Gamma-Ray Bursts as Probes for Quantum Gravity

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1 Introduction

Gamma ray bursts (GRBs) are short and intense pulses of γ-rays arriving from random directions in the sky. Several years ago Amelino-Camelia et al. [1] (see also [2]) pointed out that a comparison of time of arrival of photons at different energies from a GRB could be used to measure (or obtain a limit on) possible deviations from a constant speed of light at high photons energies. I review here our current understanding of GRBs and reconsider the possibility of performing these observations (see also Norris, Bonnell, Marani, & Scargle [3] for a review of the same topic). I begin (in Sect. 2) with a brief discussion of the motivation to consider an energy dependent variable speed of light. I turn (in Sect. 3) to a general discussion of the detectability of deviations from a constant speed of light via time-lag measurments. I derive constraints on the Energy range, the distance to the sources and the needed temporal resolution of the sources and the detectors. I then turn (in Sect. 4) to a short description of our current understanding of GRBs. This section is included as a background material as for the rest of the discussion GRBs are just cosmological sources of high energy photons and we don't really care how are these photons they produced. In Sect. 5 I return to the subject of the talk and I describe the temporal structure and spectral properties of GRBs. These are the key issues that are relevant for the observations of a variable speed of light. I conclude (in Sect. 6) by confronting the observations needed for determination of (or obtaining a limit on) a variable speed of light with the properties of GRBs. I discuss some recent attempts to obtain limits on Quantum Gravity effects [4, 5, 6, 7] and prospects for future improvements.

2 An Energy Dependent Speed of Light

An energy dependent speed of light arises in a variety of Quantum Gravity models, ranging from critical or noncritical string theories, via noncommutative

T. Piran: *Gamma-Ray Bursts as Probes for Quantum Gravity*, Lect. Notes Phys. **669**, 351–362 (2005)
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geometry, to canonical quantum gravity. These models, which involve a breakdown or a modification of Lorentz invariance at high energies, have been discussed extensively in other lectures in this school and are reviewed elsewhere in this volume. I focus here on a simple linear velocity-energy relation (see (1) below) that arises in models for the breakup of Lorentz symmetry proposed by Amelino-Camelia et al., [1]. It appears that a similar analysis is also applicable to the case of "DSR deformation" of Lorentz symmetry, since the same time-of-flight studies are considered in that framework [9, 10, 11, 12]. In fact I would expect that this simple linear velocity-energy relation (1) would be valid, to a leading order, in many other models.

On the phenomenological side an energy dependent speed of light was suggested as a possible resolution of the GZK paradox [13, 14]: The observations of UHECRs (Ultra High Energy Cosmic Rays) above the expected (GZK) threshold for interaction of such cosmic rays with the Cosmic microwave background [15, 16, 17, 18, 19, 20]. Such energy dependence could be related to a threshold violation at very high energies. Another possible indication for this phenomenon is the observation of TeV photons from distant sources [21, 22, 23]. Such photons are expected to be annihilated due to the interaction with the IR background. Again threshold anomalies (that would be associated with an energy dependent speed of light) could resolve this problem [20, 24, 25, 26]. In fact Amelino-Camelia and Piran [20] have pointed out that a simple Lorentz invariance deformation with parameters of the order expected in various quantum gravity theories (namely $\eta \sim 1$ in the notations used below) could resolve both paradoxes.

3 On the Detection of Energy Dependent Time Lags Due to an Energy Dependent Speed of Light

In this short review I will not discuss the theoretical or the phenomenological motivations for an energy dependent speed of light. Instead I focus on the detectability of this phenomenon. I stress that the deviations that I discuss here are drastically different from those that arise from appearance of a photon mass. The effects of a photon mass are most pronounced at low energies. However, the deviations considered here depend on E/M_{pl} and are relevant only at very high energies.

Amelino-Camelia et al. [1] (see also [8] and other talks in this volume) pointed out that even a small variations in the speed of photons with different energies could lead to observable energy dependent time of arrival lags for photons arriving from a cosmological source. Following Amelino-Camelia et al. [1], I consider a linear energy dependence of the form:

$$v = c\left(1 - \frac{E}{\eta M_{pl}}\right) \ , \tag{1}$$

where M_{pl} is the Planck mass and η is a dimensionless constant. Quantum gravity effects that cause the deviation in the speed of light are expected to take place around the Planck energy, M_{pl}. I characterize the exact energy in which these take effect as $E_{QG} \equiv \eta M_{pl}$. The sign of η determines the direction of these changes.

One can easily generalize the discussion and consider a more general velocity-energy dependance, such as: $v = c[1 - (E/\eta M_{pl})^{\alpha}]$ [20, 17]. However, for $\alpha > 2$ and for the relevant energy range and for $\eta \approx 1$ the resulting time delays will be so short that I don't discuss this case here.

This velocity law (1) leads to a time lag between a photon at energy E and a very low energy photon of:

$$\delta t(E) \approx 10 \text{ msec } \eta^{-1} d_{Gpc} E_{GeV} \ , \tag{2}$$

where d_{Gpc} is the distance to the source in units of Gpc and E_{GeV} is the photon's energy in GeV. Ellis et al., [6] provide an exact expression as a function of the redshift of the source. However, the approximate expression given above is sufficient for the purpose of this work. The dotted lines in Fig. 1 depict the relation between d and E for different values of $\eta\delta t$. A detection, for a given value of $\eta\delta t$, is possible only above the corresponding line. The value of δt is the minimal time delay that can be detected in the particular source.

It is clear from (2) that we need a very high energy source. However for these sources, because of the enormous energy that each of the photons carries the rate of arrival of high energy photons, $R(E)$, is very often too small. I call these sources which are limited by a too small rate of arrival of photons: *photon starved sources*. This has to be taken into account as the low photon rate limits the shortest possible detectable temporal variation as:

$$\frac{1}{R(E)} = \frac{4\pi d^2 E}{AL(E)} = 180 \text{ msec } \frac{d_{Gpc}^2 E_{GeV}}{A_4 L_{50}(E)} \leq \delta t_{min} \ , \tag{3}$$

where $L(E)$ is the luminosity at energy E and where I have ignored for simplicity cosmological correction factors. $L_{50}(E)$ is the luminosity at the relevant energy interval in units of 10^{50} ergs/sec and A_4 is the area in units of m^2. Again δt_{min} is the minimal time scale that can be detected in the particular source.

The exact limit that the combination of (3) and (2) imply depends on the spectral shape, on the overall luminosity and on the variability time scale at the source. Quite generally these conditions lead to an *upper limit* on the distance from which the effect could be measured and to a *lower limit* on the energy. As I show in Sect. 6 this limit is important for GRBs. As an example the solid lines in Fig. 1 correspond to equal values of $AL\delta t_{min}$, for the case when the luminosity per decade is constant (i.e. the spectral index is -2) and for the case that the inequality (3) is satisfied as an equality. The dashed line on this figure depicts the same graph for $L(E) \propto E^{-1/2}$

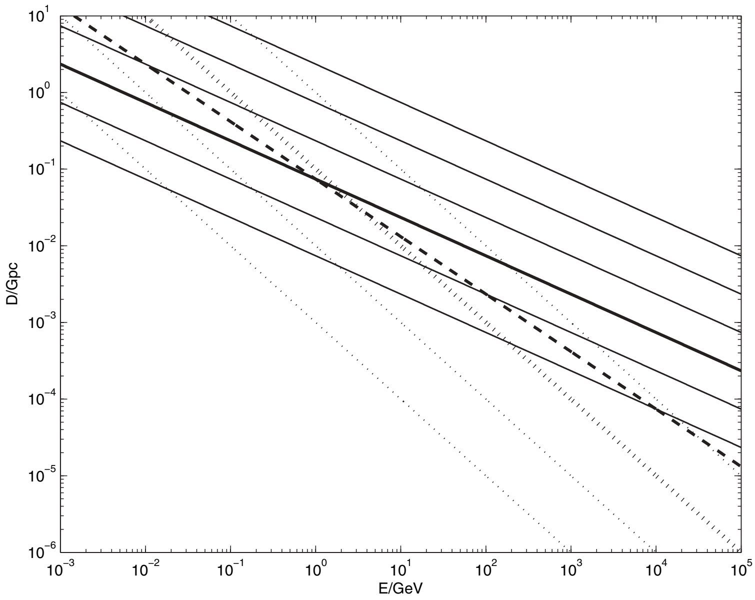

Fig. 1. Lines of a constant values of $\delta t_{ms} L_{50} A_4$ (*solid lines*) for $\delta t_{ms} L_{50} A_4 = 0.01, 0.1, 1, 10, 100, 1000$. δt_{ms} is in units of msec. The canonical value $\delta t_{ms} L_{50} A_4 = 1$ is marked by a *thicker line*. Detection is possible only below a given *solid line*. The single *dashed line* corresponds to $L(E) \propto E^{-1/2}$ and is normalized so that $\delta t_{ms} L_{50}(1\,\mathrm{GeV})\mathrm{A}_4 = 1$. The *dotted lines* mark lines of constant values of $\delta_{ms}\eta = 0.01, 0.1, 1, 10$, where again δt_{ms} is in units of msec. The canonical value of $\delta_{ms}\eta = 1$ is marked by a *thicker line*. Detection is possible only above a given *dotted line*. The combination of both constraints yields an allowed wedge with a maximal distance and minimal energy. Note that the vertical scale of distances ranges from cosmological distances at the *top* ($d_{Gpc} > 1$) to local (galactic) distances at the *bottom* ($d_{Gpc} < 10^{-5}$)

which is normalized so that the luminosity per decade of energy at 1 GeV is 10^{50} ergs/sec. A detection is possible only below these lines. For a given combination of $\eta\delta t$ and $LA\delta t$ a detection is possible only within a wedge outlined by the corresponding solid line and dotted line. Namely, for a given set of parameters there is a **maximal** distance and a **minimal** energy for which the time-lag can be detected. This suggests that in some cases (but not in the general case) a local (galactic) source with a strong very high energy signal might be advantageous over a weak source at a cosmological source. Indeed this was used by Kaaret [27] to obtain a meaningful limit on $\eta > 1.310^{-4}$ using the emission from the Crab pulsar which is only at 2.2 kpc

It is clear from (2) that a cosmological distance and a high energy are needed for a significant δt. However, the interaction of high energy photons with the cosmic IR background limits the distance that high energy photons can travel. For $E \sim 100\,\mathrm{GeV}$ the optical depth to $z = 0.5$ is unity [28][1]. Thus, we must consider photons with $E < 100\,\mathrm{GeV}$. This, in turn gives an upper limit of $\sim 6/\eta\,\mathrm{sec}$ to possible magnitude of the time delay between photons of different energies. This is independent of the source of the emitted photons. It immediately follows that to observe this phenomenon we need cosmological sources of $\sim$ GeV photons with a rapid and detectable variability on the time scale of seconds or less. Amelino-Camelia et al. [1] point out that Gamma-ray bursts are the natural candidates for this task, and indeed several groups obtained lower limits on η using GRBs [4, 5, 6, 7].

4 Gamma-Ray Bursts

GRBs are short and intense pulses of γ-rays that are located at cosmological distances. As such GRBs are ideal sources for the effect that we are looking for. For the purpose of this work GRBs are just a cosmological source of high energy photons. Their exact nature is unimportant for our ability to use the photons to test the predictions of quantum gravity. However, it is worthwhile, for completeness, to review briefly our current understanding of this phenomenon. I refer the readers to several extensive reviews [29, 30, 31, 32, 33, 34, 35, 36, 37] for more details.

It is generally accepted that GRBs are described by the internal-external shocks model [38, 39, 40, 41]. According to this model GRBs are produced when the kinetic energy of an ultra-relativistic flow is dissipated. Internal shocks within the relativistic flow produce the GRB. These shocks take place at a distance of $\sim 10^{13} - 10^{15}\,\mathrm{cm}$ from the center. The short observed time scales (which violates the simple naive rule of $\delta t < R/c$) arises because of the relativistic motion of the flow (with a Lorentz factor $\gamma \geq 100$) towards us. Subsequent interaction of the relativistic outgoing flow with the surrounding matter leads to the production of an afterglow (in x-ray, optical and radio) that lasts days, weeks, months and in some cases even years. This takes place at distances of $\sim 10^{16} - 10^{18}\,\mathrm{cm}$ from the center. The flow is slowed down due to this interaction and eventually it becomes Newtonian.

It is worthwhile to mention what is the validity of this model. Indirect determination of the size of the afterglow of GRB 970508 [42] and direct measurement of the size of the afterglow of GRB 030329 [43] confirmed the predicted relativistic motion . Additionally there is a good agreement between the observed spectra and light curves of the afterglows and the predictions of the relativistic shock synchrotron model. There is also good observational evidence for the "internal-external" shocks transition. On the other hand, little is known about the details of the "inner engine" and the details how does the collapsing core produce the required relativistic jet.

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[1] Different authors make different assumptions on the IR background and find different estimates for the optical depth. These quantitative differences are not important for the purpose of this work.

The discovery of long lasting x-ray, optical and radio afterglow enabled the determination of the redshifts and the positions of some bursts. The identification of bursts within star forming regions and the identification of Supernovae (SNe) signatures (SNe bumps) in the afterglow of some bursts (most notably GRB 980425 and GRB 030329) revealed that long[2] bursts are associated with type Ic Supernovae. As the rate of SNe Ic is much larger than the rate of GRBs it is clear that not all Supernovae are associated with GRBs. Jet-breaks detected in the afterglow of many bursts revealed that the bursts are beamed into cones of a few degrees and that their total energy is rather constant $\sim 10^{51}$ ergs [45, 46].

The GRB-SNe association is explained according to the Collapsar model [47], which is a model for the "inner engine". According to this model a black hole – accretion disk system forms during the core collapse. This system produces a relativistic jet that manages to punch a hole in the supernova envelope. The burst and the afterglow are produces along the internal-external shocks model, once the relativistic jet has emerged from the envelope.

5 GRB Observations and Testing of a Variable Speed of Light

The possibility of observing the energy dependent time-lags depend on four factors the distances to the sources, their temporal structure, their spectrum and their intensity. I discuss these three features here:

- **Distances** It is established that the bursts arise from cosmological distances. The identified redshift record is 4.5 (GRB 000131) but it is likely that more distant bursts has been observed but their redshift is unknown [48].
- **Temporal Structure** The bursts durations vary lasting from a few milliseconds to a thousand seconds. The paucity of bursts with a duration around two seconds suggest a classification of the bursts to two groups according to their durations – long bursts with durations longer than 2 seconds and short one with a durations shorter than 2 seconds.
  What is most important for our purpose is that most bursts show a highly variable light curve (see for example Fig. 2). Nakar and Piran [49], for example analyzed the TTE (high resolution data of the short bursts and of the first two seconds of long ones) find in many burst sub-pulses on a time scale of 10 ms (which was about the minimal possible temporal resolution). with sub-pulses on a scale as short as a fraction of a millisecond [50].
- **Spectrum** The bursts's spectrum usually peaks around a few hundred keV. Recently a subgroup of bursts, x-ray flashes, that emits most of their

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[2] As afterglow was seen so far only from long burst it is not clear if short bursts are also associated with Supernovae. In fact there are some theoretical considerations that suggest that they are not related.

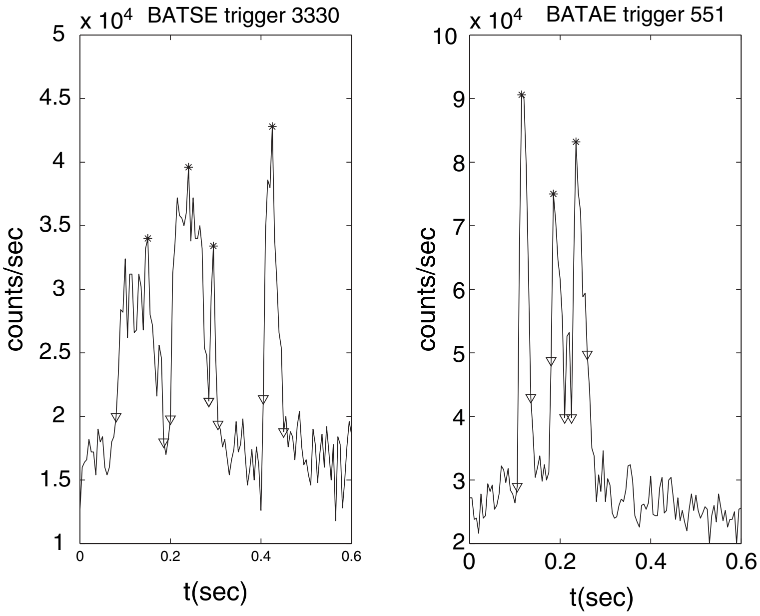

Fig. 2. (*Left*) The beginning of BATSE trigger 3330: a long bright burst with $T_{90} = 62$ sec. (*Right*) The whole light curve of BATSE trigger 551: a bright short burst with $T_{90} = 0.25$ sec. The peaks are marked by stars and the triangles mark the pulses' width. The figure demonstrates similar short time scale structure in these bursts (at a 5 msec resolution). From [49]

energy in X-ray was discovered. In many cases a high energy tail, with photon energies from 100 MeV to 18 GeV has been observed [51]. The TeV detector, Milagrito, discovered (at a statistical significance of 1.5e-3 or so, namely at 3σ) a TeV signal coincident with GRB 970417 [52, 53]. However no further TeV signals were discovered so far from other 53 bursts observed by Milagrito [52] or from several bursts observed by the more sensitive Milagro [54]. One should recall however, that due to the attenuation of the IR background TeV photons could not be detected from $z > 0.1$. Thus even if most GRBs emit TeV photons those photons won't be detected on Earth. Similarly these photons are too energetic for our purpose.

- **Intensity** The last factor that is important in our consideration is the intensity of the signals. This is important because a significant number of photons is needed to determine exactly the timing of a pulse. The strongest observed bursts have a fluence of 10^{-4} ergs/cm^2 corresponding to 1000 (100 keV photons)/cm^2. The peak photon flux (on the BATSE[3] 64 msec channel) is $\sim$180 photons/cm^2/sec. With typical detectors' area of several

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[3] BATSE, the Burst and Transient Source Experiment on board on NASA's Compton-GRO, is the largest GRB detector flown so far.

square meters this leads to a (100 keV range) photon rate of more than a photon per μsec that in principle could be used to determine the temporal structure down to a very short time scales.

The situation looks at first promising. GRBs are highly variable bright cosmological sources providing γ-ray photons at the right distances. Equation (2) reveals that energies higher than 100 MeV are needed to produce a time delay of a few millisecond and many GRBs have such photons. At the same time many GRBs show variability on such a time scale. However, as we see in the next section one should proceed with cation before concluding that GRB signals could provide a real measure of a variable speed of light.

6 Caveat, Past Observations and Future Prospects

A careful look at the properties of GRBs uncovers, however, problems. The main problem is that it is not clear that the high and low energy photons seen from GRBs are emitted simultaneously. In fact the current understanding is just the opposite. The highest energy (18 GeV) photons discovered by EGREAT (a detector on Compton – GRO), were observed more than an hour after the main burst [55, 56]. Similarly, when Gonzalez et al. [57] combined the BATSE (30 keV–2 Mev) data with the EGRET data they discovered in GRB 941017 a high energy tail that extended up to 200 MeV. This high energy component appeared 10–20 sec after the beginning of the burst and displayed a roughly constant flux up to 200 sec, while the main lower energy burst decayed after several dozen seconds.

One may hope that this non-simulteneity appears only in a "global" sense and that on a short time scale high energy photons are emitted simultaneously with the low energy ones. While there is not enough information on the generic time lag between very high (100 MeV and higher) and low energy (100 keV) GRB photons there is a lot of "alarming" information on lack of simultaneity within the BATSE band (25 keV to 2 MeV). Already in 1992 Fishman et al., [58] (see also Link et al., [59]) noticed that the duration of GRB pulses depend on their energy and that at lower energy the pulses are wider. Band [60] classifies this as a hard to soft evolution. Later Norris et al., [61] noticed that this evolution corresponds to a time lag between pulses at different energies. Typically the higher energy pulses peak before the corresponding low energy ones. For a sample of 174 bright bursts Norris et al., [61] find typical lags between channel 1 (25–50 keV) to channel 4 (300 keV–2 Mev) of the order of 0.1–0.2 sec with a maximal lag of 5 sec. A small fraction ($\sim$5%) of the bursts have negative lags of the order of less than 0.1 sec. These lags are larger by a factor of 2–3 than the lags suggested in (2) for a GeV photon!

For the bursts with a known redshift Norris et al. [61] find interesting anticorrelation between the time lags and the peak luminosities of the bursts. This correlation, for which there is no clear theoretical explanation, has been used by Norris et al. [61] to estimate the luminosity of other bursts. It is in a general agreement with other luminosity indicators such as the variability of the bursts [62]. While this correlation is not of interest for the purpose of this work the existence of intrinsic time lag between photons of different energies may jeopardize the whole prospect of detection of energy dependent time of arrival lags arising from an energy dependent travel time. It is clear that such an observation requires a simultaneous emission of photons at different energies.

Ellis et al. [6] suggest to use the redshift dependence of the velocity induced time lags to distinguish them from the intrinsic lags that are produced at the source. By plotting the time lags for several BATSE bursts with a known redshifts they obtain a limit $E_{QG} > 6.9 \cdot 10^{15}$ GeV or in our notations $\eta > 6.9 \cdot 10^{-4}$. As the highest energy photons used are of $\sim$1 MeV, this corresponds, according to (2) above to the conclusion that the redshift dependent time lags are less than $\sim$0.1 sec, which is comparable with the intrinsic time lags of these bursts [61]. Given the time resolution this limit ($\eta > 10^{-3}$ seem to be (see in (2)) the best that can be done using "low" energy ($\sim$ MeV) photons.

However, there is another observational factor that appears here. Norris et al. [65] describe the tendency for wide pulses to be more asymmetric, to peak later at lower energy and to be spectrally softer, while narrow bursts are harder, more symmetric, and nearly simultaneous. This implies that the narrowest peaks, those that are most interesting for this experiment have a chance of being simultaneous in both low and high energies. Schafer [4] uses, along these lines, the observations of one of BATSE's brightest bursts, GRB 930131 with 30 keV and 80 MeV photons to obtain a limit of $E_{QG} > 8.3 \cdot 10^{16}$ GeV (or $\eta > 8.3 \cdot 10^{-3}$). Also along this line Boggs et al., [7] analyze GRB 021206. They used the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) with an energy range of (3 keV to 17 MeV). They noticed that while the lower energy (<2 MeV) light curve of the burst is rather irregular at higher energies the light curve exhibits a single sharp pulse of photons extending to energies above 10 MeV with a duration of 15 msec. This enables Boggs et al., [7] to set a limit of $\delta t/E = 0.0 \pm 0.34\,\mathrm{sec}\,\mathrm{GeV}^{-1}$ from which they obtain $E_{QG} > 1.8 \cdot 10^{17}$ GeV ($\eta > 0.018$). Considering (2) this seems to be the best that can be done with 10 MeV photons. To improve we have to get to lower temporal resolution (which might not be possible) or to higher photon energies.

But here arises a second simple but important problem. In spite of the fact that GRBs are the most luminous objects in the universe at GeV energies they are *photon starved*: the observed flux is simply low. The maximal GRB fluxes at energies of a few hundred keV are of $\sim$100 $\mathrm{photons}_{100\,\mathrm{keV}}/\mathrm{cm}^2/\mathrm{sec}$. With a several square meter detector this corresponds to a flux of 10^6 100 keV photons/sec or to a photon rate of one per µsec. However even if GRBs emit the same energy flux at the GeV range this flux corresponds to a meager $10^{-3}/\mathrm{cm}^2/\mathrm{sec}$ GeV-photons or to 10 GeV-photons per second with a square meter class detector. As the minimal temporal resolution is larger than the reciprocal of the rate of observed photons it will be impossible to obtain a temporal resolution of better than ∼100 msec at the GeV range. From (2) this corresponds to a limit on η of order unity if all other problems are resolved.

The comparison of (2) and (3) (shown in Fig. 1 for a constant energy per logarithmic interval) yields that to resolve the time lags we need a nearby ($d < 1$ Gpc) very luminous GRB with a significant GeV component. Truly the rather "small" distance will reduce δt. However, only in this way there will be enough photons to obtain a sufficient temporal resolution. The requirement of short distances implies that we won't be able to use the redshift effect to distinguish between intrinsic lags and time of flight lags. However, the fact that we consider only very luminous bursts may resolve this problem as the luminosity-lag correlation indicates that intrinsic lags are smaller for more luminous bursts and they may disappear for the very bright ones. These simple considerations are indeed supported by the present observations. Boggs et al., [7] considered a single very bright burst: GRB 0211206 which was one of the most powerful bursts ever [63] and was most likely at $z \approx 0.3$, and obtained $\eta > 0.018$. This should be compared with $\eta > 0.00069$ obtained by Ellis et al. [6] who considered a family of weaker bursts at cosmological distances $z \geq 1$. One has to recall however, that such a burst occurs once per decade and it is not clear when will the next one take place. Hopefully a suitable GRB detector will be in orbit at that time.

The best prospect to estimate the variable velocity energy dependent effect will be with a single observatory that could observe both the low energy γ-rays as well as the GeV emission. Luckily there are two planed mission that can perform this job.

The Italian **Agile** (Astro-rivelatore Gamma a Immagini LEggero) detector [64] is scheduled to be launched in 2005. It is a GRB detector at the energy range of 30 MeV–50 GeV and a low energy detector at 10–40 keV. Thus it is expected to detect GRBs at both very high and very low energy. The temporal resolution is about 1msec. The expected detection rate is about 10 GRBs per year at energies above 100 MeV. The basic limitation of Agile is its relatively small area ($\sim 0.16\text{m}^2$).

An ideal observatory will be NASA's **GLAST** (Gamma Ray Large Area Space Telescope). GLAST is scheduled for launch in 2007 (Norris et al., [3]). GLAST will include the Large Area Telescope, LAT, which will have an effective area of 8m^2 and will be sensitive to photons in the 20 MeV–300 GeV range and GRM, a Gamma-Ray burst Monitor which will be sensitive to photons in the 10 keV to 25 MeV range. Both the LAT and the GBM provide the arrival time of each photon with a resolution requirements of <10 µsec (with a goal of <10 µsec) and will give energies for each detected photon. One cannot ask for more, in terms of the experimental design needed to study the energy dependent time lag. Thus, if the intrinsic time lags will be resolved or shown to be unimportant in some sub class of pulses or bursts, and this is a very big IF in my mind, we might be able to obtain a limit of η around unity towards the end of this decade.

I thank D. Band, E. Nakar and G. Amelino-Camila for helpful remarks. This research was supported by the US-Israel Binational Science Foundation.

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