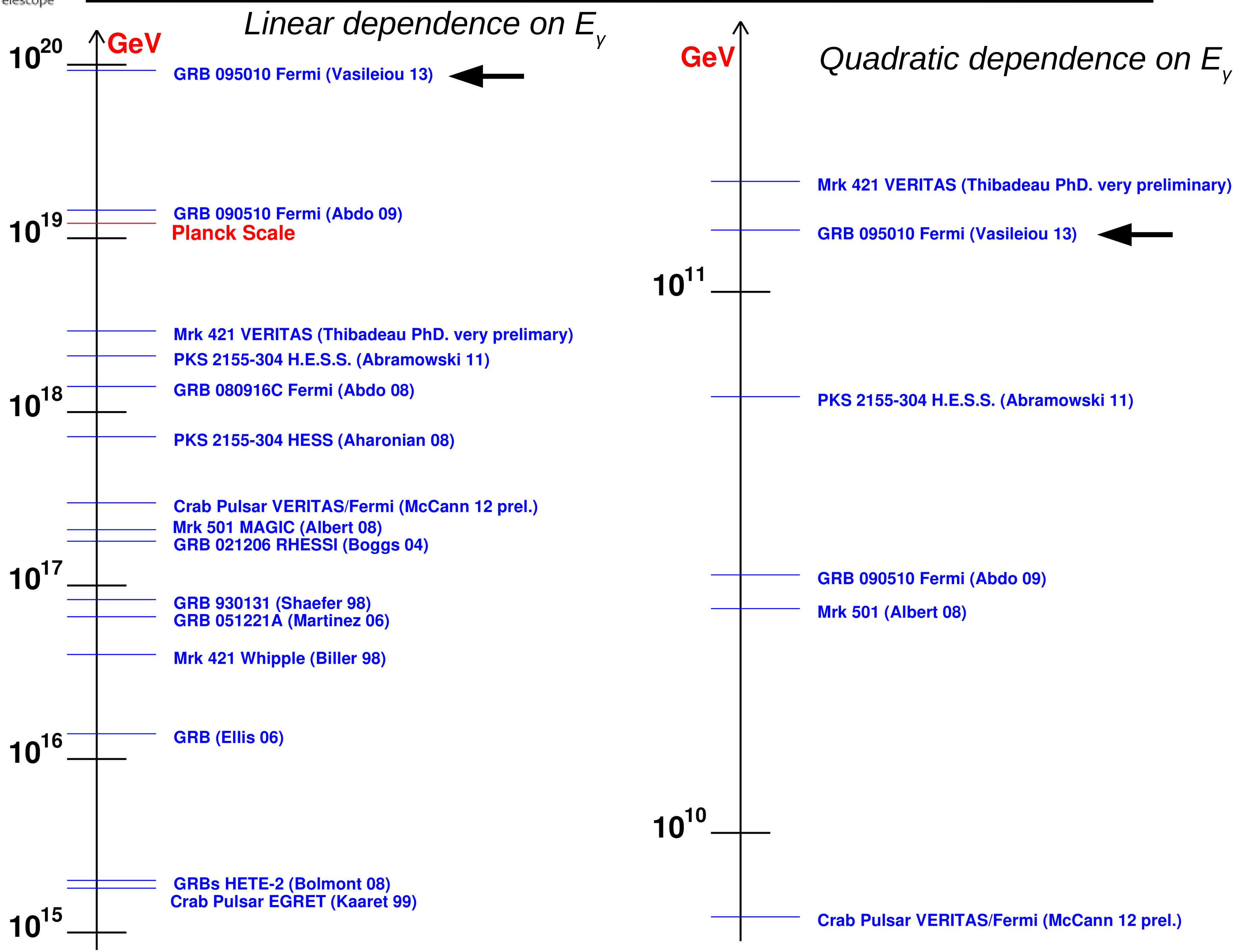
95% lower limits on E_{QG} (subluminal case)





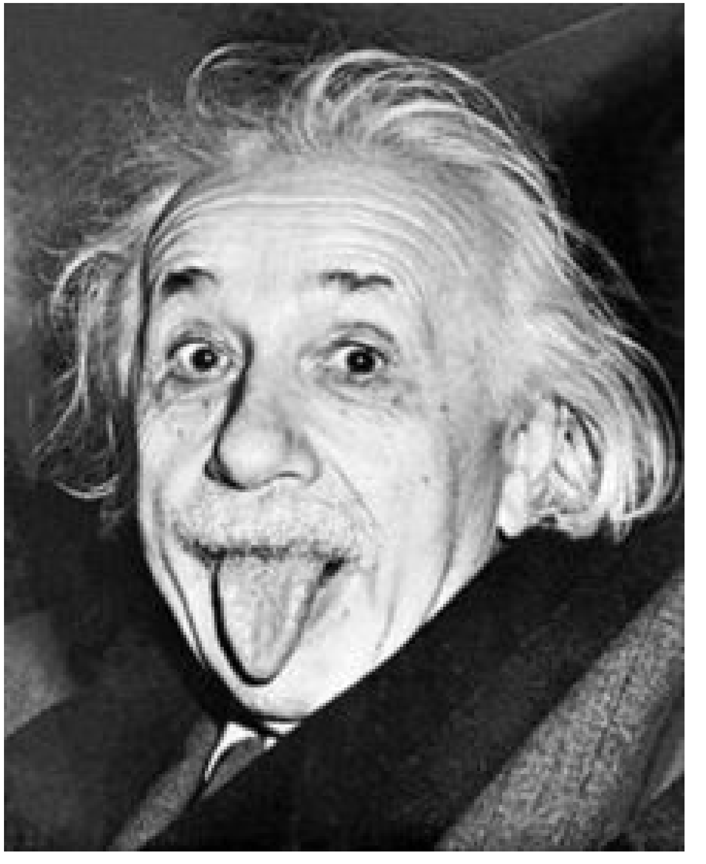
- Markers → our constraints not accounting for GRB-intrinsic effects
- Horizontal lines → current most constraining limits not accounting for GRB-intrinsic effects
  - GRB 090510 – Fermi LAT & GBM (Abdo et al. Nature, 462, 2009)
  - PKS 2155-304 – H.E.S.S. (Abramowski et al., Astroparticle Phys. 34, 2011)
  - We improve these limits by factor of ~ 2–4 depending on LIV type and CL (GRB 090510)
    - n=1: $E_{QG} \gtrsim 8\ E_{Pl}$
    - n=2: $E_{QG} \gtrsim 1.3 \times 10^{11}$ GeV
- Horizontal bars → our average constrain accounting for GRB-intrinsic effects
  - *Still over the Planck scale for n=1: $E_{QG} \gtrsim 2\ E_{Pl}$*

Lower Limits on E_{QG} (subluminal LIV)



Conclusion

- **Numerous studies have searched for evidence of vacuum dispersion but have yet found none.**
- Latest Fermi-LAT analysis (under journal review), produced the most stringent and robust constraints for both linear and quadratic LIV.
- Limits for
  - linear LIV have reached (and surpassed) the physically meaningful boundary of the Planck Mass
  - quadratic LIV are several orders of magnitude below it → need GeV/TeV data!
- The future of searches for LIV-induced vacuum dispersion lies in producing
  - stronger measurements (HAWC/CTA w. Fermi)
  - more robust/reliable measurements (combination of measurements, better source modeling).



THANK YOU!