Exploring Quantum Gravity with Very-High-Energy Gamma-Ray Instruments – Prospects and Limitations[1]

Robert Wagner

Max-Planck-Institut für Physik, D-80805 München, Germany

Abstract. Some models for quantum gravity (QG) violate Lorentz invariance and predict an energy dependence of the speed of light, leading to a dispersion of high-energy gamma-ray signals that travel over cosmological distances. Limits on the dispersion from short-duration substructures observed in gamma-rays emitted by gamma-ray bursts (GRBs) at cosmological distances have provided interesting bounds on Lorentz invariance violation (LIV). Recent observations of unprecedentedly fast flares in the very-high energy gamma-ray emission of the active galactic nuclei (AGNs) Mkn 501 in 2005 and PKS 2155–304 in 2006 resulted in the most constraining limits on LIV from light-travel observations, approaching the Planck mass scale, at which QG effects are assumed to become important. I review the current status of LIV searches using GRBs and AGN flare events, and discuss limitations of light-travel time analyses and prospects for future instruments in the gamma-ray domain.

Keywords: Quantum gravity; Lorentz invariance violation; Active galactic nuclei; BL Lacertae objects; Gamma-ray bursts
PACS: 04.60.-m, 04.60.Bc, 98.54.Cm, 98.70.Rz

INTRODUCTION

Currently we have two extremely successful fundamental theories at hand in physics: general relativity, describing space, time and gravitation; and quantum theory, describing electroweak and strong interactions by means of quantum field theories. The interface of both theories was not explored for a long time, because there have been no experiments that could probe regimes in which both quantum and gravitational effects become important. Still, not only from a philosophical point of view, physicists aspire a unified theory of both, which is usually called quantum gravity (QG). In standard relativistic quantum field theory (QFT), space-time is considered a fixed arena in which physical processes take place. Quite in contrast, QG theories require drastic modifications of space-time when structures approach the QG mass scale [1, 2, 3], often identified with the Planck mass $M_{\text{Planck}} \equiv \sqrt{\hbar c/G_N} = 1.22 \times 10^{19}\,\text{GeV}$. However, the energies at which QG effects lead to deviations from conventional quantum mechanics might lie well below the QG energy scale. As a non-renormalizable interaction gravity may leave distinctive imprints also at energies much below the preferred QG scale, if violating any fundamental symmetry. Thus, we might spot QG effects not only on extreme energy

[1] This artice has been submitted to AIP Conference Series. After it is published, it will be found at `http://link.aip.org/link/?apc`

scales, but use GeV/TeV photons as "low-energy" probes.

An energy dependence of the speed of light in vacuum may arise from photon propagation through a gravitational medium containing quantum fluctuations on distance scales on the order of the Planck length $l_{\mathrm{Planck}} \equiv \sqrt{\hbar G_N / c^3} \approx 10^{-33}$ cm and on timescales $\approx M_{\mathrm{Planck}}^{-1}$. While being smooth at large distances, space-time at short distances of the order of l_{Planck} might show a complex, foamy, structure due to quantum fluctuations [4, 5, 6]. Such Planck-size topological defects, viz. black holes with microscopic event horizons, appearing and evaporating spontaneously, might lead to quantum decoherence and Lorentz invariance (LI) violation. There are numerous formal mathematical approaches to QG. Among the most popular ones are loop QG [7, 3], which is the canonical non-perturbative quantization of general relativity, and superstring theory, which originally has been developed to describe the behavior of hadrons. (See [8] for a review on QG theories). In Liouville string theory [9], modified dispersion relations (MDR) are enabled by higher-order derivatives in effective Maxwell and Dirac equations.

It has been pointed out by Amelino-Camelia et al. [1] that different approaches to QG lead to a similar description of first-order effects of such a time dispersion:

$$\Delta t \simeq \xi \frac{E}{E_{\mathrm{QG}}} \frac{L}{c} \qquad (1)$$

where Δt is the time delay relative to the standard speed of light, ξ is a model-dependent factor of the order 1, E is the energy of the observed radiation, and L is the distance traversed by the radiation. Thus, LI violation (LIV) is expected as a generic signature of approaches to QG. A rather general review on the status of LIV tests is given by Mattingly [10].

A number of predicted new phenomena lead to testable astrophysical effects. Dispersion [1] and vacuum birefringence [3] (leading to polarization-dependent LIV) are purely kinematical effects and require only an MDR and a standard definition of the group velocity. Below, we will particularly elaborate on astrophysical time-of-flight tests of the dispersion relation of photons. Other effects, like anomalous threshold reactions, threshold shifts in standard reactions, or reactions affected by "speed limits" (e.g. synchrotron radiation), need additional assumptions on energy/momentum conservation and dynamics, or on effective QFT, and will not be discussed here. Note that a non-constant speed of light may also occur with maintained Lorentz invariance, e.g., in doubly-special relativity [11]; this underlines the necessity for astrophysical tests of LIV (LIV tests on Earth would yield negative results!).

In the remaining sections, we will review astrophysical probes of QG with high energy γ-rays.

PROBING QUANTUM-GRAVITY WITH PHOTON TIME-OF-FLIGHT MEASUREMENTS

When looking for QG phenomena, we expect deviations from QFT, presumably suppressed by some power of the Planck mass (or the QG mass scale). From a purely phenomenological point of view [1], such effects can be treated using a perturbative expansion, assuming the involved energies $E \ll M_{\rm Planck}$:

$$c^2 p^2 = E^2 \left(1 + \xi \left(\frac{E}{M_{\rm Planck}}\right) + \zeta \left(\frac{E^2}{M^2_{\rm Planck}}\right) + \mathscr{O}\left(\frac{E^3}{M^3_{\rm Planck}}\right) + \ldots\right) \tag{2}$$

Note that an explicit breaking of LI is expected at the Planck mass scale. A linearly-deformed dispersion relation arises, e.g., in noncritical Liouville string theory, while in critical string theory, only quadratic deviations are expected [12]. An MDR implies an energy-dependent speed of light,

$$v = \frac{\partial E}{\partial p} \simeq c\left(1 - \xi\left(\frac{E}{M_{\rm Planck}}\right)\right) \tag{3}$$

or, in other words, the vacuum acquires non-trivial optical properties, namely a refractive index $v(E) = c/n(E)$. This translates into a delay, including cosmological effects,

$$\Delta t = \xi \frac{\Delta E}{M_{\rm QG}} \frac{L}{c} = \xi \frac{\Delta E}{M_{\rm QG}} H_0^{-1} \int {\rm d}z/h(z). \tag{4}$$

To measure any such time delay, very fast transient astrophysical phenomena are required, which provide a time stamp for the simultaneous emission of photons of different energies (Fig. 1). The corresponding figure of merit for QG tests is given by the sensitivity to a given QG mass scale,

$$M_{\rm QG} = \xi \frac{L}{c} \frac{E}{\Delta t} \tag{5}$$

The photon energy E acts as lever arm, implying that both an instrument for measuring γ-ray energies as high as possible, but also astrophysical sources that deliver these energies are advantageous. But also the time resolution of the instrument and the fineness of the structures in the γ-ray signal, described by Δt, are decisive, and the source has to provide enough photon statistics per time as to allow for a binning as small as possible. L denotes the luminosity distance of the source.

QUANTIFICATION OF TIME DELAYS

In the X-ray to VHE γ-ray domain, photon data are characterized by arrival directions, energies, and arrival times of X-rays, gamma rays, or gamma-ray candidates. A very basic method of assessing any time delay of very high energy photons, motivated also by the sparse statistics at these energies, relies on finding peaks in the cross-correlation function of light curves of different photon energy bandpasses [13, 14, 15]. Note, however, that such analyses do not take into account the full available information

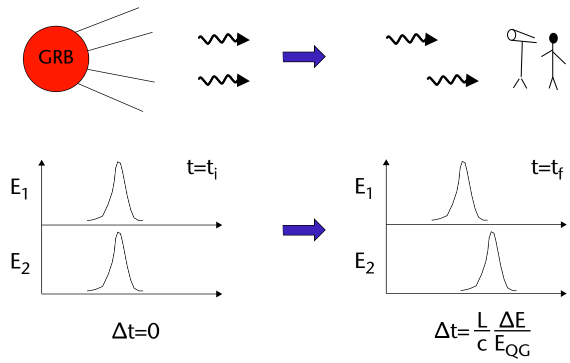

FIGURE 1. In photon time-of-flight measurements, it is assumed that the energy dispersion at the source is known or negligible. Any additional dispersion can then be attributed to the dispersive properties of the vacuum, and this dispersion can be measured by the observer. Original drawing courtesy A. Morselli.

each individual photon carries [16]. Therefore, more appropriate methods have been developed, as summarized in the following.

- In the energy-cost-function method [16], it is assumed that traveling through any dispersive medium will increase the spread of the photon arrival time distribution.[2] Thus, by minimizing the spread of an observed, dispersive-broadened pulse by an “energy cost function”, the original pulse and the dispersion can be reconstructed [16, 17].
- A log-likelihood fit, describing the flare peak form σ_E (which might be assumed, e.g., as Gaussian pulse), the instrumental energy smearing G, the energy spectrum $\Gamma(E_s)$ of the flare, and the observed photon arrival times $F_s(t_s)$ can be applied to the unbinned data [18, 19], e.g.,

$$\frac{\mathrm{d}P}{\mathrm{d}E\,\mathrm{d}t} = k\int_0^\infty \Gamma(E_s)G(E-E_s,\sigma_E(E_s))F_s(t_s)\mathrm{d}E_s. \qquad (6)$$

- Cross-correlation of oversampled light curves [20]. This “modified cross-correlation function” (MCCF) method allows for resolving features (as time delays) in the light curves well below the duration of the flux bins.
- A wavelet analysis suppresses noise in the data and identifies “genuine variation points” [21], which can be attributed to flares and can be used as time stamps in different energy bandpasses. This method is particularly useful if the observational data are noisy and the (multiple or complex) flare structure is not very significant.

[2] Note that the dispersion needs not be source-extrinsic, thus even dispersive regions inside a γ-ray source can be modeled using the ECF approach.

PRESENT REACH USING HIGH-ENERGY GAMMA-RAYS

Pulsars have very distinct periodic light-curve forms, and due to the periodicity, these light curves can be sampled very accurately. In observations of photons up to $E = 2\,\text{GeV}$ from the Crab pulsar, at a distance of 2.0 ± 0.5 kpc [22], using the sub-millisecond timing of EGRET, $\Delta t = 10^{-3}$ s was achieved. With these numbers, a sensitivity to $M_{\text{QG}} \approx 10^{15}\,\text{GeV}$ can be achieved. For active galactic nuclei (AGN; typical distances: in excess of 100 Mpc $\cong 10^{27}$cm), Imaging Air Cerenkov Telescopes (IACT [23, 24, 25]) currently may observe bright γ-ray flares with energies up to around $E_\gamma \approx 10\,\text{TeV}$ with sufficient statistics and a time resolution (given by the AGN flare timescales) of $\approx 50-100\,\text{s}$. This enables a sensitivity up to the Planck energy scale, $M_{\text{QG}} \approx 10^{19}\,\text{GeV}$. In the absence of a linear term in the MDR, the quadratic reach would be around $M_{\text{QG}} = 6 \times 10^9\,\text{GeV}$. Gamma-ray bursts, at distances beyond 7000 Mpc, will be routinely observed by *Fermi* [26] at energies up to $\mathscr{O}(\text{GeV})$, which will yield a sensitivity of $M_{\text{QG}} \approx 10^{19}\,\text{GeV}$. Note, however, that current GRB studies are restricted to $M_{\text{QG}} = 10^{17}\,\text{GeV}$, as until recently only $\Delta E \approx 100\,\text{keV}$ was available ($M_{\text{QG}} = 10^6\,\text{GeV}$ in the quadratic case).

ASTROPHYSICAL VHE GAMMA-RAY SOURCES

Pulsed emission from the Crab nebula

The Crab pulsar has a pulsation period of 33.18 ms. As its pulsations are well aligned in time from radio through X-ray wavelengths, it seems likely that photons of different energies are produced nearly simultaneously. Using the sub-ms timing of the EGRET experiment, it could be shown [27] that > 2 GeV photons trail those at $70-100$ MeV by no more than 0.35 ms (95% c.l.), implying $M_{\text{QG}} > 1.8 \times 10^{15}\,\text{GeV}$. Recently, pulsed emission from the Crab was also detected at energies up to 60 GeV [28, 29]: About 8,500 γ-ray events form a signal at the 6.4-σ significance level. This observation might yield a lower limit for quantum gravity effects of $M_{\text{QG}} \approx 1.2 \times 10^{16}\,\text{GeV}$ [30], exceeding the limit given by the EGRET-Crab analysis.

Gamma-Ray Bursts

Gamma-ray bursts (GRBs; [31]) have rather complex individual time profiles. Once a relativistic fireball is created in the gigantic explosions thought to be the origin of GRBs, the physics ought to be insensitive to the nature of the progenitor object. GRBs have been found at redshifts exceeding $z = 5$ (7% of the presently known GRBs; the average redshift is $z = 2.8$). Thus GRBs seem to be a natural proxy to test QG predictions. The key issue is to distinguish possible QG signatures from intrinsic delays, particularly as delays in GRBs have been observed. QG effects should increase predictably with the distance of the individual GRB. The accessible energies, however, have been smaller than or at most some GeV; IACT, which are sensitive in the above 30 GeV region, are still awaiting the first GRB detection [32, 33]. An additional complication arises from the fact that establishing the distance of GRBs is not trivial and works only for a fraction of the observed GRBs. The strongest QG constraint from an individual GRB is that from GRB 930229 [34], where during a rise time of $220 \pm 30\mu$s the dispersion of photons was measured to be $\Delta t < 25$ ms at energies $\Delta E = 30$keV – 80MeV, yielding $M_{QG} > 8.3 \times 10^{16}$ GeV. The caveat of this observation is that GRB 930229 has no measured redshift(!), thus with an assumed peak flux of 10^{57} photons s^{-1} and the peak width–redshift relation [35] a distance $D = 260$ Mpc was inferred. For GRB 051221A, which occurred in a galaxy at $z = 0.55$, no time delay of photons between 15 and 350 keV was observed [36], leading to a limit of $M_{QG} > 6.6 \times 10^{16}$ GeV.

A more robust method is to study large samples of GRB. In [37], a total of 36 GRBs observed by BATSE (9 bursts), *HETE-2* (15 bursts), and *Swift* (11 bursts) up to $z = 6.3$ was used. The energy difference of photons in that sample is around 200 keV, and to account for possible source effects, a "universal source uncertainty" of 54 ms was accounted for. A limit of $M_{QG} > 0.9 \times 10^{16}$ GeV was deduced.

Fermi Large-Area Tracker (LAT) and Gamma-Ray Bursts. In LAT, around 250 bursts per year are expected [38] to be detected, and about 50 of them will survive a high-energy cut, i.e., contain $>$ 550 MeV photons. LAT itself should detect around 15 bursts without Gamma-ray Burst Monitor triggers. Kuehn et al. [39] simulated the LAT response to GRB photons, focusing on the prompt GRB emission. Due to the wide field of view, LAT in contrast to the TeV instruments is quite unique in detecting prompt GRB emission. For the simulations, spectral indices have been taken from BATSE and extrapolated to LAT energies. Even with a binned analysis, a simultaneous fit to multiple GRBs (at $z = 1$) was shown to have a sensitivity at 10^{19} GeV. An alternative method [17] also has this sensitivity. Recently, the LAT collaboration reported the first detection of high-energy photons from three GRBs [40], and used the strongest burst, GRB 080916C, to derive a lower QG energy scale limit of $M_{QG} > (1.5 \pm 0.2) \times 10^{18}$ GeV.

Flares from Active Galactic Nuclei

The study of high energy ($E \gtrsim 100$ MeV) γ-ray emission from active galactic nuclei (AGN) is one of the major goals of space-borne and ground-based γ-ray astronomy.

The vast majority of the currently known VHE γ-ray emitting AGNs [41] are blazars [42],[3] a subclass characterized by high variability over the whole electromagnetic spectrum, a characteristic peak in their spectral energy distributions (SEDs) from nonthermal synchrotron emission, and a second peak at γ-ray energies. In synchrotron-self-Compton (SSC) models it is assumed that the observed γ-ray peak is due to the inverse-Compton (IC) emission from the accelerated electrons up-scattering previously produced synchrotron photons to high energies [43]. In hadronic models, instead, interactions of a highly relativistic jet outflow with ambient matter, proton-induced cascades, or synchrotron radiation off protons, are responsible for the high-energy photons.

The duty cycle of *Fermi* enables a quasi-continuous monitoring of blazar flaring activity (also monitoring programs by IACTs are in place, [44]), while the high sensitivity

[3] See `http://www.mpp.mpg.de/~rwagner/sources/` for an up-to-date source list.

of current IACT is advantageous for understanding the particle acceleration mechanisms in flares, the origin of the high-energy γ-rays, as well as the relations between photons of different energies (from radio to VHE; particularly between the two emission populations [45]).

The Whipple QG Limit from a Mkn 421 Flare

The first rapid flare from a TeV blazar was observed by the Whipple telescope from Markarian (Mkn) 421 ($z = 0.030$) on 1996 May 15 [46]. The peak of the flare is concentrated in one 280 second bin, and as there were no > 2 TeV γ-rays observed outside this bin, it was concluded that the γ-rays < 1 TeV and > 2 TeV are in step with $>$95% probability [14]. This observation translates in a lower limit $M_{\mathrm{QG}} > 4 \times 10^{16}$ GeV.

The July-2005 Flares of Mkn 501

MAGIC [23] recorded fluxes exceeding four times the Crab-nebula flux from Mkn 501 ($z = 0.034$) in 2005, and revealed rapid flux changes with doubling times as short as 3 minutes or less [15]. For the first time, short ($\approx$ 20 minute) VHE γ-ray flares with a resolved time structure could be used for detailed studies of particle acceleration and cooling timescales. The two flares behaved differently (Fig. 2): While the 2005 June 30 flare is only visible in 250 GeV–1.2 TeV, the 2005 July 9 flare is apparent in all energy bands (120 GeV to beyond 1.2 TeV). Additionally, at a zero-delay probability of $P = 0.026$, a marginal time delay $\Delta t = \tau_l E$ with $\tau_l = (0.030 \pm 0.012)\,\mathrm{s\,GeV^{-1}}$ towards higher energies was found using two independent analyses, both exploiting the full statistical power of the dataset (see [16, 19] for details). For a quadratic effect (vanishing first-order term in eq. 2), $\Delta t = \tau_q E^2$ with $\tau_q = (3.71 \pm 2.57) \times 10^{-6}\,\mathrm{s\,GeV^{-2}}$ is obtained correspondingly. Several explanations for this delay have been considered up to now:

1. Electrons inside the emission region moving with constant Doppler factor are gradually accelerated to energies that enable them to produce corresponding γ rays [15].
2. The γ-ray emission has been captured in the initial acceleration phase of the relativistic blob in the jet, which at any point in time radiates up to highest γ-ray energies possible [47].
3. An one-zone SSC model, which invokes a brief episode of increased particle injection at low energies [48].
4. When assuming a simultaneous emission of the γ-rays (of different energies) at the source at $z = 0.034$, an observed time delay can be converted in QG mass scales $M_{\mathrm{QG1}} = 1.445 \times 10^{16}\mathrm{s}/\tau_l$ and $M_{\mathrm{QG2}} = 1.222 \times 10^{8}(\mathrm{s}/\tau_q)^{1/2}$, respectively. As the measured time delay is marginal, they translate in a lower limit of $M_{\mathrm{QG1}} > 0.21 \times 10^{18}$ GeV (95% c.l.) for the linear case and $M_{\mathrm{QG2}} > 0.26 \times 10^{11}$ GeV (95% c.l.) for a quadratic dependence on energy [16]. Results for the 2005 June 30 exhibit a similar sensitivity, but this flare is not very significant. Both limits increase further if any delay towards higher energies in the source itself is present.

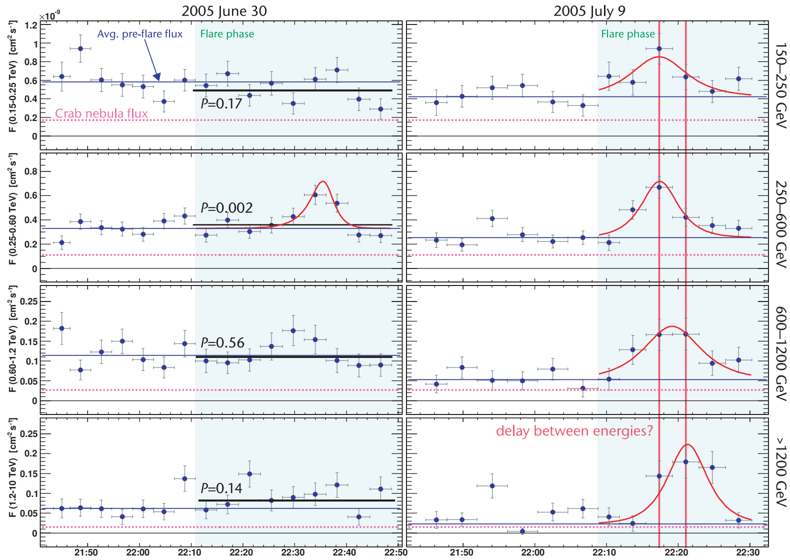

FIGURE 2. Light curves for the observations on 2005 June 30 (left panels) and July 9 (right panels) [15] with a time binning of 4 minutes, and separated in different energy bands ranging from 150 GeV to >1.2 TeV. For comparison, the Crab nebula emission level is shown. The data are divided in into 'stable' and 'variable' emission. The probabilities given in the left panels are for fits with constant lines in the 'variable' region. Only the constant-line fit in the energy range 0.25–0.6 TeV is not satisfactory. In the right panels, the 'variable' regions were fitted with a flare model. A more quantitative photon-by-photon analysis of these data was performed in [16].

The 2006 Giant PKS 2155–304 Flare

In the night of 2006 July 28, the H.E.S.S. array [24] observed a giant (> 10 Crab) outburst of the blazar PKS 2155–304, almost four times as distant as Mkn 421 and Mkn 501 ($z = 0.116$). Also in this case, fast variability on the order of 3 minutes and an energy coverage up to a few TeV is given [49]. For searching for time delays, a MCCF method [20] and a wavelet method were employed, both yielding a zero time delay within errors, and thus $\tau_l > 0.073\,\mathrm{s\,GeV}^{-1}$ and $\tau_q = 45 \times 10^{-6}\,\mathrm{s\,GeV}^{-2}$, respectively (95% c.l.). This translates into lower limits of $M_{\mathrm{QG1}} > 0.52 \times 10^{18}$ GeV and $M_{\mathrm{QG2}} > 0.014 \times 10^{10}$ GeV.

Source-Intrinsic Lags and the Blazar Ensemble 2008

Most acceleration and cooling mechanisms scale in energy, although there is no definite need for a strong energy dependence. In X-ray observations, however, soft and hard lags have been observed (most recently, e.g., by [50]), and lead to characteristic loops in flux–spectral hardness plots [51]. Those diagnostic plots may also be used in the VHE regime [52]. Intrinsic lags may strongly depend on the individual blazar and even on the individual flare, as the three AGN outburts used for QG searches have proven. With our current understanding of blazar physics, intrinsic delays cannot be corrected for individually. They will, however, not scale with the source distance, so

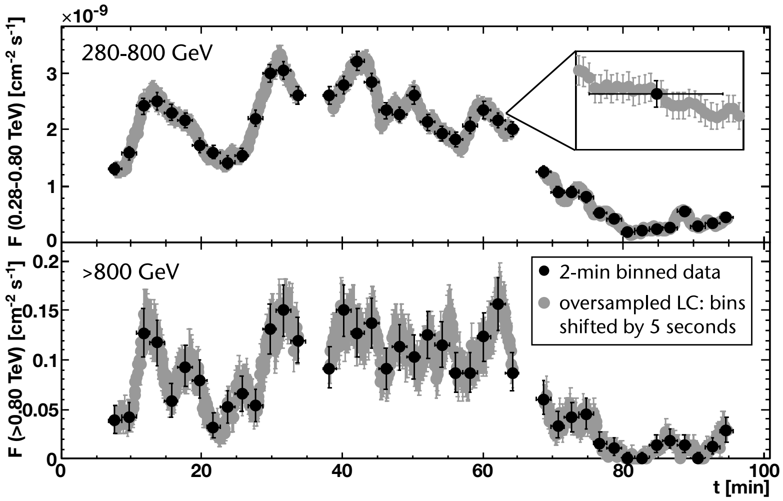

FIGURE 3. The PKS 2155–304 flare [49]. Black points show the light curves measured between 280 – 800 GeV (upper panel) and >800 GeV (lower panel), binned in two-minute time intervals. Gray points show the oversampled light curve using the MCCF method [20], for which the two-minute bins are shifted in units of five seconds. The inlay in the upper panel illustrates this in a zoom, where the horizontal error bar shows the duration of the bin in the original light curve.

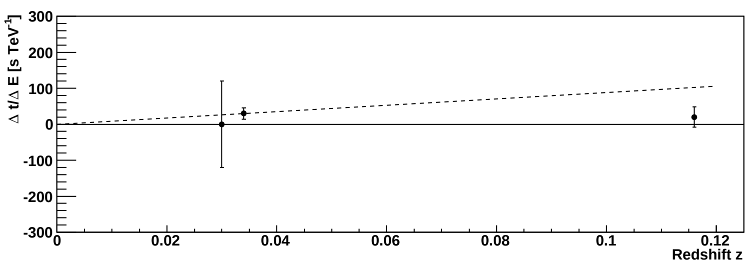

FIGURE 4. The blazar flare ensemble 2008: Three limits on the energy dispersion as measured in flares of Mkn 421, Mkn 501, and PKS 2155–304. If the marginal time delay in Mkn 501 is extrapolated, it is found to be incompatible with the null result for PKS 2155-304.

robust conclusions on QG effects ultimately require the study of samples of very fast flaring objects at different redshifts. These are expected to be observed by the current and next-generation [53] IACTs and *Fermi* thanks to the high sensitivity of these instruments. Note that multi-wavelength observations of flares are complementary to QG searches and essential, as they will allow to study possible source-intrinsic mechanism and effects and enhance the understanding of AGN source physics. Any such understanding will enhance QG limits.

Note further that obviously source-instrinsic and QG effects may cancel out, leading to an observation of a null effect. This scenario has been dubbed “conspiracy of Nature” [14] and while it is still conceivable that both effects do exhibit the same timescale, but the opposite sign, also here a sample of blazar flares from blazars at different redshifts will help to separate an eventual QG effect from blazar physics. Fig. 4 shows the current blazar flare ensemble observed in VHE γ-rays.

THE FUTURE: PROSPECTS AND LIMITATIONS

High energy observations of fast pulses enable measurements of the energy dependence of the speed of light. Such a possible LIV is predicted by many QG models. An energy-dependent lag of TeV γ-rays on the 2.5-σ level has been observed in a flare of the blazar Mkn 501. The constraints derived from the ≈ 4 times more distant blazar PKS 2155–304, however, are consistent with a null result, as are robust ensemble analyses from GRBs at a lower $M_{\rm QG}$ sensitivity. All in all, VHE observations of blazars constitute the most stringent limits on a linear (PKS 2155–304) and quadratic (Mkn 501) energy dependence in the speed of light. Future improvements in VHE searches may be expected from:

- Δt – Even the high time-resolution IACTs have not yet explored the shortest blazar variability timescales, although high photon statistics are available; e.g., more than 10,000 photons in the PKS 2155–304 flare. Thus, only "brighter flares" or even more sensitive instruments will help to improve on Δt. Observing faster variations, or flares/subflares with shorter timescales (say 30 seconds instead of currently 3 minutes), might increase the QG sensitivity by about $\times 5$. GRBs with their fine time structures are interesting to observe, particularly with *Fermi*.
- ΔE – Gaining access to higher energy γ-rays enlarges the lever arm in the QG sensitivity. However, the bright VHE blazars usually exhibit rather steep spectra, $\sim E^{-2.5} \ldots E^{-3.5}$ [41], thus it is rather unlikely to gain an order of magnitude more sensitivity, perhaps a factor $\times 3$ is feasible.
- L – It it difficult to improve much using the known bright, close-by blazars, as we have not yet seen flares exceeding the 15-Crab level, even not during the giant 1997 flare of Mkn 501 [54]; More distant blazars, however, seem to exhibit steep spectra (e.g. 3C 279 [55, 23]), which are expected due to γ-ray attenuation by the extragalactic background light [56, 57, 55, 58]. A major flare in, e.g., 3C 279, extending the distance from $z = 0.12$ to 0.54, corresponds to a gain by $\times 5$ in sensitivity. As discussed above, for robust ensemble studies, we need to find flares at various redshifts; thus, improved IACT facilities [53] to reach lower energies than the currently reachable (≈ 30 GeV by MAGIC; ≈ 100 GeV by VERITAS/H.E.S.S.).

The overall increase to be hoped for with future IACT observations is thus about $\times 70$.

Fermi will regularly detect distant ($z > 1$) GRBs, thus collecting statistics and be able to build a robust GRB sample. This will increase the sensitivity for such a robust GRB study by about $\times 20$.

ACKNOWLEDGMENTS

My thanks go to A. S. Sakharov and the referee for helpful comments regarding this manuscript, as well as to the MAGIC group at MPI for Physics for its excellent support. I am grateful for financial support by the Max Planck Society.

REFERENCES

1. G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, S. Sarkar 1998, *Nature*, 393, 319.
2. L. J. Garay 1998, *Phys. Rev. Lett.*, 80, 2508.
3. R. Gambini, J. Pullin 1999, *Phys. Rev. D*, 59, 124021.
4. J. A. Wheeler 1963, in: Relativity, Groups and Topology, (New York: Gordon and Breach), 1.
5. S. Hawking 1982, *Commun. Math. Phys.*, 87, 395.

6. J. Ellis, J. Haegelin, D. V. Nanopoulos, M. Srednicki 1984, *Nucl. Phys. B*, 241, 381.
7. L. J. Garay 1995, *Int. J. Mod. Phys. A*, 10, 145.
8. L. Smolin, preprint (arXiv:hep-th/0303185).
9. J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, 1999, preprint (arXiv:gr-qc/9909085).
10. D. Mattingly 2005, *Living Rev. Rel.*, 8, 5.
11. J. Magueijo, L. Smolin 2002, *Phys. Rev. Lett.*, 88, 190403.
12. J. Ellis, N. E. Mavromatos, D.V. Nanopoulos 2008, *Phys. Lett. B*, 665, 412.
13. D. L. Band 1997, *Astrophys. J.*, 486, 928.
14. S. D. Biller et al. (Whipple Collab.) 1999, *Phys. Rev. Lett.*, 83, 2108.
15. J. Albert et al. (MAGIC Collab.) 2007, *Astrophys. J.*, 669, 862.
16. J. Albert et al. (MAGIC Collab.) and J. Ellis et al. 2008, *Phys. Lett. B*, 668, 253.
17. J. D. Scargle, J. P. Norris, J. T. Bonnell 2008, *Astrophys. J.*, 673, 972.
18. R. Lamon 2008, *J. Cosm. Astropart. Phys.*, 8, 22.
19. M. Martínez, M. Errando 2008, *Astropart. Phys.* submitted, preprint (arXiv:0803.2120 [astro-ph]).
20. T.-P. Li, J.-L. Qu, H. Feng, L.-M. Song, G.-Q. Ding, L. Chen 2004, *Chin. J. Astron. Astrop.*, 4, 583.
21. J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov 2003, *Astron. Astrophys.*, 402, 409.
22. D. L. Kaplan, S. Chatterjee, B. M. Gaensler, J. Anderson 2008, *Astrophys. J.*, 677, 1201.
23. J. Rico, R. M. Wagner (MAGIC Collab.) these proceedings.
24. E. de Oña-Wilhelmi (H.E.S.S. Collab.) these proceedings.
25. M. Beilicke (VERITAS Collab.) these proceedings.
26. J. McEnery these proceedings.
27. P. Kaaret, 1999, *Astron. Astrophys.* 345, 32.
28. E. Aliu et al. (MAGIC Collab.), 2008, *Science*, 322, 1221.
29. M. Shayduk (MAGIC Collab.), these proceedings.
30. H. Anderhub et al. (MAGIC Collab.), in preparation.
31. T. Piran 2005, *Rev. Mod. Phys.*, 76, 1143; A. Dar, A. De Rújula 2003, *Phys. Rept.*, 405, 203.
32. J. Albert et al. (MAGIC Collab.) 2007, *Astrophys. J.*, 667, 358; 2006, ibid., 641, L9.
33. P. H. Tam, S. J. Wagner, G. Pühlhofer (H.E.S.S. Collab.) 2006, *Nuovo Cimento B*, 121, 1595.
34. B. E. Schaefer 1999, *Phys. Rev. Lett.*, 82, 4964.
35. E. E. Fenimore, R. I. Epstein, C. Ho, R. W. Klebesadel, J. Laros 1992, *Nature*, 357, 140.
36. M. R. Martínez, T. Piran, Y. Oren 2006, *J. Cosm. Astropart. Phys.*, 5, 17.
37. J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov, E. K. G. Sarkisyan 2006, *Astropart. Phys.*, 25, 402; 2008, ibid., 29, 412.
38. N. Omodei these proceedings.
39. F. Kuehn, R. Hughes, B. Winer (GLAST-LAT Collab.) 2007, in: Proc. CPT and Lorentz Symmetry, p. 214; doi:10.1142/9789812779519_0031
40. A. Bouvier 2008, talk given at 24th Texas Symposium on Relat. Astrophysics, Vancouver, Canada.
41. R. M. Wagner 2008, *Mon. Not. R. Astr. Soc.*, 385, 119.
42. P. Padovani, P. Giommi 1995, *Astrophys. J.*, 444, 567.
43. L. Maraschi, G. Ghisellini, A. Celotti 1992, *Astrophys. J.*, 397, L5.
44. K. Satalecka, C.-C. Hsu, E. Bernardini, G. Bonnoli, F. Goebel, E. Lindfors, P. Majumdar, A. Stamerra, R. M. Wagner (MAGIC Collab.) these proceedings.
45. R. M. Wagner 2008, PoS(BLAZARS2008)013.
46. J. Gaidos et al. (Whipple Collab.) 1996, *Nature*, 383, 319.
47. W. Bednarek, R. M. Wagner 2008, *Astron. Astrophys.*, 486, 679.
48. A. Mastichiadis, K. Moraitis 2008, *Astron. Astrophys.*, 491, L37.
49. F. Aharonian et al. (H.E.S.S. Collab.) 2008, *Phys. Rev. Lett.*, 101, 170402.
50. G. Fossati et al. 2008, *Astrophys. J.*, 677, 906.
51. J. G. Kirk, F. M. Rieger, A. Mastichiadis 1998, *Astron. Astrophys.*, 333, 452.
52. M. Georganopoulos, J. G. Kirk, A. Mastichiadis 2001, *Astrophys. J.*, 561, 111.
53. M. Teshima these proceedings.
54. F. A. Aharonian et al (HEGRA Collab.) 1999, *Astron. Astrophys.*, 342, 69.
55. J. Albert et al. (MAGIC Collab.) 2008, *Science*, 320, 1752.
56. D. Mazin these proceedings.
57. M. G. Hauser, E. Dwek 2001, *Ann. Rev. Astron. Astrophys.*, 39, 307.
58. F. Aharonian et al. (H.E.S.S. Collab.) 2006, *Nature*, 440, 1018.