Constraining Lorentz Invariance violation using directional correlations of Gamma-Ray Bursts with IceCube cosmic neutrinos

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Abstract. A violation in Lorentz invariance (LIV) proposed in quantum gravity theories, delays the flight of extremely high energy gamma rays and neutrinos from their origin. Gamma ray bursts (GRBs) are one of the promising candidate sources of extremely energetic gamma rays and neutrinos at high redshift, as these particles propagate over long distances to develop any LIV induced propagation delays. Additionally GRBs are transient events, which gives a certain time stamp for gamma-ray emission to measure delays. With the recent discovery of astrophysical neutrino events by the IceCube observatory, a path is opened to search for Lorentz invariance at PeV energies. We use directional correlations of IceCube neutrino events and GRBs to constrain the LIV parameters at PeV energies from the observed time delay between the prompt gamma-ray and the neutrino events.

1. Introduction

IceCube Neutrino Observatory, the world's largest neutrino detector, has detected 54 neutrino events within 1347 days with energies between 20 TeV and 2.3 PeV [1][2]. Shower events, most likely due to ν_e or ν_τ charge current νN interactions and also due to neutral current νN interactions of all flavors, dominate the event list (39 including 3 events with 1–2 PeV energy) while track events, most likely due to ν_μ charge current interactions, constitute the rest. Among a total of 54 events about 21 could be due to the atmospheric neutrino ($9.0^{+8.0}_{-2.2}$) and muon (12.6 ± 5.1) backgrounds. A background-only origin of all 54 events has been rejected at a 6.5-σ level [2]. Therefore a cosmic origin of a number of neutrino events is robust. The track events have on average $\sim 1^\circ$ angular resolution, but the dominant, shower events have much poorer angular resolution, $\sim 15^\circ$ on average [2]. Searching for the sources of these events is now one of the major challenges in astrophysics. Pinpointing the astrophysical sources of these neutrinos is difficult, due to a large uncertainty in their arrival directions.

High energy cosmic rays (CRs) can interact with low energy photons and/or low energy protons to produce neutrinos and high energy gamma rays inside the source or while propagating to the Earth. Gamma Ray Bursts (GRBs) are promising candidates for producing neutrino by this process [4][5]. However a small violation in the Lorentz invariance (LI) can lead to time delay or advance in the detection of the neutrino event with respect to the GRB. The prospect

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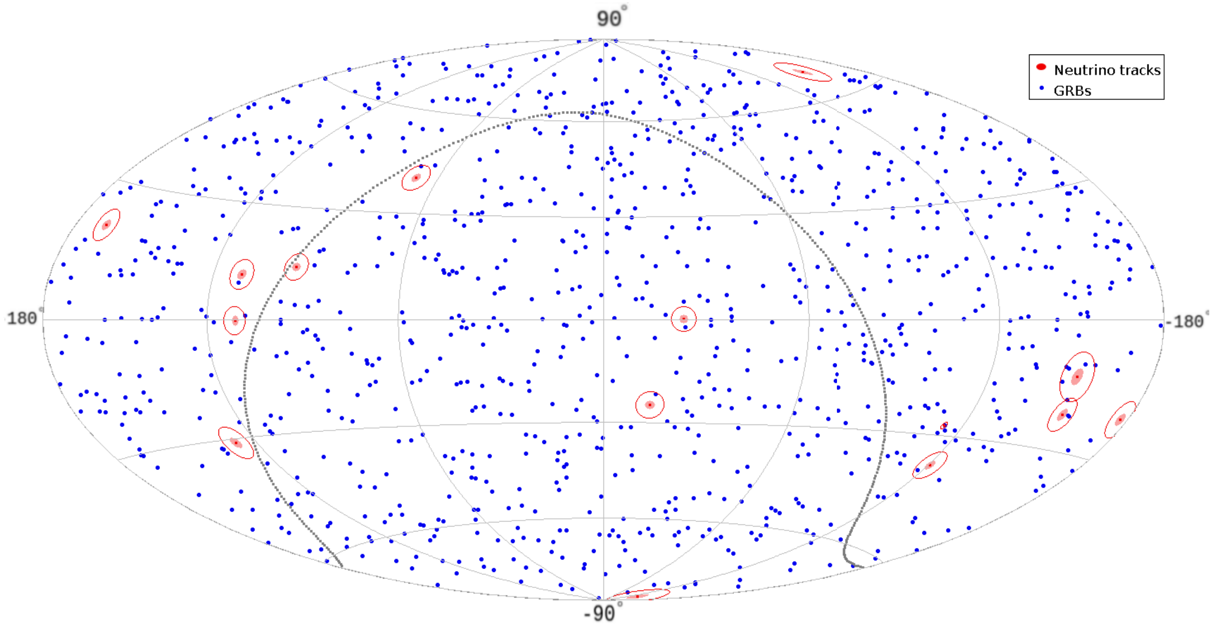

Figure 1. Sky map of total 15 neutrino track events, 13 from the IceCube 4 year HESE and the 2.6 up going event detected by IceCube [3] and one detected by ANTARES, with red dots and the red shaded area around the neutrino events shows the reported angular resolution while the red ellipses represent, three times the angular resolution in the equatorial coordinate. The Galactic plane is shown with the dotted gray line. The 1017 GRBs detected by *Swift* are shown with the blue dots.

of exploring the possible minute violation in LI with energetic gamma rays, neutrinos has been proposed earlier [6][7].

Here we have correlated the high energy neutrino events detected by IceCube and one event from the ANTARES [10] with the *Swift*[2] detected GRBs. Then we calculated the LIV parameter using the events that correlated with the GRBs.

2. High energy neutrino events and Gamma Ray Bursts

Out of all neutrino events we have considered only track events, as these kind of events leave a long muon track inside the detector which helps to reconstruct the arrival direction of the neutrino with better accuracy compared to shower events. With better angular resolution, muon track events can therefore give an idea of the location of the sources. This would help to claim for the sources. There are 14 track events in the 54 IceCube detected neutrino events, however two track events (event numbers 28 and 32) are coincident hits in the IceTop surface array and are almost certainly a pair of atmospheric muon background events [1]. Apart from the 54 events IceCube has also detected an up-going track event with an energy of 2.6 PeV [3]. In our analysis we have also included the ANTARES event having energy between 50 TeV to 100 TeV [10][11]. We have taken the energy of this event as 50 TeV with 10% of error due to lack of exact number. Now in total we have taken 15 high energy neutrino track events shown in the equatorial coordinate sky map, Fig. 1 along with their reported angular resolution and and with three times the angular resolution (outer ellipses).

The GRB catalogue used for correlation are selected from the swift detected GRBs within

[2] http://swift.gsfc.nasa.gov/

Table 1. The list of the GRBs that correlated with the detected high energy neutrino events.

Sources	Neutrino ID	Redshift	Δt [10^8 sec]
Known Redshift			
GRB 050724A	ANTARES event	0.257	3.19
GRB 070411A	IceCube 5	2.954	1.13
GRB 061110A	IceCube 44	0.758	2.27
Pseudo Redshift			
GRB 080915B	IceCube 23	0.124	1.05
GRB 090720A	IceCube 23	0.1518	0.8
GRB 110212A	IceCube 13	0.271	0.13
GRB 120913B	IceCube 23	0.006	0.2
GRB 130919A	IceCube 23	0.153	0.52
GRB 131202A	IceCube 18	0.4127	0.6
Assumed Redshift (z=2.3)			
GRB 050801A	IceCube 43		2.6
GRB 070809A	IceCube 43		2
GRB 080727A	IceCube 23,43		1.1, 1.7
GRB 120328A	IceCube 53		0.65

time period 2004 to 31 October 2014 [3]. It contains a total 1017 GRBs. These GRBs are shown with blue dots on the skymap in figure 1. Out of these 1017 GRBs we found 14 correlated with the neutrino track events within three times the reported angular resolution ($\delta\gamma_i$), listed in table 1. We determined the number of correlations using the following method.

We mapped the Right Ascension and Declination (RA, Dec) of the GRBs and the neutrino events directions into unit vectors on a sphere as,

$$\hat{x} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)^T,$$

where $\phi = RA$ and $\theta = \pi/2 - Dec$. The scalar product of the neutrino and GRB direction vectors ($\hat{x}_{\text{neutrino}} \cdot \hat{x}_{\text{GRB}}$) is therefore independent of the coordinate system. The angle between the two vectors

$$\gamma = \cos^{-1}(\hat{x}_{\text{neutrino}} \cdot \hat{x}_{\text{GRB}}), \tag{1}$$

is an invariant measure of the angular correlation between the neutrino event and the GRB directions [8][9]. We found the number of GRBs for which $3\delta\gamma_i$ is less than the separation γ, is 14.

3. Time Delay due to violation in Lorentz Invariance

We briefly mentioned above about the formalism of the LIV used in the present work. The details are discussed in [7]. For the particles with energies $E_\nu < \xi M_{pl}$, where M_{pl} is the Planck

[3] `https://swift.gsfc.nasa.gov/archive/grb_table/`

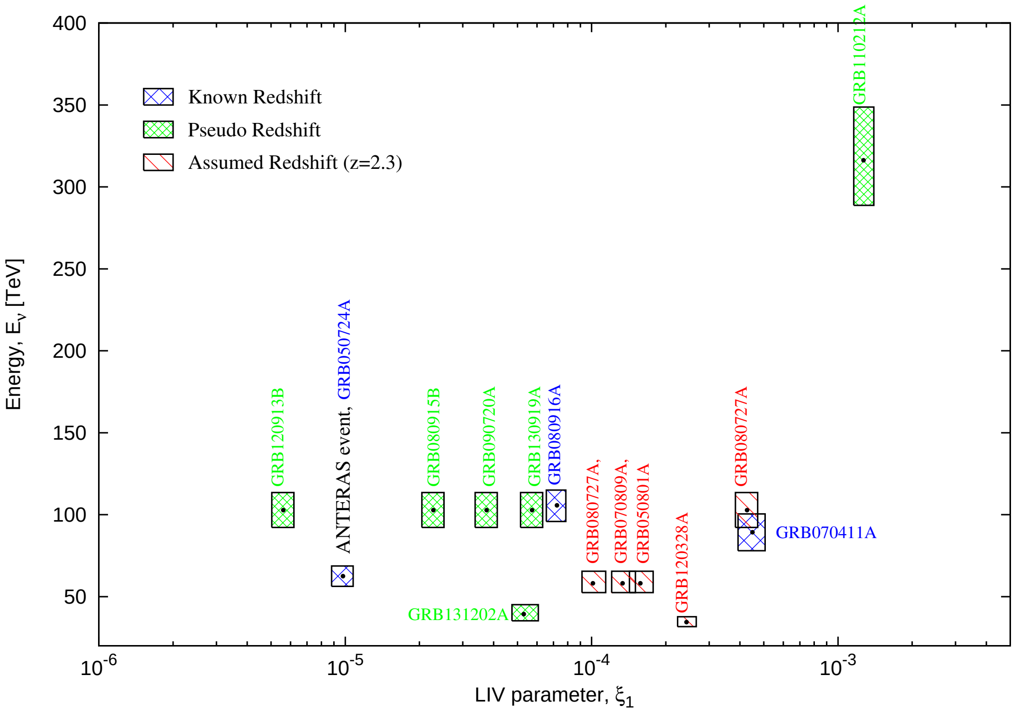

Figure 2. LIV parameter ξ_1 for different high energy neutrino events calculated for different GRBs which are correlated with the neutrino events, using the time delay of the neutrino events from the GRB. The red boxes are for GRBs that for which we have assumed the redshift to be 2.3, the green boxes represent the GRBs, for which we calculated the pseudo-redshifts according to [14], while the blue boxes are for GRBs with known redshifts.

mass, will have a dispersion relation,

$$E^2 - p^2c^2 - m^2c^4 \simeq \pm E^2 \left(\frac{E}{\xi_n M_{pl}} \right)^n . \quad (2)$$

As a result of this dispersion relation, the time needed for an ultra-relativistic particle to travel from a given sources to a given detector is, $t = t_0 + \Delta t$ [13], where t_0 is the time that would be predicted in classical space-time, and Δt is the time delay between photons and neutrinos from GRBs. The LIV time delay of a massless particle with an observed energy E_ν, emitted at redshift z is,

$$\Delta t = \frac{1}{H_0} \int_0^z \left(\frac{1+n}{2} \left(\frac{E_\nu}{\xi_n M_{pl}} \right)^n (1+z')^n \right) \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} . \quad (3)$$

Where $H_0 = 71\, km/sec/Mpc$, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$ are the cosmological parameters evaluated at present. Here the leading LIV parameter ξ_n is corrected for order n, considering only lower order corrections, hence we have taken n=1 or 2. We have calculated this time delay factor for the 14 GRBs that correlated with the neutrino track events.

4. Results and Discussions

We have calculated the LIV parameters ξ_1 and ξ_2 for all the 14 GRBs correlated with the neutrino events. Out of 14 only 3 GRBs have known redshifts. We have calculated the pseudo

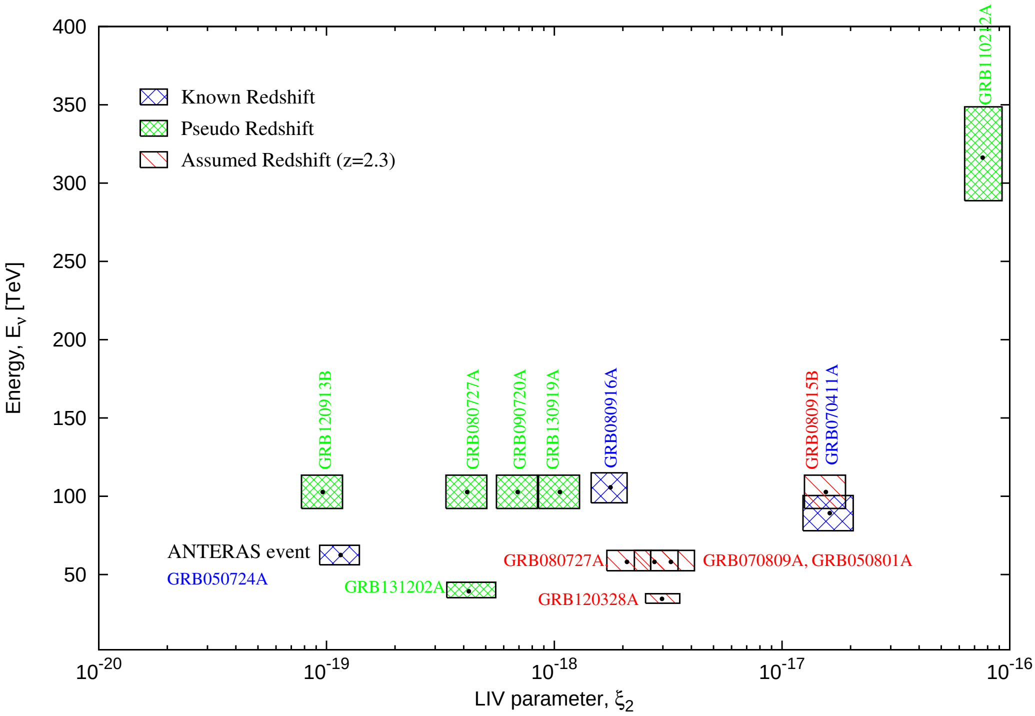

Figure 3. Similar to figure 2 but for LIV parameter ξ_2.

redshift of the GRBs (6 GRBs) for which the peak energy, E_{peak} is the photons energy at the peak of the energy spectrum fitting the gamma-ray data in the 10 keV - 10 MeV range and S is the corresponding energy fluence (S) for the same energy range, is given publicly. The pseudo-redshift is calculated using the popular Amati relation [14], the correlation of the peak energy and isotropic energy. Particularly we have used the formula as in[15],

$$E_{peak} = 480 \left(\frac{4\pi D_L^2 \mathrm{S}}{10^{51}\mathrm{erg}} \right)^{0.7} \mathrm{keV}. \tag{4}$$

Where D_L is the luminosity distance of the GRBs. For the other GRBs we have taken an estimated value of redshift as 2.3, as the median redshift value of *Swift* [12]. The values of ξ_1 with respect to the neutrino track event energies are plotted in figure 2. The box represent the reported error in the energy of the events. The value of the LIV parameters ξ_1 varies from $5 \times 10^{-5} - 10^{-3}$ for GRB 120913B to GRB 110212A for the respective limits. The different category of GRBs that is known redshift, pseudo redshift and assumed redshift are shown with blue, green and red colored boxes respectively. A similar calculation shows that ξ_2 varies between $8 \times 10^{-20} - 9 \times 10^{-17}$.

The energy scale ($\xi_1 M_{pl}$) to explain the time delay corresponding to the ξ_1 limits is $10^{11} - 10^{13}$ GeV. This limit is not as constraining as earlier reported by *Fermi* detected gamma rays of energy GeVs for GRB 090510 and GRB 080916C [16][17] with limits $\xi_1 > 1.2$ and 0.1 respectively. However this is the first neutrino data analysis for the Lorentz invariance violation at TeV energy scale.

5. Summary

The IceCube neutrino observatory has detected at least 54 neutrino events within the 30 TeV–2 PeV energy range. The Origin of these events is still a puzzle for both particle physics and astrophysics. On the other hand these high energy particles can probe exotic physics like a small violation in Lorentz invariance. Another high energy neutrino observatory ANTARES, has also detected a neutrino track event with an energy between 50 TeV to 100 TeV. Gamma ray bursts are promising sources for high energy neutrino. Assuming that, where GRBs correlated with the track events, assuming the neutrino events originate from the GRBs, we have calculated the LIV parameter. We found 14 times the track events correlated with the GRBs, and the result showed LIV parameter $\xi_1 M_{pl}$, to have lower limit as $10^{11} - 10^{13}$ GeV.

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