

# Constraints on Lorentz Invariance Violation using INTEGRAL/IBIS observations of GRB041219A

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(Dated: June 7, 2011)

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 objects. 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 4 orders of magnitude the existing constraint on Lorentz invariance violation, arising from the phenomenon of vacuum birefringence.

PACS numbers: 98.70.Rz,95.30.Sf,11.30.Cp,95.55.Ka

## 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 vacuum 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 [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 di-

rection 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 nebulae [8]. In this paper, we derive much stronger constraints from a polarization measurement of a Gamma-Ray Bursts (GRB), a source at cosmological distance.

To date only a few polarization measurements are available for GRBs. Coburn & 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

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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 section II, we will present the INTEGRAL/IBIS observations of polarization during the burst, and the recent measure of the burst distance we obtained thanks to far infrared observations of its host galaxy. In section III, we will derive constraints on LIV from these observations and we will conclude in section IV.

## II. OBSERVATIONS OF GRB041219A

### A. INTEGRAL/IBIS observations

Thanks to its two position sensitive detector layers IS-GRI [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

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

where  $r_0^2$  is the classical electron radius,  $E_0$  the energy of the incident photon,  $E'$  the energy of the scattered photon,  $\theta$  the scattering angle, and  $\phi$  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

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

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 ten 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 non polarized sources. We use in this work the calibrations made with a  $^{113}\text{Sn}$  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 in ten subsets containing each a similar number of Compton events as in the observations we show in figure 1. In all these subsets, we found systematics at a level up to 15% maximum, with a polarization angle around  $40^\circ$ . We made another tests 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  $180^\circ$ . Both value 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.

To derive the Gamma-Ray Burst flux as a function of  $\phi$ , the Compton photons were divided in 6 bins of  $30^\circ$  as a function of the azimuthal scattering angle. To improve the signal-to-noise ratio in each bin, we took advantage of the  $\pi$ -symmetry of the differential cross section (see Eq. 2), i.e. the first bin contains the photons with  $0^\circ < \phi < 30^\circ$  and  $180^\circ < \phi < 210^\circ$ , 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 PSF 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  $\phi_0$ , and the errors on the parameters are dominated by the statistics of the data points.

We computed the scatter angle distribution into two energy band 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 figure 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  $21^\circ \pm 47^\circ$ .

Also, as an exemple, we show in figure 2 and figure 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 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  $PA = 80_{-28}^{+26}$  deg. and  $PA = 45_{-40}^{+38}$  deg., that is consistent at the  $2\sigma$  level (see figure 3). Propagation of errors gives an upper limit of  $68^\circ$  at the 90% level, for a possible phase shift.

### B. Distance determination

Götz et al. [23] performed deep infra-red imaging of the GRB region using the WIRCam instrument at the 3.6 m Canadian French Hawaiian Telescope (CFHT) at Mauna Kea. Thanks to multi-band ( $YJHK_s$ ) imaging they were

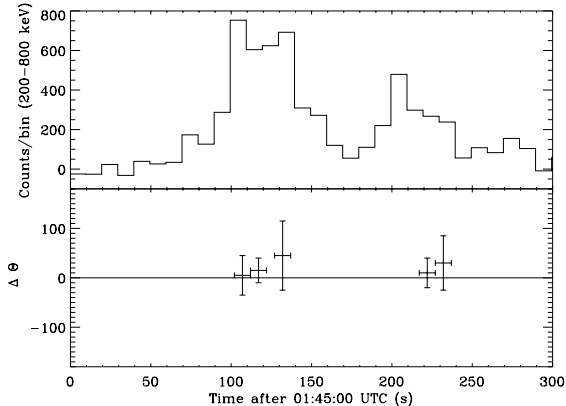


FIG. 1. Evolution during the burst duration of the polarimetric angle shift measured between the [200-250 keV] and in the [250-325 keV] energy range. The mean value,  $21^\circ \pm 47^\circ$ , is consistent with zero.

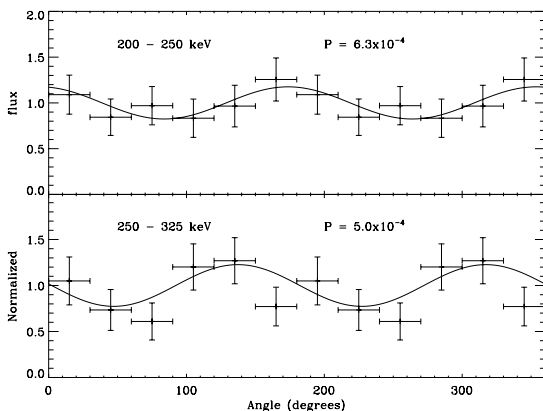


FIG. 2. Scatter angle distribution of GRB041219A in the 200-250 keV and in the 250-325 keV energy band during the P9 time interval (see text). These distributions give the source count rate by azimuthal angle of the Compton scattering, and are consistent with a highly polarized signal. The chance probability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

able to identify the host galaxy of GRB 041219A, and to give an lower limit to its photometric 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).

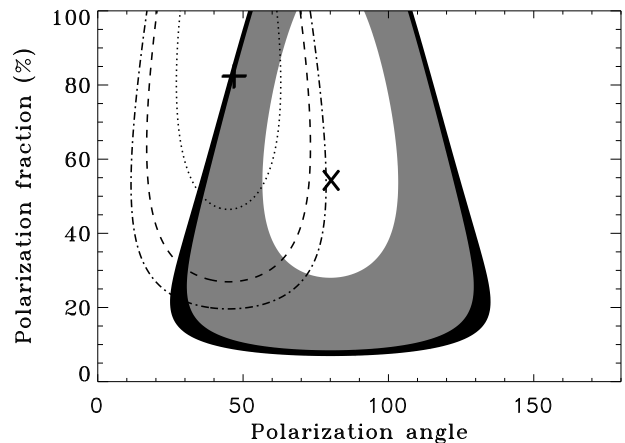


FIG. 3. Contour plot of the composed error on polarisation angle and polarisation fraction for the two energy bands, during the P9 time interval. The X cross shows the best fit position for the first energy band. Contour levels are at the 67, 90, and 95 % level (from white toward black fill). The + cross 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.

### 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 ( $\approx 2.4 \cdot 10^{18}$  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 5 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]:

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

where  $n^\mu$  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  $p = \hbar k$ ):

$$\omega^2 = k^2 \pm \frac{2\xi k^3}{M_{Pl}} \equiv \omega_\pm^2. \quad (4)$$

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:

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

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  $\Delta\theta(k) = 47^\circ$ , derived from the measures we made along the burst duration, and the lower limit luminosity distance reported above of  $d = 85$  Mpc =  $2.6 \cdot 10^{26}$  cm, corresponding to  $z=0.02$ , we get an upper limit on the vacuum birefringence effect:

$$\xi < \frac{2M_{Pl}\Delta\theta(k)}{(k_2^2 - k_1^2)d} \approx 1.1 \cdot 10^{-14} \quad (7)$$

### B. dimension 6 operators

Although the dimension 5 operator (3) is unique, it is physically relevant only if there does 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  $\Lambda^2$ , where  $\Lambda$  is an ultra-violet 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  $\text{TeV}^2$ , 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  $\Delta\theta(k) = 47^\circ$  and the luminosity distance  $d = 85$  Mpc =  $2.6 \cdot 10^{26}$  cm, corresponding to  $z=0.02$ , we get an upper limit on the vacuum birefringence effect:

$$\xi < \frac{2M_{Pl}^2\Delta\theta(k)}{(k_2^3 - k_1^3)d} \approx 2.6 \cdot 10^8 \quad (11)$$

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 4 orders of magnitude the existing constraint on Lorentz invariance violations, arising from birefringence. Turned into a constraint on the coupling  $\xi$  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 ( $\xi$  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.

## ACKNOWLEDGMENTS

ISGRI has been realized and maintained in flight by CEA-Saclay/Irfu with the support of CNES. Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA.

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