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

J. Albert et al., arXiv:0708.2889v1

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# Lorentz不変性の破り方

- 光速度のずれ
  - $c_{\mathrm{m}}$ : 物質速度の最大値
  - $c_{\mathrm{em}}$ : 電磁波の伝播速度

$$\varepsilon \equiv 1 - \left( \frac{c_{\mathrm{em}}}{c_{\mathrm{m}}} \right)^2$$

: Lorentz不変性の破れ : 実験的には$<3\times10^{-22}$

- $c_{\mathrm{m}} \neq c_{\mathrm{em}} \Rightarrow$「禁じられた過程」が開く
  - $c_{\mathrm{m}} < c_{\mathrm{em}}$ : 光子の崩壊 $\gamma \to e^+e^-$
  - $c_{\mathrm{m}} > c_{\mathrm{em}}$ : 荷電粒子の真空中でのチェレンコフ放射
- 光速度のエネルギー依存

$$c_0 p^2 = E^2 \quad \Rightarrow \quad c_0 p^2 \approx E^2[1 + f(E)]$$

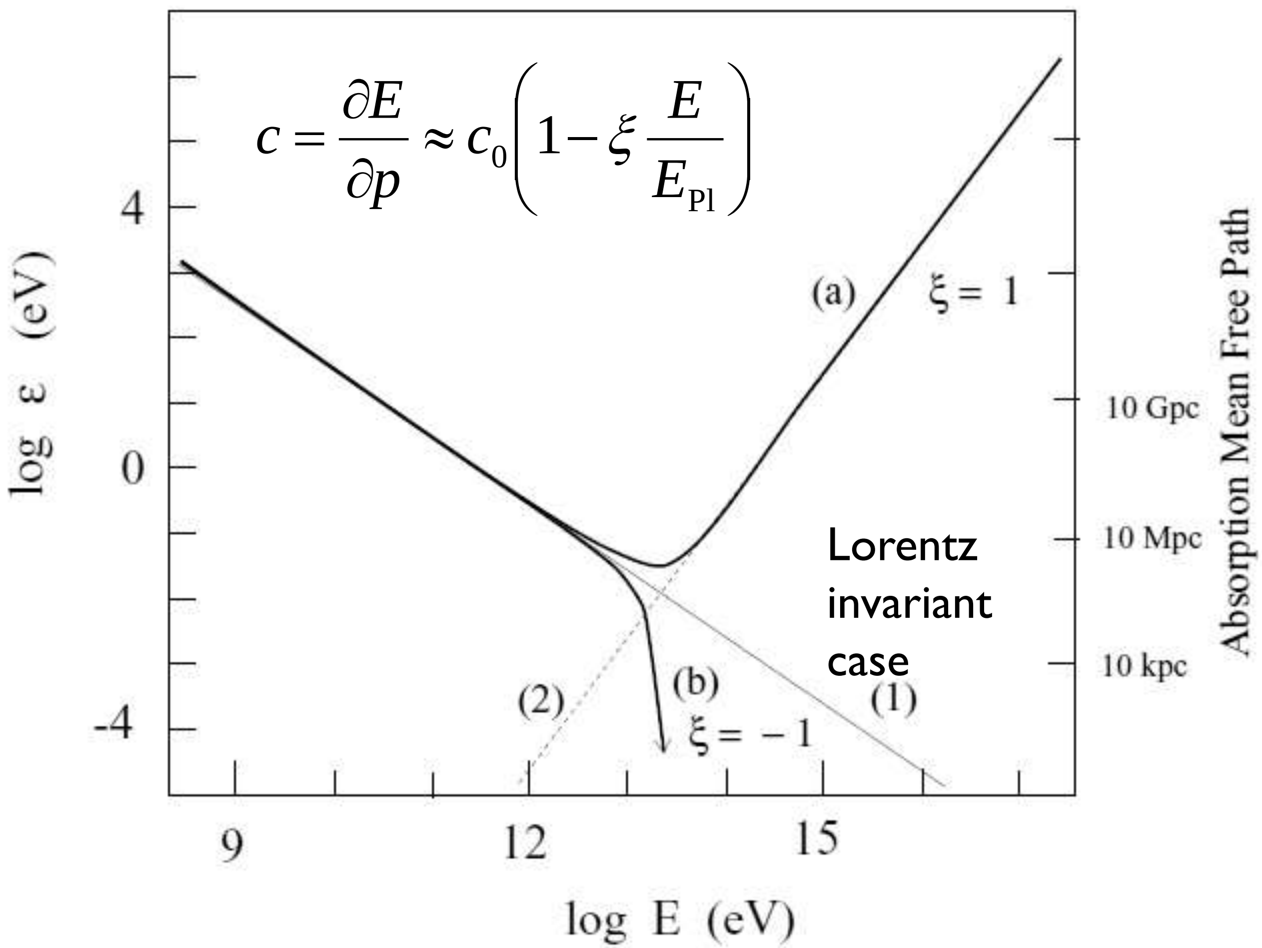
- 量子重力の場合

$$c = \frac{\partial E}{\partial p} \approx c_0 \left( 1 - \xi \frac{E}{E_{\mathrm{Pl}}} \right) \qquad E_{\mathrm{Pl}} = \sqrt{\hbar c/G} = 10^{19}\,\mathrm{GeV}$$

$\xi = \pm 1$ : モデルによる不定性

Coleman and Glashow, Phys. Lett. B405, 249 (1997)
Amelino-Camelia et al., Nature, 393, 763 (1998)

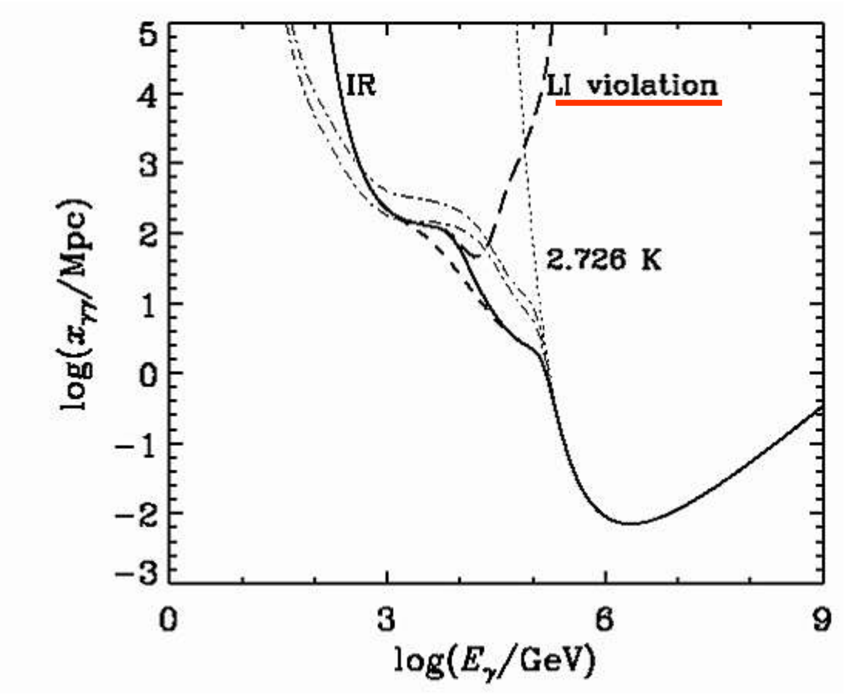
# 量子重力によるLorentz不変性の破れ

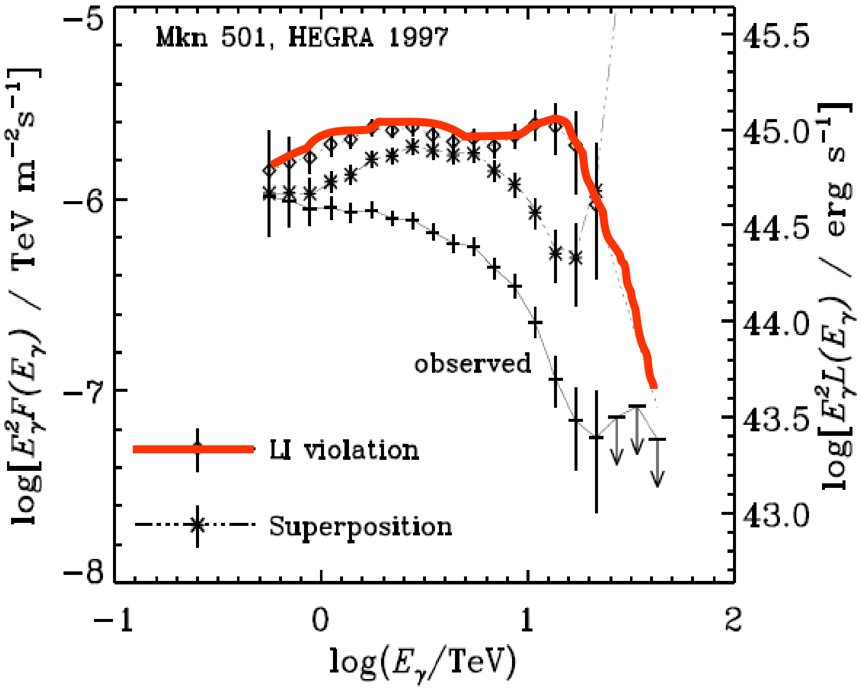



平均自由行程が延びる可能性！

Kifune, ApJ 518, L21 (1999)

# Mrk501のTeVスペクトルへの影響




Protheroe & Meyer, Phys.Lett. B493 (2000) 1

# 光子の到達時間差

Large extra dimension models

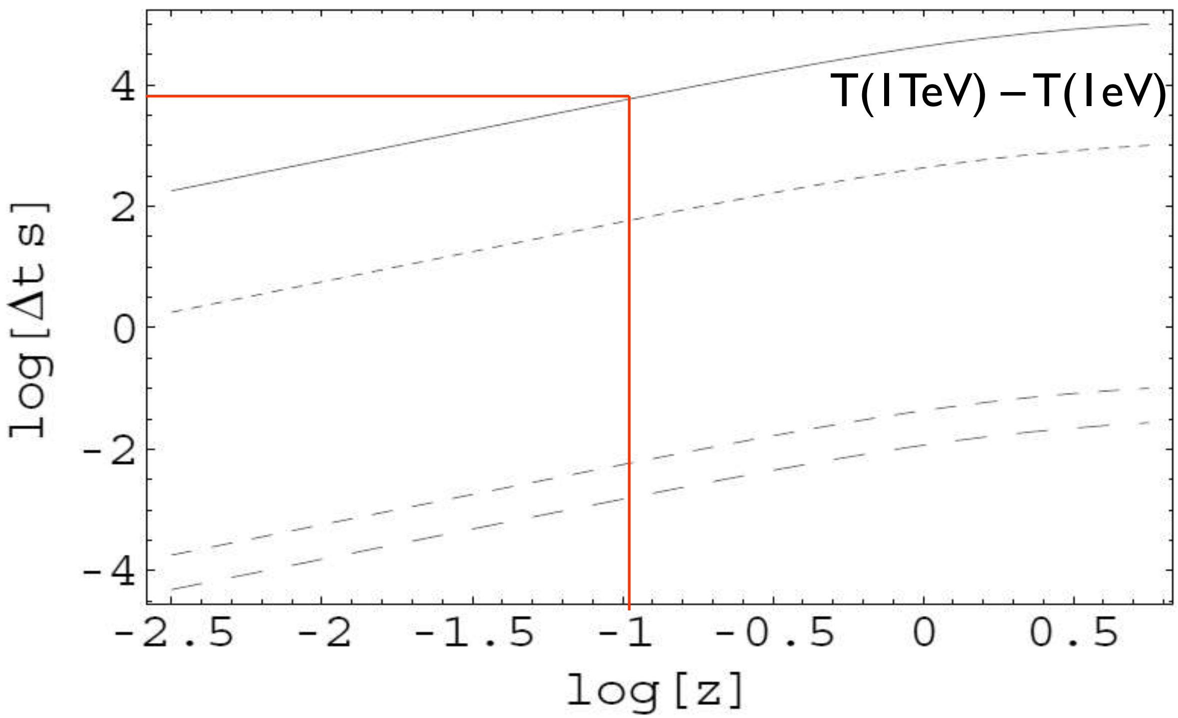



Fig. 3.— Variation of the photon time delay as a function of the redshift $z$ (in a logarithmic scale) in cosmological models with large extra-dimensions for a fundamental energy scale $E_F = 7 \times 10^{15}$ GeV and for different photon energy values: $E_1 = 1$ TeV, $E_2 = 1$ eV (solid curve), $E_1 = 10$ GeV, $E_2 = 1$ MeV (dotted curve), $E_1 = 1$ MeV, $E_2 = 1$ eV (short dashed curve) and $E_1 = 300$ keV, $E_2 = 30$ keV (long dashed curve). For the mass, dark energy and dark radiation parameters we have used the values $\Omega_M = 0.3$, $\Omega_\Lambda = 0.68$ and $\Omega_U = 0.02$, respectively.

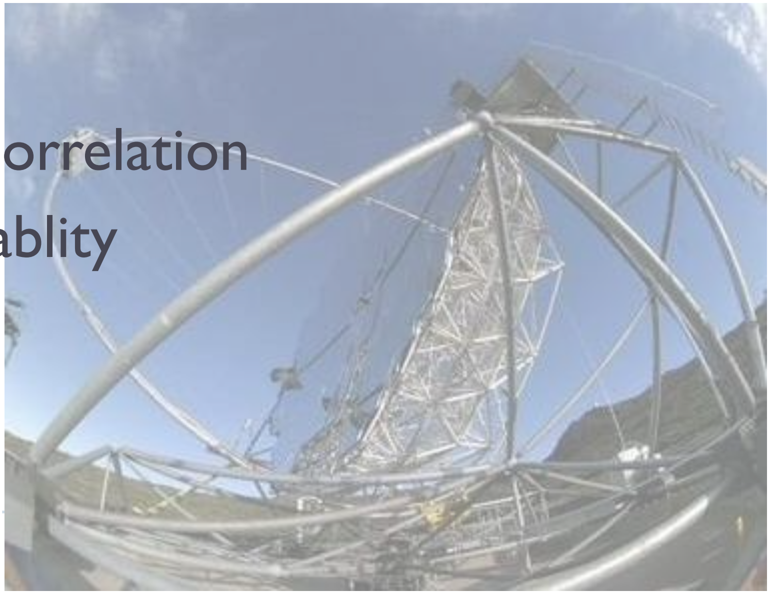
Harko & Cheng, ApJ 611, 633 (2004)

# Time delay by QG effects

- Linear
  - $\Delta c/c = -E/M_{QG1}$
  - Ref: J. Ellis, astro-ph/0010474
- Quadratic
  - $\Delta c/c = -(E/M_{QG2})^2$
  - Ref: Alfaro et al, PRL 84, 2318 (2000)
- QG scale $M_{QG1}$, $M_{QG2}$ ~ $M_{P'}$=2.4×10$^{18}$GeV (reduced Planck scale) but could be smaller

# Data: Mrk 501 by MAGIC

- May-July 2005, 30 nights
- 31.6hr over 24 nights, zenith angle: 10-30deg $\rightarrow$ >150 GeV
- $\Delta E/E \sim 23\%$ over 170 GeV – 10 TeV
- Average flux (>150 GeV) $(11.0 \pm 0.3) \times 10^{-10}$ $cm^{-2}s^{-1}$
- Two flare nights: June 30 and July 9
  - June 30: 250 GeV – 1 TeV
  - July 9: 150 GeV – 10 TeV
  - X-ray obs: not sensitive to identify correlation
  - Optical: no strong indication of variablity



J. Albert et al., astro-ph/0702008v2

# Light curves on June 30 and July 9

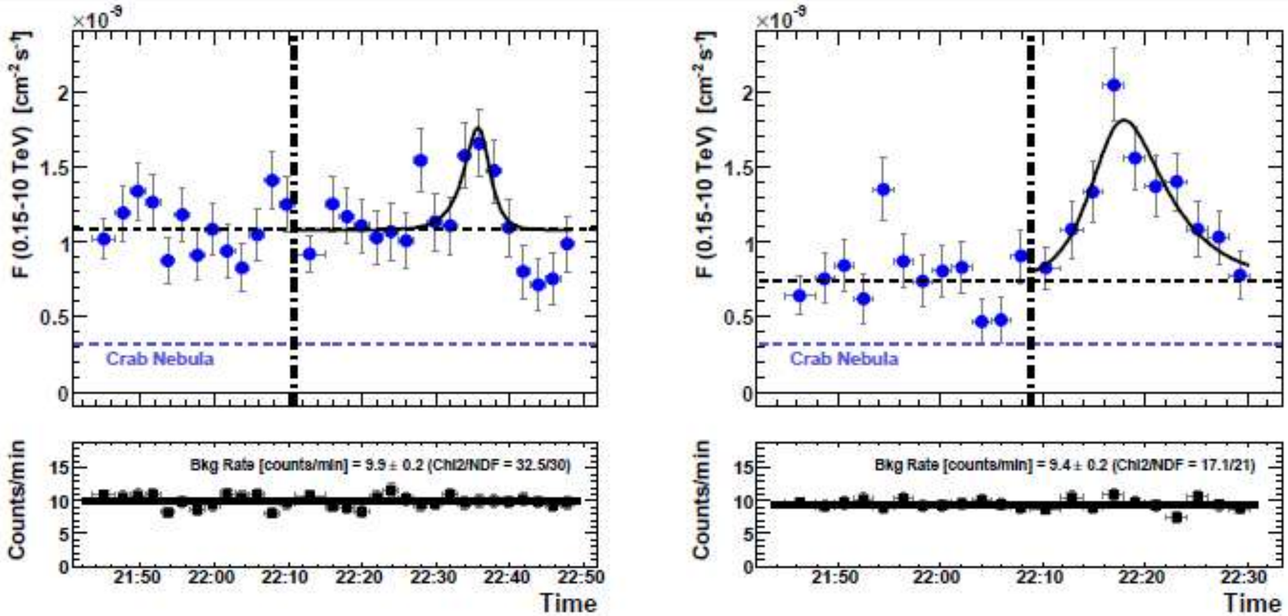
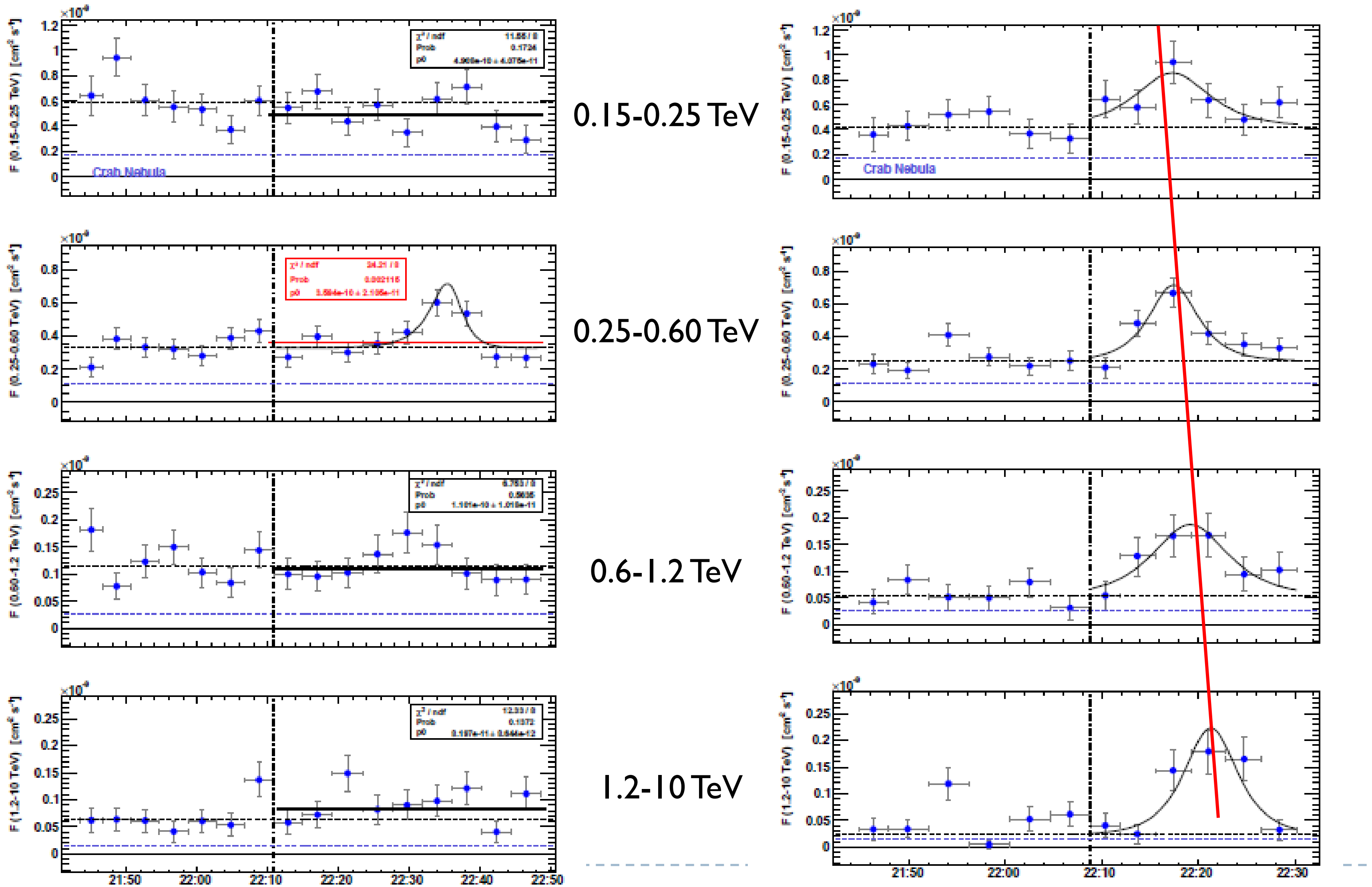



Fig. 5.— Integrated-flux LCs of Mrk 501 for the flare nights of June 30 and July 9. Horizontal bars represent the 2-minute time bins, and vertical bars denote $1\sigma$ statistical uncertainties. For comparison, the Crab emission is also shown as a lilac dashed horizontal line. The vertical dot-dashed line divides the data into 'stable' (i.e., pre-burst) and 'variable' (i.e., in-burst) emission. The horizontal black dashed line represents the average of the 'stable' emission. The solid black curve represents the best-fit flare model (see eq. 2). The bottom plots show the mean background rate during each of the 2-minute bins of the LCs. The insets report the mean background rate during the entire night, resulting from a constant fit to the data points. The goodness of such fit is also given.

J. Albert et al., astro-ph/0702008v2

# June 30 / July 9, 2005



# Analysis strategy

- True shape of the time profile at the source is not known…
- Correct time shift in a spatially-flat universe

$$\Delta t(E) = H_0^{-1}(E/M_{\mathrm{QG1}}) \int_0^z h^{-1}(z)dz$$
$$h(z) = \sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}$$

- A pulse of electromagnetic radiation propagating through a dispersive media becomes diluted so that its power (the energy per unit time) decreases.
- If the parameter $M_{\mathrm{QG1}}$ or $M_{\mathrm{QG2}}$ is chosen correctly, the power of the recovered pulse is maximized.

# Implementation

- Choose a time interval ($t_1; t_2$) containing the most active part of the flare, as determined using a Kolmogorov-Smirnov (KS) statistic.
- Time shift is applied to obtain the undispersed signal.
  - $\Delta t = \pm\tau_l E$ or $\Delta t = \pm\tau_q E$ with $\tau_l$ and $\tau_q$ having units s/GeV and s/GeV$^2$.
- Calculate 'energy cost function' (ECF) by summing, for each given $\tau_l$ or $\tau_q$, the energies of the photons in the interval ($t_1; t_2$).

# Energy cost function

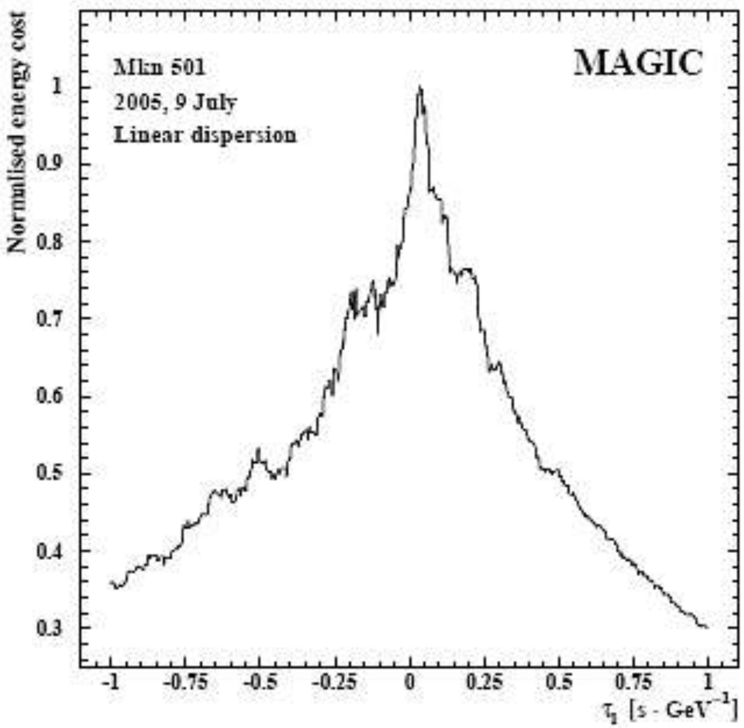



FIG. 1: *The energy cost function (ECF) obtained from one realization of the MAGIC measurements with photon energies smeared by Monte Carlo, for the case of a vacuum refractive index that is linear in the photon energy.*

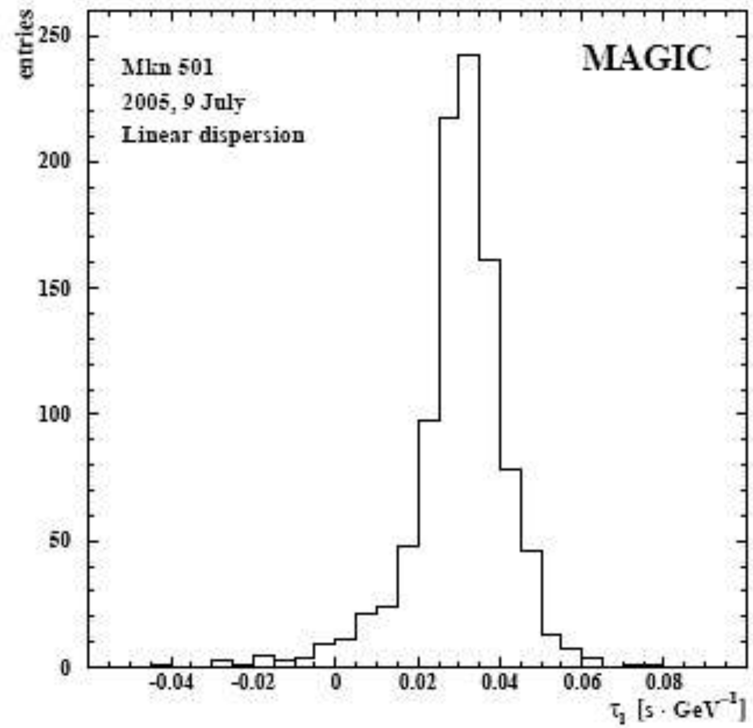



FIG. 2: *The $\tau_l$ distribution from fits to the ECFs of 1000 realizations of the July 9 flare with photon energies smeared by Monte Carlo.*

# Results (1)

- Linear case
  - $\tau_l = (0.030 \pm 0.012)$ s/GeV
  - $M_{QG1} = 1.398 \times 10^{16}(1\ \text{s}/\tau_l) = (0.47^{+0.31}{}_{-0.13}) \times 10^{18}$ GeV,
  - $M_{QG1} > 0.26 \times 10^{18}$ GeV at the 95% C.L.
- Quadratic case
  - $\tau_q = (3.71 \pm 2.57) \times 10^{-6}$ s/GeV$^2$
  - $M_{QG2} = 1.182 \times 10^{8}(1\ \text{s}/\tau_q)^{1/2} = (0.61^{+0.49}{}_{-0.14}) \times 10^{11}$ GeV
  - $M_{QG2} > 0.27 \times 10^{11}$ GeV at the 95% C.L.

# Another technique

- optimize the sharpness of the transformed signal
- 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 $\Gamma(E_s)$ at the source, and the time distribution $F_s(t_s, M_{QGn})$ at emission obtained from the measured arrival times of the photons assuming a non-trivial refractive index.
- Likelihood function for $\frac{dP}{dE\,dt} = k \int_0^\infty \Gamma(E_s)\,\hat{G}(E - E_s, \sigma_E(E_s))\,F_s(t_s)\,dE_s$, where G is the photon-energy smearing.
- Power-law source $E^{-\beta}$, $\beta$=2.7 for const, 2.4 for flare

# Chi-squared function

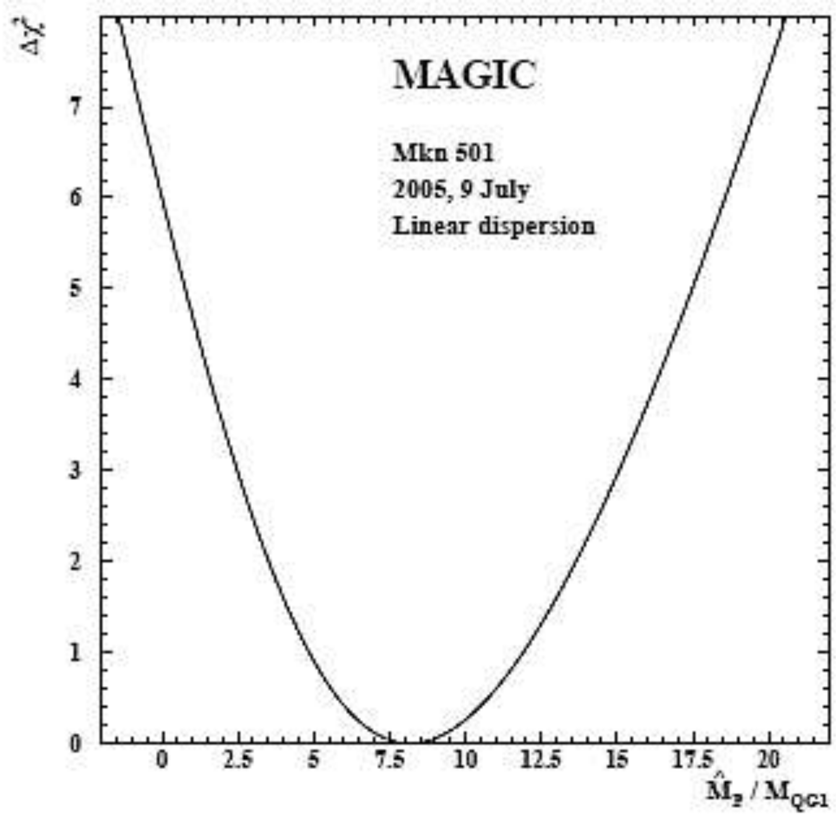



FIG. 3: *The* $\chi^2$ *function for the July 9 flare, which exhibits a quite symmetric parabolic minimum as a function of* $1/M_{\mathrm{QG1}}$.

# Results (2)

- Linear case
  - The best four-parameter overall fit to the July 9 data yields $M_P/M_{QG1} = 8.2^{+3.7}_{-3.4}$, corresponding to $M_{QG1} = 0.30^{+0.24}{-0.10} \times 10^{18}$ GeV
- Quadratic case
  - $M_{QG2} = 0.57^{+0.75}_{-0.19} \times 10^{11}$ GeV.

# Discussion

- Their results exhibit, assuming energy-independent emission at the source, a sensitivity to MQG1  $0.4 \times 10^{18}$ 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 MQG2 $0.6 \times 10^{11}$ GeV (> $0.27 \times 10^{11}$ GeV at the 95% C.L.), far beyond previous limits on quadratic effect on photon propagation.
- 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.
- 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.

$$\Delta t = D(\alpha^2 T^2/6q^2)\ln^2(qT/m_e^2)$$