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Constraints on Lorentz Invariance Violation using integral/IBIS observations of GRB041219A

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One of the experimental tests of Lorentz invariance violation is to measure the helicity dependence of the propagation velocity of photons originating in distant cosmological obejcts. Using a recent determination of the distance of the gamma-ray burst GRB 041219A, for which a high degree of polarization is observed in the prompt emission, we are able to improve by four orders of magnitude the existing constraint on Lorentz invariance violation, arising from the phenomenon of vacuum birefringence.

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I. INTRODUCTION

On general grounds one expects that the two fundamental theories of contemporary physics, the theory of general relativity and the quantum theory in the form of the standard model of particle physics, can be unified at the Planck energy scale. This unification requires to quantize gravity, which leads to very fundamental difficulties. One is related with the energy of the fundamental vacumm state. Another one is the status of Lorentz invariance: the fuzzy nature of space time in quantum gravity may lead to violations of this fundamental symmetry. For the last two decades theoretical studies and experimental searches of Lorentz Invariance Violation (LIV) have received a lot of attention [see e.g. the reviews by [1–3]]. Possible consequences of LIV are energy and helicity-dependent photon propagation velocities. The energy dependence can be constrained by recording the arrival times of photons of different energies emitted by distant objects at approximately the same time [4], e.g. during a gamma-ray burst (GRB) [5] or a flare of an active galactic nucleus [6]. On the other hand, the helicity dependence can be constrained by measuring how the polarization direction of an x-ray beam of cosmological origin changes as function of energy [7].

Recently, an upper limit on the helicity dependence of photon propagation has been set using INTEGRAL/SPI observations of the polarization of the Crab nebula [8]. In this paper, we derive much stronger constraints from a polarization measurement of a GRB, a source at cosmological distance.

To date only a few polarization measurements are available for GRBs. Coburn and Boggs [9] reported a high degree of polarization, $\Pi = 80\% \pm 20\%$, for GRB 021206. However, successive reanalysis of the same data set could not confirm this claim, reporting a degree of polarization compatible with zero [10,11]. Willis *et al.* [12] reported a strong polarization signal in GRB 930131 ($\Pi > 35\%$) and GRB 960924 ($\Pi > 50\%$), but this result could not be statistically constrained. GRB 041219A was detected by the INTEGRAL Burst Alert System (IBAS; Mereghetti [13]), and is the longest and brightest GRB localized by INTEGRAL [14] to date [15]. McGlynn *et al.* [16], using the data of the INTEGRAL spectrometer [SPI;[17]], reported a high degree of polarization of the prompt emission ($\Pi = 68 \pm 29\%$) for the brightest part of this GRB. Also, Götz *et al.* [18] have performed a similar measurement, using this time the INTEGRAL/IBIS telescope, reporting variable polarization properties of the burst all along its duration. In this paper, we reuse these data in order to measure the polarization in two energy bands and check for a shift in the polarization angle as a possible effect of Lorentz Invariance Violation.

In Sec. II, we will present the INTEGRAL/IBIS observations of polarization during the burst, and the recent

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measure of the burst distance we obtained thanks to near infrared observations of its host galaxy. In Sec. III, we will derive constraints on LIV from these observations and we will conclude in Sec. IV.

II. OBSERVATIONS OF GRB041219A

A. INTEGRAL/IBIS observations

Thanks to its two position sensitive detector layers ISGRI [19] (made of CdTe crystals and sensitive in the 15–1000 keV energy band), and PICsIT [20] (made of CsI bars and sensitive in the 200 keV–10 MeV energy band), IBIS can be used as a Compton polarimeter [21]. The concept behind a Compton polarimeter is the polarization dependency of the differential cross section for Compton scattering

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E_0}\right)^2\left(\frac{E'}{E_0} + \frac{E_0}{E'} - 2\sin^2\theta\cos^2\phi\right), \qquad (1)$$

where r_0^2 is the classical electron radius, E_0 the energy of the incident photon, E' the energy of the scattered photon, θ the scattering angle, and ϕ the azimuthal angle relative to the polarization direction. Linearly-polarized photons scatter preferentially perpendicularly to the incident polarization vector. Hence by examining the scatter angle distribution of the detected photons

$$N(\phi) = S[1 + a_0\cos(2(\phi - \phi_0))], \qquad (2)$$

one can derive the polarization angle $PA = \phi_0 - \pi/2 + n\pi$ and the polarization fraction $\Pi = a_0/a_{100}$, where a_{100} is the amplitude expected for a 100% polarized source, derived by Montecarlo simulations of the instrument.

To measure the polarization, we followed the same procedure described in Forot *et al.* [22] that allowed to successfully detect a polarized signal from the Crab nebula. One important difference, anyway, is that the Crab measurement was integrated over several observation periods and a long time (>1 Ms), while this measurement here integrates over only a few seconds. So we have checked if instrumental azimuthal variations, potentially washed out by the long Crab observation, could be important in the GRB case. To do so, we have simulated 10 GRB-like observations using data from the INTEGRAL Payload Ground Calibrations campaign. This campaign, made with the full flight model of the telescope, was done with standard radioactive nonpolarized sources. We use in this work the calibrations made with a ^{113}Sn source with a peak energy of 392 keV, the closest to the energy bands we are considering here. To simulate GRBs, we divide the data set into 10 subsets, each containing a similar number of Compton events as in the observations we show in Fig. 1. In all these subsets, we found systematics at a level up to 15% maximum, with a polarization angle around 40°. We made another test considering spurious events, as described in Forot *et al.* [22], and again we found a systematic azimuthal variation of less than 9%, with a polarization angle of 180°. Both values are far from the ones we derived below for the source and give confidence that our results are not due to instrumental azimuthal variations, even if such variations effectively exist.

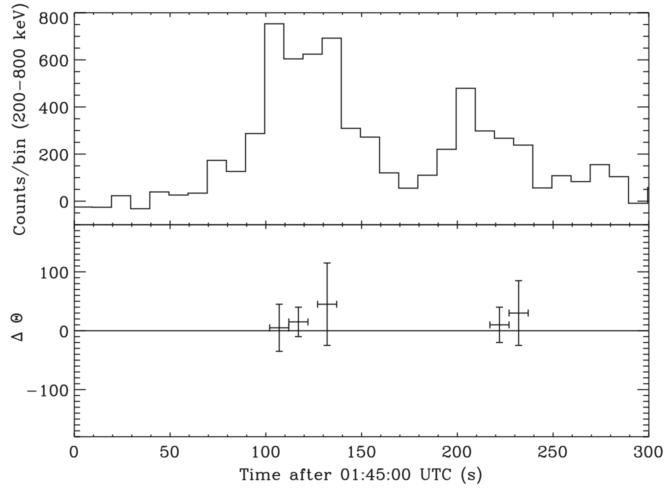

FIG. 1. Evolution during the burst duration of the polarimetric angle shift measured between the [200–250 keV] and in the [250–325 keV] energy range. The mean value, 21° ± 47°, is consistent with zero.

To derive the gamma-ray burst flux as a function of ϕ, the Compton photons were divided into six bins of 30° as a function of the azimuthal scattering angle. To improve the signal-to-noise ratio in each bin, we took advantage of the π-symmetry of the differential cross section (see Eq. (2)), i.e., the first bin contains the photons with $0° < \phi < 30°$ and $180° < \phi < 210°$, etc. The derived detector images were then deconvolved to obtain sky images, where the flux of the source in each bin is measured by fitting the instrumental point spread function to the source peak. We finally fitted the polarigrams to Eq. (2) using a least squares technique (see Fig. 2) in order to derive a_0 and ϕ_0, and the errors on the parameters are dominated by the statistics of the data points.

We computed the scatter angle distribution into two energy bands in order to detect a possible polarimetric angle shift with energy, reminiscent of a possible LIV effect. The two bands were chosen to be [200–250 keV] and [250–325 keV] where the source has merely the same signal-to-noise ratio. In Fig. 1, we show the measured evolution of the polarimetric angle shift between these two energy bands, along the burst duration. These shifts are all consistent with zero with a mean value of 21° ± 47°.

Also, as an example, we show in Fig. 2 and 3, the portion of the GRB light curve where the polarimetric signal was strong, that is starting at 01:47:02 U.T. until 01:47:12 U.T. (P9 interval in Götz *et al.* [18]). A modulated signal is seen in the two energy bands, corresponding to $\Pi = 55\%$ for

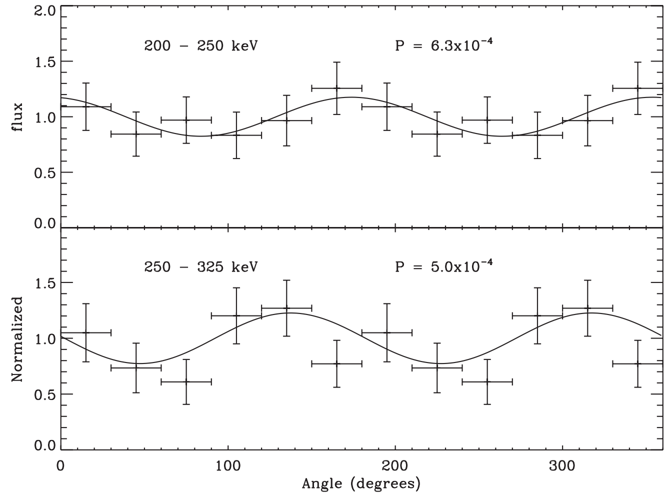

FIG. 2. Scatter angle distribution of GRB041219A in the 200–250 keV and in the 250–325 keV energy band during the P9 time interval (see text). These distributions give the source count rate by azimuthal angle of the Compton scattering, and are consistent with a highly polarized signal. The chance probability of a nonpolarized signal is reported in each panel. The polarization angles derived from these distributions are consistent within 68° (see text).

the first band, and $\Pi = 82\%$ for the second ones (see Fig. 3 for error contours). To evaluate the goodness of our fits, we computed the chance probability (see Eq. (2) in Forot *et al.* [22]) that our polarigrams are due to an unpolarized signal, and reported these values in Fig. 2. The corresponding polarimetric angles were $**PA = 80^{+26}_{-28}$ deg and $PA = 45^{+38}_{-40}$ deg, that is consistent at the 2σ level (see Fig. 3).

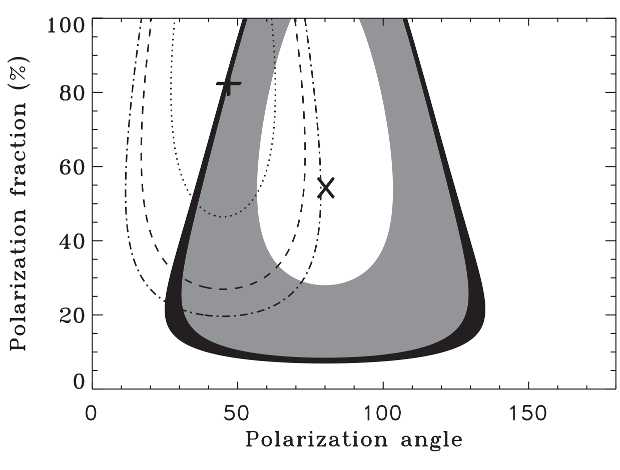

FIG. 3. Contour plot of the composed error on polarization angle and polarization fraction for the two energy bands, during the P9 time interval. The X cross shows the best fit position for the first energy band. Contour levels are at the 67, 90, and 95% level (from white toward black fill). The + cross and dotted, dashed, and dash-dotted lines show the best fit parameters obtained for the second energy band, consistent at 95% with the first energy band best fit.

Propagation of errors gives an upper limit of 68° at the 90% level, for a possible phase shift.

B. Distance determination

Götz *et al.* [23] performed deep infrared imaging of the GRB region using the WIRCam instrument at the 3.6 m Canadian French Hawaiian Telescope (CFHT) at Mauna Kea. Thanks to multiband ($YJHK_s$) imaging they were able to identify the host galaxy of GRB 041219A, and to give an lower limit to its photomeric redshift of $z = 0.02$, at the 90% confidence level. This implies a luminosity distance of 85 Mpc, assuming standard cosmological parameters ($\Omega_m = 0.3$, $\Omega_\lambda = 0.7$, and $H_0 = 70$ km$/s/$Mpc).

III. CONSTRAINTS ON LORENTZ INVARIANCE VIOLATION

On general grounds, Lorentz violating operators of dimension $N = n + 2$ modify the standard dispersion relations $E^2 = p^2 + m^2$ by terms of the order of $f_n p^n / M_{Pl}^{n-2}$ where M_{Pl} is the reduced Planck scale ($\approx 2.410^{18}$ GeV), used as a reference scale since LIV is expected to arise in the quantum regime of gravity. In order to account for the severe limits on LIV, one therefore usually only considers operators of dimension greater or equal to five which provide corrections which are tamed by at least one inverse Planck scale.

A. dimension 5 operators

If we restrict our attention to pure electrodynamics, there is a single term of dimension-5 which gives corrections of order p^3/M_{Pl} and is compatible with gauge invariance and rotational symmetry [24]:

$$\mathcal{L} = \frac{\xi}{M_{Pl}} n^\mu F_{\mu\nu} n^\rho \partial_\rho (n_\sigma \tilde{F}^{\sigma\nu}), \tag{3}$$

where n^μ is a 4-vector that characterizes the preferred frame and $\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$. The uniqueness of this term makes the analysis somewhat model-independent (see however below).

The light dispersion relation is given by ($E = \hbar\omega$ and $p = \hbar k$):

$$\omega^2 = k^2 \pm \frac{2\xi k^3}{M_{Pl}} \equiv \omega_\pm^2, \tag{4}$$

where the sign of the cubic term is determined by the chirality (or circular polarization) of the photons, which leads to a rotation of the polarization during the propagation of linearly polarized photons. This effect is known as vacuum birefringence.

Since we have the approximative relation:

$$\omega_\pm = |p| \sqrt{1 \pm \frac{2\xi k}{M_{Pl}}} \approx |k| \left(1 \pm \frac{\xi k}{M_{Pl}}\right), \tag{5}$$

the direction of polarization rotates during propagation along a distance d by an angle:

$$\Delta\theta(p) = \frac{\omega_+(k) - \omega_-(k)}{2} d \approx \xi \frac{k^2 d}{2M_{Pl}}. \quad (6)$$

For GRB041219A, if we set $\Delta\theta(k) = 47°$, derived from the measures we made along the burst duration, and the lower limit luminosity distance reported above of $d = 85$ Mpc $= 2.610^{26}$ cm, corresponding to $z = 0.02$, we get an upper limit on the vacuum birefringence effect:

$$\xi < \frac{2M_{Pl}\Delta\theta(k)}{(k_2^2 - k_1^2)d} \approx 1.110^{-14}. \quad (7)$$

B. Dimension-6 operators

Although the dimension-5 operator (3) is unique, it is physically relevant only if there do not appear operators of lower dimensions. In the general case, however, radiative corrections induced by dimension-5 operators lead to dimension-3 operators through quadratic divergences which contribute an extra factor Λ^2, where Λ is an ultraviolet cut-off of order M_{Pl}. Barring extreme fine tuning, one needs a symmetry argument to cancel such terms. Supersymmetry appears to be the only symmetry which cancels such contributions [25]. It is true that supersymmetry is broken in nature but, in the case where it is softly broken, quadratic divergences contribute a factor M_S^2, where M_S, the scale of supersymmetry breaking, is of the order of a TeV^2, thus providing an extra factor $(M_S/M_{Pl})^2 \sim 10^{-30}$ compared to untamed dimension-3 operators.

Unfortunately, the dimension-5 operator of (3) is not compatible with supersymmetry [25]. We therefore have to resort in this case to dimension-6 operators. We thus assume that the light dispersion relation is given by:

$$\omega_\pm^2 = k^2 \pm \frac{\xi k^4}{M_{Pl}^2}. \quad (8)$$

We can derive then the approximate relation:

$$\omega_\pm = |k|\sqrt{1 \pm \frac{\xi k^2}{M_{Pl}^2}} \approx |k|\left(1 \pm \frac{\xi k^2}{2M_{Pl}^2}\right), \quad (9)$$

which implies that the direction of polarization rotates during propagation of:

$$\Delta\theta(k) = \frac{\omega_+(k) - \omega_-(k)}{2} d \approx \xi \frac{k^3 d}{M_{Pl}^2}. \quad (10)$$

Again, for GRB041219A, if we set $\Delta\theta(k) = 47°$ and the luminosity distance $d = 85$ Mpc $= 2.610^{26}$ cm, corresponding to $z = 0.02$, we get an upper limit on the vacuum birefringence effect:

$$\xi < \frac{2M_{Pl}^2\Delta\theta(k)}{(k_2^3 - k_1^3)d} \approx 2.610^8. \quad (11)$$

This is still too large an upper bound to be really constraining since one expects couplings at most of order one.

IV. CONCLUSIONS

Using a recent determination of the distance of GRB041219A [23] for which a high degree of polarization is observed [16,18], we were able to increase by four orders of magnitude the existing constraint on Lorentz invariance violations, arising from birefringence. Turned into a constraint on the coupling ξ of dimension-5 Lorentz violating interactions, that is of corrections of order k/M_{Pl} to the dispersion relations, this gives the very stringent constraint $\xi < 10^{-14}$. Most presumably, this means that such operators are vanishing, which might point towards a symmetry such as supersymmetry in action. In that case, the pressure is on the next corrections of order $(k/M_{Pl})^2$ corresponding to operators of dimension-6. We showed that, although astrophysical constraints are not yet really constraining, they are getting closer to the relevant regime (ξ of order 1 or smaller). Our result can be compared to the limits derived using the possible energy dependence of the group velocity of photons in distant GRBs derived with Fermi [5]. However, written in the same way as we did in this work, this limit was $\xi < 0.8$ that is much less constraining.

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Note added in proof—During the editing process, an upper limit on LIV from GRB 041219A consistent with ours was found independently using the Integral/SPI telescope data (see [26]).

[1] T. Jacobson, T. Liberati, and D. Mattingly, Ann. Phys. (N.Y.) **321**, 150 (2006).

[2] S. Liberati and L. Maccione, Annu. Rev. Nucl. Part. Sci. **59**, 245 (2009).

[3] D. Mattingly, Living Rev. Relativity **8**, 5 (2005).
[4] G. Amelino-Camelia, J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, and S. Sarkar, Nature (London) **393**, 763 (1998).
[5] A. A. Abdo, M. Ackermann, M. Ajello *et al.*, Nature (London) **462**, 331 (2009).
[6] F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida *et al.*Phys. Rev. Lett. **101**, 402 (2008).
[7] R. Gambini and J. Pullin, Phys. Rev. D **59**, 124021 (1999).
[8] L. Maccione, S. Liberati, A. Celotti, J. G. Kirk, and P. Ubertini, Phys. Rev. D **78**, 103003 (2008).
[9] W. Coburn and S. E. Boggs, Nature (London) **423**, 415 (2003).
[10] R. E. Rutledge and D. E. Fox, Mon. Not. R. Astron. Soc. **350**, 1288 (2004).
[11] C. Wigger *et al.*, Astrophys. J. **613**, 1088 (2004).
[12] D. R. Willis, E. J. Barlow, A. J. Bird *et al.*, Astron. Astrophys. **439**, 245 (2005).
[13] S. Mereghetti *et al.*, Astron. Astrophys. **411**, L291 (2003).
[14] C. Winkler, T. J.-L. Courvoisier, G. Di Cocco *et al.*, Astron. Astrophys. **411**, L1 (2003).
[15] G. Vianello, D. Götz and S. Mereghetti, Astron. Astrophys. **495**, 1005 (2009).
[16] S. McGlynn, D. J. Clark, A. J. Dean *et al.*, Astron. Astrophys. **466**, 895 (2007).
[17] G. Vedrenne, J.-P. Roques, V. Schönfelder *et al.*, Astron. Astrophys. **411**, L63 (2003).
[18] D. Götz *et al.*, Astrophys. J. **695**, L208 (2009).
[19] F. Lebrun, J. P. Leray, P. Lavocat *et al.*, Astron. Astrophys. **411**, L141 (2003).
[20] C. Labanti, G. Di Cocco, G. Ferro *et al.*, Astron. Astrophys. **411**, L149 (2003).
[21] F. Lei *et al.*, Space Sci. Rev. **82**, 309 (1997).
[22] M. Forot *et al.*, Astrophys. J. **688**, L29 (2008).
[23] D. Götz *et al.*, Mon. Not. R. Astron. Soc. **413**, 2173 (2011).
[24] R. C. Myers and M. Pospelov, Phys. Rev. Lett. **90**, 211601 (2003).
[25] S. G. Nibbelink and M. Pospelov, Phys. Rev. Lett. **94**, 081601 (2005).
[26] F. Stecker, arXiv:1102.2784 [Astropart. Phys. (to be published)].