arXiv:0708.2889v1 [astro-ph] 21 Aug 2007

Probing Quantum Gravity using Photons from a Mkn 501 Flare Observed by MAGIC

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We use the timing of photons observed by the MAGIC gamma-ray telescope during a flare of the active galaxy Markarian 501 to probe a vacuum refractive index $\simeq 1 - (E/M_{\rm QGn})^n$, $n = 1, 2$, that might be induced by quantum gravity. The peaking of the flare is found to maximize for quantum-gravity mass scales $M_{\rm QG1} \sim 0.4 \times 10^{18}$ GeV or $M_{\rm QG2} \sim 0.6 \times 10^{11}$ GeV, and we establish lower limits $M_{\rm QG1} > 0.26 \times 10^{18}$ GeV or $M_{\rm QG2} > 0.39 \times 10^{11}$ GeV at the 95% C.L. Monte Carlo studies confirm the MAGIC sensitivity to propagation effects at these levels. Thermal plasma effects in the source are negligible, but we cannot exclude the importance of some other source effect.

PACS numbers: 12.60.Jv, 04.60.-m, 11.25.Wx, 96.50.S-

It is widely speculated that space-time is a dynamical medium, subject to quantum-gravitational (QG) effects that cause the fabric of space-time to fluctuate on the Planck time and distance scales [1]. It has also been widely suggested that this 'foaming' of space-time might be reflected in modifications of the propagation of energetic particles, namely dispersive effects due to a non-trivial refractive index induced by the QG fluctuations in the space-time foam [2, 3, 4]. The calculation of such effects is beyond the scope of current theoretical methods, but heuristic arguments have been given that the velocities of energetic massless particles *in vacuo* might deviate from the velocity of light by an amount that increases with energy [2, 3, 4]. Various models suggest that any such deviation should be subluminal [3] and might be either linear: $\Delta c/c = -E/M_{\rm QG1}$, or quadratic: $\Delta c/c = -E^2/M_{\rm QG2}^2$. One might guess that the QG scales $M_{\rm QG1,QG2} \sim \hat{M}_{\rm P}$, where $\hat{M}_{\rm P} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass, but smaller values might be possible in some string theories [3], or models with large extra dimensions [5].

A favored way to search for such a non-trivial dispersion relation is to compare the arrival times of photons of different energies arriving on Earth from distant astrophysical sources [2]. If the time structure of the *emission* is non-trivial and assumed independent of energy, comparisons between the *arrival* times of photons of different energies are sensitive to QG parameters such as $M_{\rm QG1,QG2}$. The greatest sensitivities may be expected from high-statistics observations of sources with fine time structures, at large distances or redshifts z, of photons observed over a large range of energies by a detector with good time resolution. In the past, studies have been made of emissions from pulsars [6], gamma-ray bursters (GRBs) [2, 5, 7, 8] and active galactic nuclei (AGNs) [9, 10]. Pulsars offer the advantage of well-defined fine time structures, but are detected only at relatively short distances. One study indicated a sensitivity to $M_{\rm QG1} \sim 1.5 \times 10^{15}$ GeV [6]. AGNs offer photons in the TeV range, and occur at moderate redshifts, but their time structures are usually not very fine. A pioneering study of a flare of Mkn421 yielded a sensitivity to $M_{\rm QG1} \sim 4 \times 10^{16}$ GeV [9]. However, as we discuss later, it is difficult in such analyses to distinguish propagation effects from effects at the source. GRBs are observed at very high redshifts, but there have been no confirmed observations of high-energy emissions, and the time structures are very irregular. Nevertheless, a combined analysis of many GRBs at different redshifts made possible some separation between energy- and source-dependent effects, and yielded a robust lower limit $M_{\rm QG1} > 0.9 \times 10^{16}$ GeV [8].

In this letter we analyze two flares of Mkn 501. The AGN Mkn 501 at a redshift $z = 0.034$ was observed by MAGIC for 30 nights during May to July 2005. After applying standard quality checks, data covering a total observation time of 31.6h spread over 24 nights survived and were analysed using the standard technique, as described in [11]. The data were taken at zenith angles of $10° - 30°$, resulting in an energy threshold (defined as the peak of the differential event-rate spectrum after cuts) of ≈ 150 GeV. About $90-99\%$ of hadronic showers are rejected, while $50-60\%$ of the γ-ray signals are retained, resulting in an effective collection area exceeding 5×10^4 m^2 above 200 GeV. The initial energies of the γ-rays are, in a first approximation, proportional to the total amounts of light recorded in the event images; corrections are applied according to other image parameters obtained from the analysis, using large samples of Monte Carlo events as a yardstick. The achieved energy resolution is between 20% and 30%, slightly dependent on energy, but reasonably constant at 23% over the range 170 GeV to 10 TeV. The arrival time of each event is obtained with high precision by signal extraction from a 300 MHz FADC, using a sliding window of fixed length (details can be found in [12]), and the absolute times are given by a rubidium clock and cross-checked with GPS.

In the course of the 24 nights of observations, variability of the Mkn 501 γ-ray flux by an order of magnitude was observed, with a maximum integrated flux above about 150 GeV exceeding $(11.0 \pm 0.3) \times 10^{-10}$ cm^{-2}s^{-1}. A clear correlation between flux and spectral index was found, with the spectral index being softer during low flux and harder for the highest fluxes. In the two nights with the highest flux, June 30 and July 9, high-intensity outbursts of short duration (flares) were recorded, with characteristic rise and fall times of $1-2$ minutes. While the flare of July 9 was clearly visible over the full energy range 150 GeV $-$ 10 TeV, and reached a peak flux more than a factor two higher than before and after the flare, that seen on June 30 was concentrated in the energy range 250 GeV $-$ 1 TeV and was less significant. X-ray observations performed during the same period were not sensitive enough to identify a correlation with the variability above 100 GeV, and neither was there a strong indication for optical variability. In the analysis below, additional quality cuts on the gamma energy ($E > 150$ GeV) and the pointing parameter α ($\alpha < 10°$) were applied. The data analyzed comprise the observed energy E and time t for each event recorded during the flaring night.

The spectral time properties of the most intense portions of the flares were quantified in [11] using a binned estimator applied in four different energy bands with boundaries of 0.15, 0.25, 0.6 and 1.2 TeV. For the flare of July 9, a time lag of about 4 minutes was found for the maximum of the time profile envelope for photons in the $1.2-10$ TeV energy band relative to those in the $0.25-0.6$ TeV. It was observed in [11] that this time lag could be interpreted within QG models that postulate a vacuum refraction effect. In the June 30 flare a signal above a uniform background appeared only in the energy band of 0.25 to 0.6 TeV, which did not permit any conclusion on the time-spectral properties of the signal. Here we improve on the binned estimator used in [11], by analyzing the complete information encoded in the time-energy distribution of individual photons in the flare, with the

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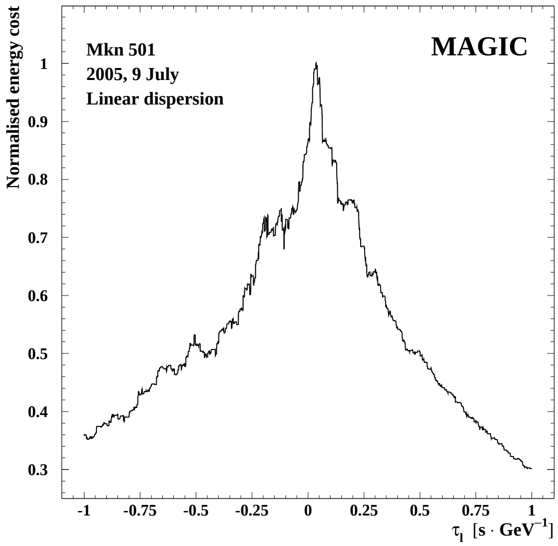

FIG. 1: *The energy cost function (ECF) obtained from one realization of the MAGIC measurements with photon energies smeared by Monte Carlo, for the case of a vacuum refractive index that is linear in the photon energy.*

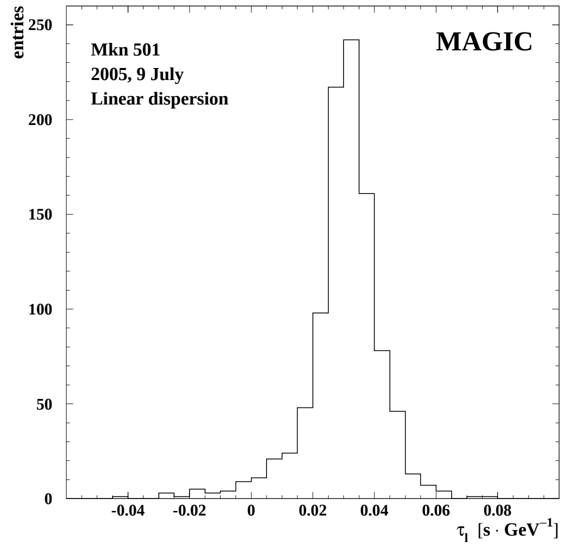

FIG. 2: *The τ_l distribution from fits to the ECFs of 1000 realizations of the July 9 flare with photon energies smeared by Monte Carlo.*

aim of probing possible systematic time lags induced by QG vacuum refraction during the propagation of the flare to the Earth, or intrinsic to the source.

The true shape of the time profile at the source is not known, so we choose the following analysis strategy. In general, the fine time structure of any flare would be blurred by an energy-dependent effect on photon propagation. Conversely, one may correct for the effects of any given parametric model of photon dispersion, e.g., the linear or quadratic vacuum refractive index, by applying to each photon with energy E the appropriate time shift [7] corresponding to its propagation in a spatially-flat universe: $\Delta t(E) = H_0^{-1}(E/M_{\rm QG1})\int_0^z h^{-1}(z)dz$ or similarly for the quadratic case, where H_0 is the Hubble expansion rate and $h(z) = \sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}$. If the correct energy-dependent QG shift is applied, the fine time structure of the emission profile is restored.

We implement this analysis strategy in two ways that yield similar results. In one analysis, the QG shift is varied so as to maximize the total energy in the most active part of the flare, and in the other analysis we use the shape of the flare as extracted from the original (untransformed) data. As we show below, these independent analyses yield similar sensitivities to the possible QG scale.

It is well known [14] that a pulse of electromagnetic radiation propagating through a dispersive media becomes diluted so that its power (the energy per unit time) decreases, whereas the opposite effect is also possible in a medium with strongly nonlinear dispersive properties. Any transform of a signal to the undispersed signal tends to recover the original power of the pulse. Hence, if the parameter $M_{\rm QG1}$ or $M_{\rm QG2}$ is chosen correctly, the power of the recovered pulse is maximized.

We implement this observation as follows. First, we choose a time interval $(t_1; t_2)$ containing the most active part of the flare, as determined using a Kolmogorov-Smirnov (KS) statistic [15]. The KS statistic is calculated from the difference between the cumulative distribution function (c.d.f.) estimated from the unbinned data and the c.d.f. of a uniform distribution. The interval $(t_1; t_2)$ covers the range where the value of the KS difference varies from its maximum over the whole time support of the signal down to almost zero. This procedure ensures that the most active (transient) part of the flare is captured. Once the proper time window is chosen, the above-mentioned time shift is applied to obtain the undispersed signal. For convenience, we re-parametrize the time-shift as $\Delta t = \pm\tau_l E$ or $\Delta t = \pm\tau_q E^2$ respectively, with τ_l and τ_q having units s/GeV and s/GeV^2. The transformation is repeated for many values of τ_l and τ_q, chosen such that the shifts Δt match precision of the arrival-time measurements made by MAGIC. We then calculate the 'energy cost function' (ECF) by summing, for each given τ_l or τ_q, the energies of the photons in the interval $(t_1; t_2)$ [13]. The position of the maximum of the ECF indicates the value of τ_l or τ_q which recovers correctly the signal, in the sense of maximizing its power. The procedure is repeated for 1000 Monte-Carlo (MC) data samples generated by applying to the measured photon energies the (energy-dependent) Gaussian measurement errors.

Fig. 1 shows the ECF for one such energy-smeared MC sample. It exhibits a clear maximum, whose position may be estimated by fitting it with a Gaussian profile in the vicinity of the peak. The results of such Gaussian fits to the ECFs constructed with τ_l for the 1000 energy-smeared realizations of the July 9 flare are shown in Fig. 2. From this distribution we can derive the value of $\tau_l = (0.030 \pm 0.012)$ s/GeV. We therefore find a preferred range for the linear QG mass scale:

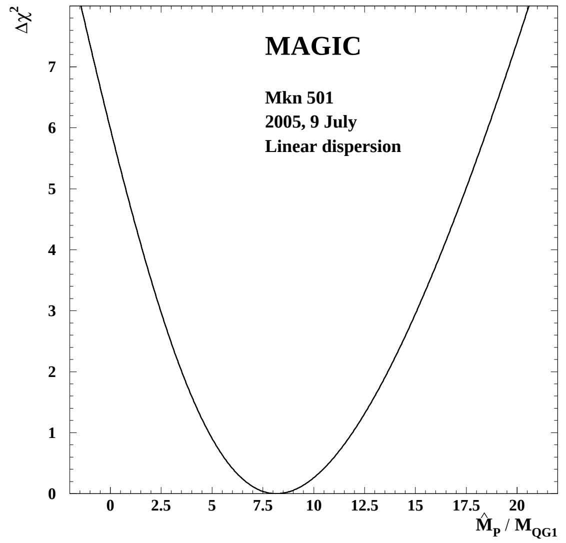

FIG. 3: *The χ^2 function for the July 9 flare, which exhibits a quite symmetric parabolic minimum as a function of* $1/M_{\rm QG1}$.

$M_{\rm QG1} = 1.398 \times 10^{16}(1\ {\rm s}/\tau_l) = (0.47^{+0.31}_{-0.13}) \times 10^{18}$ GeV, and a lower limit $M_{\rm QG1} > 0.26 \times 10^{18}$ GeV at the 95% C.L. [16]. The same procedure applied to the ECF obtained using τ_q leads to $\tau_q = (3.71 \pm 2.57) \times 10^{-6}$ s/GeV^2, corresponding to $M_{\rm QG2} = 1.182 \times 10^8 (1\ {\rm s}/\tau_q)^{1/2} = (0.61^{+0.49}_{-0.14}) \times 10^{11}$ GeV ($M_{\rm QG2} > 0.27 \times 10^{11}$ GeV at the 95% C.L.). We have found similar sensitivities in an ECF analysis of the June 30 flare but, since this flare is not very significant, it cannot be used to strengthen our results, although the results are compatible. We note that the effect found would correspond to subluminal propagation, as suggested by QG models [2, 3].

We have confirmed this result using another technique to optimize the sharpness of the transformed signal, motivated by the initial time and energy-binned analysis performed in [11], which showed that the intrinsic light-curve is described well by a Gaussian flare superimposed on a time-independent background with a softer spectral index. Using a likelihood method, we fit the data to a probability density function (p.d.f.) $P(E,t)$ of the observed energy E and arrival time t, using variables describing the energy spectrum $\Gamma(E_{\rm s})$ at the source, and the time distribution $F_{\rm s}(t_{\rm s}, M_{\rm QGn})$ at emission obtained from the measured arrival times of the photons assuming a non-trivial refractive index. We compute the likelihood function $\mathcal{L}$ for $\frac{dP}{dE\,dt} = k \int_0^\infty \Gamma(E_{\rm s})\, G(E - E_{\rm s}, \sigma_E(E_{\rm s}))\, F_{\rm s}(t_{\rm s})\, dE_{\rm s}$, where k is a normalization factor and $G(E - E_{\rm s}, \sigma_E(E_{\rm s}))$ is the photon-energy smearing produced by the instrument, which is modelled as a Gaussian distribution with width $\sigma_E(E_{\rm s})$ in the range mentioned above. In order to model the photon energy at the source, a power law $\Gamma(E_{\rm s}) \sim E_{\rm s}^{-\beta}$ is taken, with $\beta = 2.7$ for the time-uniform part of the flare and 2.4 for the flaring part. The time distribution is parameterized as a Gaussian flare of width t_W and position t_0 relative to the first photon arrival time, on top of a flat background distribution.

The likelihood function $\mathcal{L}$ is fitted to the July 9 MAGIC data minimizing $-\log \mathcal{L}$ as a function of four parameters, namely (i) $\hat{M}_P/M_{\rm QG1}$, (ii) the position of the intrinsic maximum of the flare t_0, (iii) its width t_W, and (iv) the normalization of the time-independent background component x_B in arbitrary units. The best four-parameter overall fit to the July 9 data yields $\hat{M}_{\rm P}/M_{\rm QG1} = 8.2^{+3.7}_{-3.4}$, corresponding to $M_{\rm QG1} = 0.30^{+0.24}_{-0.10} \times 10^{18}$ GeV [16]. The shape of the function $\chi^2 \equiv -2 \log \mathcal{L} + {\rm const}$ around the minimum in these variables is quite parabolic almost up to the 2-σ level. In view of the correlations with these parameters, the sensitivity to $M_{\rm QG1}$ would be improved if they were known more precisely. Fig. 3 shows the behavior of the χ^2 function around its minimum; the single-parameter 1-σ uncertainties are estimated by $\Delta\chi^2 = 1$. A similar procedure in the case of quadratic vacuum refraction gives $M_{\rm QG2} = 0.57^{+0.75}_{-0.19} \times 10^{11}$ GeV.

In order to check the robustness of the ECF and likelihood analyses, we have applied them blindly to a set of 1000 artificial MC samples resembling the July 9 flare, but with different types of energy-dependent dispersion encoded artificially. The encoded effects have been successfully recovered by the two estimators within the expected uncertainties. In addition, the analysis techniques have been applied to MC samples with no energy-dependent dispersive signal, where no effect has been found, and both techniques also returned null results when applied to a set of Mkn 501 data from outside a flare. The outcome of these MC tests confirm the numerical sensitivities of the analyses and the estimates of the uncertainties given above.

The results of the two independent analyses of the July 9 flare of Mkn 501 are quite consistent within the errors. Their results exhibit, assuming energy-independent emission at the source, a sensitivity to $M_{\rm QG1} \sim 0.4 \times 10^{18}$ GeV ($> 0.17 \times 10^{18}$ GeV at the 95% C.L.), probing the Planck mass range for the first time. The findings also demonstrate a sensitivity to $M_{\rm QG2} \sim 0.6 \times 10^{11}$ GeV ($> 0.27 \times 10^{11}$ GeV at the 95% C.L.), far beyond previous limits on quadratic effect on photon propagation [5, 7, 9]. We cannot exclude the possibility that the delay we find, which is significant beyond the 95% C.L., may be due to some energy-dependent effect at the source. However, we can exclude the possibility that the observed time delay may be due to a conventional QED plasma refraction effect induced as photons propagate through the source. This would induce [17] $\Delta t = D(\alpha^2 T^2/6q^2) \ln^2(qT/m_e^2)$, where α is the fine-structure constant, q is the photon momentum, T is the plasma temperature, m_e is the mass of electron, D is the size of the plasma, and we use natural units: $c, \hbar = 1$. Plausible numbers such as $T \sim 10^{-2}$ MeV and $D \sim 10^9$ km (as estimated from the extension of the magnetic field [18]) yield a negligible effect for $q \sim 1$ TeV. Exclusion of other source effects, such as time evolution in the mean emitted photon energy, might be possible with the observation of more flares, preferably of different AGNs at varying redshifts. This pioneering study demonstrates clearly the potential scientific value of such an analysis.

The MAGIC Collaboration thanks the IAC for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN and the Spanish CICYT is gratefully acknowledged. This work was also supported by ETH Research Grant TH 34/04 3 and the Polish MNiI Grant 1P03D01028. The work of J.E. and N.E.M. was partially supported by the European Union through the Marie Curie Research and Training Network UniverseNet MRTN-CT-2006-035863, and that of D.V.N. by DOE grant DE-FG02-95ER40917.

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