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Constraints on Quantum Gravity from Fast TeV Gamma-Ray Flares of AGN

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Abstract: VHE observations of the Blazar PKS 2155-304 at redshift z=0.116 with H.E.S.S. are used to constrain the energy dependent time-delay that might result from modified dispersion relations expected from quantum gravity induced violations of Lorentz Invariance (LI). PKS 2155-304 underwent a strong outburst in July/August 2006 during which its peak flux increased onehundred-fold above the quiescent level. Rise-times as short as 67 sec and high photon numbers permit searches for energy-dependendent time-delays as short as tens of seconds. We find a time-delay of less than 60 sec between lightcurves different energy bands above 200 GeV (with a typical mean difference in photon energy of 500 GeV). Given the distance of the source, we constrain the emergence of quantum gravity induced breakdown of Lorentz Invariance to an energy scale of several 10^{17} GeV, a few percent of the Planck mass $M_{\rm Planck}$.

Testing Quantum Gravity

Most quantum gravity models imply the existence of a fundamental length scale. Since this would be independent of the reference frame, the existence of such a scale violates LI. Assuming quantum gravity to have a semiclassical limit, one can search for falsifiable predictions from quantum gravity to low orders in $E/E_{\rm Planck}$ (e.g. [2, 3, 4, 5]). One of the predictions of many quantum gravity models is a modification of the standard photon dispersion relation to
$E^2 = k^2(1 + \xi_1(k/M) + \xi_2(k/M)^2 + ...)$.
Predictions differ in detail. While, e.g., k>0 avoids superluminal propagation, loop-gravity does not respect this and consequently allows dispersion relations of either sign [6]. Some models suppress odd powers of k/M by selection rules (e.g. rotational invariance in a preferred frame) [7] and thus make the quadratic term the leading deviation from classical dispersion.
Any of the dispersion relations can be tested by comparing the time of flight of photons having different energy. Since $E_\gamma << E_{\rm Planck}$ for all experiments, sources at cosmological distances must be used.
It should be pointed out that other tests of the validity of LI using high energy photons have also been suggested [2, 4, 5].
The most common experimental test for deviations from the classical dispersion relation have been proposed for Gamma Ray Bursts. These are bright, short-lived (0.1-100 sec) flares of hard X-ray/soft γ-ray radiation, which often show substructure on time-scales of milliseconds. Afterglow emission associated with the GRB proper has enabled redshift measurements, revealing distances out to z>5. Applying different techniques for determining the lag between photons of different energies in the case of different burst, different authors arrived at a range on upper limits. While Ellis et al. [3, 8], using wavelets on binned data, found upper limits of 6.9 and 9 10^{15}, GeV, respectively, Lamon et al. [9] challenged this approach and argued for Maximum Likelihood on individual photon arrival times and concluded that the limit was no tighter than about 10^{14} GeV. Bolmont et al. [10] arrived at a similar conclusion with lower limits of a few 10^{14} GeV determined using GRBs observed by HETE. One of the main limitations of GRBs is a luminosity (and hence distance-) dependent intrin-

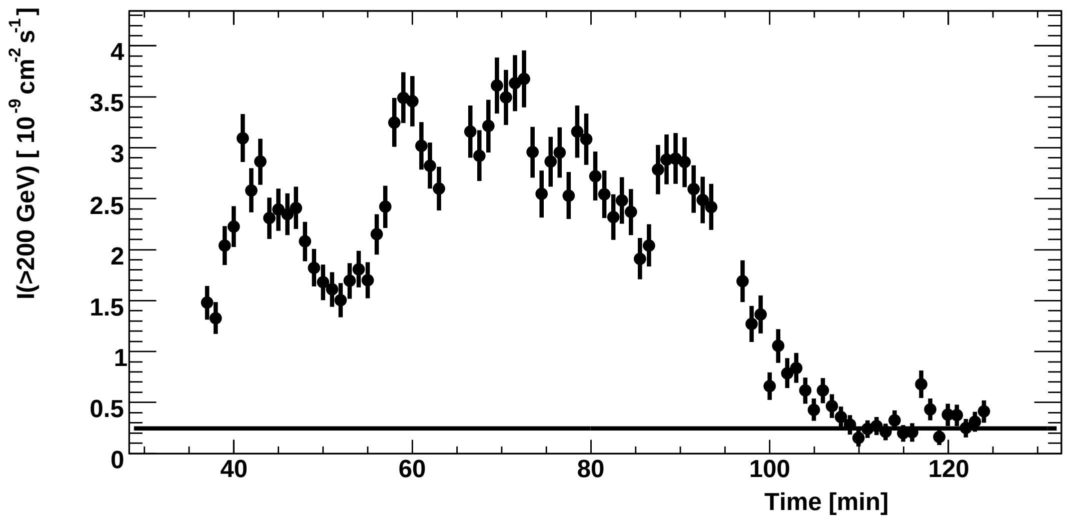

Figure 1: Light-curve of PKS 2155-304 (integral flux above 200 GeV) during MJD 53944 (part of the big flare in July/August 2006). The light curve is binned into 1 minute intervals (typically about 60 photons per bin) and is continuous apart from two gaps separating the 28 min runs of uninterrupted data acquisition. The solid line indicates the flux level of the Crab Nebula. The light-curve can be described by five generalized Gaussian curves with significant kurtosis [1]. Rise- and decay timescales vary between 67 sec and 657 sec.

sic lag of low energy photons with respect to high energy photons. These delays, frequently seen in nearby bursts, where quantum gravity imprinted delays would be small, are not quantitatively understood in terms of self-consistent szenarios, but modeled in a statistical way in the discussions listed above.

An alternative test of modified dispersion relations can be performed using VHE observations of Blazars. This subclass of radioloud AGN is the dominant class of extragalactic sources of VHE radiation. With photon energies 6 to 7 orders of magnitude higher, they can outperform GRBs if variability time-scales or order 100 sec come within reach. Blazars cannot be observed at VHE energies to redshifts beyond a few tenths, because the TeV photons pair-annihilate on the diffuse, extragalactic IR background, effectively limiting the transparency to an energy-dependent threshold of order z≈.1 to z≈.5 for present-day instruments. A first attempt to constrain LI using Blazars [11] arrived at a limit of 4 10^{16} GeV using the bunching of 4 photons above 2 TeV into one 280-sec bin during a flare in Mrk 421.

An extraordinary VHE outburst in Blazar PKS 2155-304

PKS 2155-304 is one of the brightest Blazars at all wavelengths. It is the brightest TeV emitting Blazar in the southern hemisphere and has been the subject of intense studies by the HESS experiment [12], [13]. A recent compilation of the behaviour of this source has been presented elsewhere at this conference (Punch et al., these proceedings). During July and August 2006 PKS 2155-304 underwent a dramatic outburst in the VHE domain ([1], Benbow et al., these proceedings). The flux increased by about two orders of magnitude over its low state, resulting in very high count statistics (on-source count rates about 1 Hz) which permit very fine binning of the light-curve with high photon statistics. Figure 1 gives a light-curve binned in intervals of one minute. The variations can be described by 5 generalized Gaussian flares

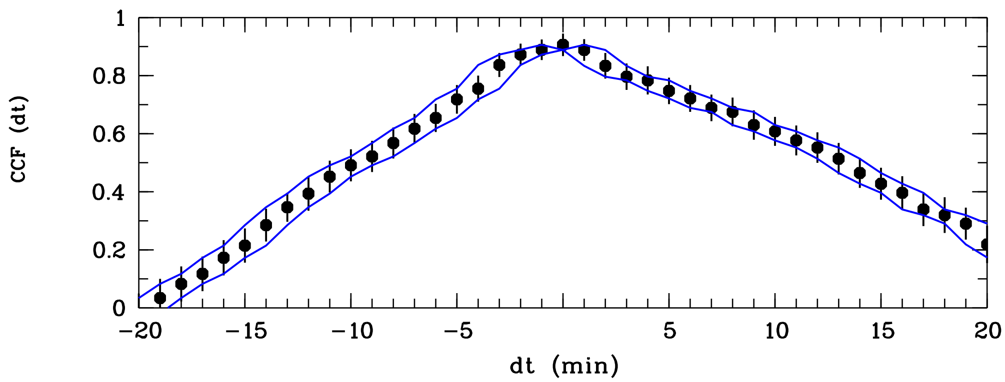

Figure 2: Central Part of discrete cross-correlation function between the light-curves obtained in the energy ranges 200-300 GeV and above 700 GeV. Error bars are computed from simulations as described in the text. The solid lines depict template cross-correlations with lags at ± 60 sec. Monte-Carlo simulations are used to constrain the lag in the cross-correlation to ± 27 sec, representing a 99% confidence upper limit to the true lag between these two energy bands.

[1] with variability time scales of order 2 min. Such rapid variations pose interesting constraints on models of the emission mechanisms and source models of Blazars (e.g. Wagner et al., in press). In most scenarios relativistic Doppler beaming much higher than derived from direct observations is required.

Energy dependent time lags

The integrated spectrum of the source can be described by a broken power law with the two branches $E < E_{\rm B}$: $\frac{\rm dN}{\rm dE} = I_\circ \, \left(\frac{E}{1\,\rm TeV}\right)^{-\Gamma_1}$
$E > E_{\rm B}$: $\frac{\rm dN}{\rm dE} = I_\circ \, \left(\frac{E_{\rm B}}{1\,\rm TeV}\right)^{(\Gamma_2-\Gamma_1)} \left(\frac{E}{1\,\rm TeV}\right)^{-\Gamma_2}$, and $I_\circ = (2.06 \pm 0.16 \pm 0.41) \times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1}, $E_{\rm B} = 430 \pm 22 \pm 80$ GeV, $\Gamma_1 = 2.71 \pm 0.06 \pm 0.10$, and $\Gamma_2 = 3.53 \pm 0.05 \pm 0.10$ [1]. The spectrum can be traced out beyond 5 TeV. We have investigated the energy dependence of the patterns in the light-curve by cross-correlating data-sets obtained in non-overlapping energy bands.

Selecting low-energy and high-energy bands such that the difference in average energy between the two bands is maximized while keeping the Poisson-noise induced errors low led to the choice of cross-correlating the light-curves in an energy band of 200-300 GeV with another one above 700 GeV. Other permutations of the bands 200-300 GeV, 300-400 GeV, 400-500 GeV, 500-600 GeV, 600-700 GeV and $>$700 GeV were cross-correlated as independent cross-checks for potential energy dependent time-lags. All light-curves had been binned into intervals of 1 minute with identical start times in the different energy bands. A discrete correlation function without interpolations was used. The errors in the individual light curves are dominated by Poisson-noise. The errors in the cross-correlation function were obtained by Monte-Carlo simulations. For each time interval 1000 realizations of the actual measurement and its probability distribution were simulated. All combinations of different realizations of the individual simulated light-curves were cross-correlated and the probability distribution of each point on the discrete correlation function CCF(τ) is represented by the error. The resulting discrete correlation function of the 200-300 GeV band and the $>$700 GeV band are shown in Figure 2.

Template cross-correlation functions were generated to determine the actual lags. Monochromatic light-curves with variability patterns following the same PDS as the actual variations were simulated. Photons energies were randomly assigned according to a broken power-law identical to the one fitted to the true data. The arrival times of individual photons were artifically shifted by $\Delta t \sim E_\gamma$. Cross-correlations were computed in a similar fashion as used for the real data and one thousand correlation functions were averaged to obtain templates. Templates with different lags were fitted to the correlation function of the real data to determine the lag of the true data.

The combination of light-curves obtained in the energy ranges 200-300 GeV and above 700 GeV shown in Figure 2 is consistent with zero and incompatible with lags larger than one minute. The cross-correlations of other the energy bands are consistent with zero lag as well. We thus derive a delay dt $<$ 60 sec between photons with Δ E $\sim$ 500 GeV after traveling the distance given by the redshift of PKS 2155-304 (z = 0.116).

The upper limits on delays of arrival times of photons of different energies can be translated into limits on extensions of the classical dispersion relation as predicted in quantum gravity models involving terms linear deviations in ξ/E to be of order 5 10^{17} GeV, i.e. about 4 % of the Planck mass $M_{\rm Planck}$ (1.2 10^{19} GeV/c^2)

Conclusions

The very bright flare of VHE gamma-ray emission detected in PKS 2155-304 in July and August 2006 has been observed with the very sensitive Air Cherenkov array HESS. Rapid variability has been detected with rise time scales as short as 67 seconds. Due to the broad-band sensitivity of the array, this permits the search for energy dependent time-lags down to delay times less than 60 seconds. No significant lags on short time scales have been found, constraining the hypothetical energy dependent dispersion expected in many models of quantum gravity. The limits on the onset of violations of Lorentz invariance are of order 0.04 $E_{\rm Planck}$ for dispersion terms linear in energy. This is significantly tighter than the limits obtained on other gamma-ray flares in AGN or from X-ray studies of Gamma-Ray Bursts, which have been studied in earlier investigations.

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References

[1] Aharonian, F. A., et al. (H.E.S.S. Collaboration), ApJ, 2007, 664, L71
[2] Amelino-Camelia, G, Lämmerzahl, C., Macias, A., & Müller, H.: AIP Proceedings 758, 30 (2005)
[3] Ellis, J., Mavromatos, N.E., Nanopoulos, D.V., & Sakharov, A.S., A&A 2003, 402, 409
[4] Kostelecký, V.A. & Mewes, M., Phys. Rev. D, 2002, 66, 056005
[5] Stecker, F. W., New Astron. Rev. 2004, 48, 437
[6] Gambini, R. & Pullin, J. Phys. Rev. D, 1999, 59, 1251
[7] Burgess, C. P., et al. JHEP, 2002, 0203, 043
[8] Ellis, J. et al. Astropart. Phys. 2006, 25, 402
[9] Lamon, R., Produit, N., & Steiner, F., 2007, arXiv:0706.4039
[10] Bolmont, J. et al., astro-ph/0603725
[11] Biller, S.D. et al., Phys. Rev. Lett., 1999, 83, 2108
[12] Aharonian, F. A., et al. (H.E.S.S. Collaboration), A&A, 2005, 430, 865
[13] Aharonian, F. A., et al. (H.E.S.S. Collaboration), A&A, 2005, 442, 895