Prospects for constraining quantum gravity dispersion with near term observations

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Abstract

We discuss the prospects for bounding and perhaps even measuring quantum gravity effects on the dispersion of light using the highest energy photons produced in gamma ray bursts measured by the Fermi telescope. These prospects are brighter than might have been expected as in the first 10 months of operation Fermi has reported so far eight events with photons over $100\,\text{MeV}$ seen by its Large Area Telescope (LAT). We review features of these events which may bear on Planck scale phenomenology and we discuss the possible implications for the alternative scenarios for in-vacuo dispersion coming from breaking or deforming of Poincare invariance. Among these are semi-conservative bounds, which rely on some relatively weak assumptions about the sources, on subluminal and superluminal in-vacuo dispersion.

We also propose that it may be possible to look for the arrival of still higher energy photons and neutrinos from GRB’s with energies in the range $10^{14} - 10^{17}\,\text{eV}$. In some cases the quantum gravity dispersion effect would predict these arrivals to be delayed or advanced by days to months from the GRB, giving a clean separation of astrophysical source and spacetime propagation effects.

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1 Introduction

The possibility of probing the physics of quantum gravity with high energy astrophysical observations has been discussed seriously now for more than a decade \[^{[1]-[14]}\], and there has been significant progress at Auger and other observatories, but with the launch of the Fermi gamma ray telescope \[^{[15]}\] in June 2008 it has become a reality. This is because of the possibility of putting bounds on, or even discovering, a generic consequence of quantum gravity models, which is the dispersion of light governed by a scale \[^{1}l_{\text{QG}} = \frac{1}{M_{\text{QG}}}.\] Here \(M_{\text{QG}}\) may be expected to be within a few orders of magnitude of \(M_{\text{Planck}} = \frac{1}{\sqrt{G_N}}.\) This leads to a variation in arrival time with energy, roughly given by (see later)

\[
\Delta t \simeq \frac{\Delta E}{M_{\text{QG}}} L,
\]

which could be as large as seconds to hours for photons in the GeV to TeV range if the distance \(L\) travelled is cosmological.

Consequently, given the timing accuracy of Fermi it has been anticipated that after many events bounds could be put on \(M_{\text{QG}}\) on the order of \(M_{\text{Planck}}.\) But, as we discuss here, the situation is better than might have been hoped for because of several features of the early data from the telescope, which have so far been reported in papers, talks by collaboration members, and notices for the Gamma-ray burst Coordinates Network (GCN).

- There are already, in the first ten months of operation, at least eight \[^{[15-17]}\] Gamma Ray Bursts (GRBs) detected whose spectrum extends to photons near or above 1 GeV in energy, with the highest energy photon reported already at 13 GeV.

- At least in one case (GRB080916C \[^{[15]}\]) the number of events at high energy was abundant enough to allow spectral studies. And in several cases numerous high-energy photons were observed.

- This has allowed a remarkable early achievement, which is the raising of the conservative bound on \(M_{\text{QG}},\) by an order of magnitude, to within ten percent of the Planck mass, based on the observation of a single GRB \[^{[15]}\]!

- Some bursts are at high redshift, with two bursts with \(z \approx 4.\)

- In these early events there are clear trends that more energetic photons arrive later, although the structure of the events is complex.

\[^{1}\text{We use units such that the Planck constant } \hbar \text{ and the speed-of-light scale } c \text{ are set to 1. Since we are considering the possibility of in-vacuo dispersion we are implicitly assuming as operative definition of the speed-of-light scale the value of the speed of light in the infinite-wavelength limit.}\]
- Already two short bursts have been observed at high energies, which offer approaches to bounding in-vacuo dispersion complementary to those possible with long bursts.

The combination of these factors means that even more stringent bounds on $M_{QG}$ may be possible in the near future. This also, as we will discuss, leads to a possibility of succeeding at the more difficult challenge of measuring a nonzero $M_{QG}$ as data accumulates, leading to a discovery of a breaking or deformation of special relativity. Making such a measurement is much harder than putting a bound, because the structure of the bursts are complicated and there are astrophysical effects at the sources over time scales comparable to $\Delta \tau$'s expected from (1). The challenge is then to find methodologies which can be applied to the accumulated data sets which separate astrophysical from possible quantum gravity effects.

To help prepare for facing this challenge we do the following in this paper. First, in the next section we survey the three basic possible scenarios which lead to effects of (1) coming from either breaking or deforming of lorentz invariance. We also review the situation which obtained before Fermi to discriminate amongst them observationally.

In section 3 we review and discuss some features of the GRB observations reported so far by Fermi and explain the reasons for the optimistic statements in the opening paragraphs. We review the reasoning behind the conservative bound on subluminal propagation published so far[15] and propose new sets of assumptions that lead to new bounds, both on subliminal and superluminal propagation. These are somewhat less conservative than the bound published in [15] but they may serve as sources of intuition for theoretical considerations. We also discuss comparisons between bounds obtained from Fermi results and preliminary indications which had been previously drawn from data on Mk501 and PKS2155-304.

In section 4 we discuss whether the data may eventually allow a measurement of rather than a bound on $M_{QG}$. We also raise the possible role of new windows involving photons and/or neutrinos at still higher energies in the range of $10^{14}$ to $10^{17}$eV. These would be above the range that can be seen from Fermi and would be observed by ground based telescopes such as Auger and ICECUBE. To measure a quantum gravity effect with these instruments would involve correlations with GRBs with delays of days to months. We will argue that such observations are not impossible and would cleanly separate astrophysical from quantum gravity effects.

Most of the literature on the phenomenology of in-vacuo dispersion concerns models of dispersion with a single parameter, $M_{QG}$. In section 5 we discuss the possibility of models with two and more parameter and discuss how they may be constrained by observations.

We close with conclusions.
2 Options for one parameter modified dispersion relations

The most basic question that can be asked about the quantum gravitational field, or indeed of any physical system, is: What is the symmetry of the ground-state?

The ground state of general relativity is (ignoring the cosmological constant) Minkowski spacetime, and its symmetry is the Poincare group. It is then natural to ask whether the Poincare group is also the symmetry group of the quantum spacetime geometry. It may be, and this is assumed in several approaches to quantum gravity, particularly perturbative approaches such as perturbative general relativity and perturbative string theory. But it is natural to feel some skepticism about the applicability of the Lorentz transformations up to and beyond extreme cases where for example, one angstrom may be Lorentz contracted by 25 orders of magnitude to the Planck length. Experts will be aware that the intuitions of theorists on the ultimate fate of Lorentz invariance are diverse, with accomplished theorists expressing views all along the spectrum of expectations from the perfect validity to the complete breaking of Lorentz transformations. Our view is that the fate of Lorentz symmetry at the extremes should be an experimental question and, happily, it is becoming so.

Research in quantum gravity phenomenology has focused on the question of the fate of Lorentz invariance largely through the lens of modifications of energy-momentum relations. Over the last years several scenarios have arisen for dispersion of light motivated by theories and hypotheses about quantum gravity. From the perspective of experimental tests, these sort themselves into three broad categories, which we will now discuss. Note that as we are discussing experimental tests we discuss them without regard to our own views as theorists as to which, if any, is more likely true. Similarly, we do not comment on whether it appears to be more likely from a theoretical perspective that the dispersion effects should first appear at linear or quadratic order in $\frac{1}{M_{QG}}$. We have the opportunity now with Fermi to put strong bounds on the linear case so we focus on these here.

2.1 Lorentz symmetry breaking without effective field theory

The first results on the implications of Planck-scale spacetime structure for the persistence or not of the symmetries of special relativity took the form $[1, 2]$ of modifications of the energy-momentum “dispersion” relation

$$m^2 = E^2 - p^2 + \Delta_{qg}(E, p; M_{QG}),$$

(2)

where $E$ and $p$ denote energy and momentum of a particle of mass $m$ and $M_{QG}$ is the reference/characteristic scale of quantum-gravity effects, which is expected to be in some relatively close neighborhood of the Planck scale. $\Delta_{qg}$ is a function with dimensions $(mass)^2$.

In Refs. $[1, 3]$ it was observed that the leading-order correction to the classical-spacetime dispersion relation could be tested experimentally. We can parametrize these leading-
order correction in the ultrarelativistic \((E \gg m)\) limit as follows:

\[
E \simeq p + \frac{m^2}{2p} - s_\pm \frac{1}{2} \frac{E^{\alpha+1}}{M_{QG}} ,
\]

(3)
a parametrization which, in addition to \(M_{QG}\), also involves the power \(\alpha\), expected to be an integer \((\alpha = 1\) for linear suppression by the quantum-gravity scale, \(\alpha = 2\) for quadratic suppression by the quantum-gravity scale), and \(s_\pm \in \{-1, 1\}\), which specifies the sign of the correction \(s_\pm = 1\) gives the “subluminal” case whereby higher energy photons go slower, while \(s_\pm = -1\) corresponds to the opposite “superluminal” case.

Starting with the studies reported in Refs. [5, 6] the phenomenology based on the dispersion relation (3) also used the (unmodified) law of energy-momentum conservation, which in particular for a \(a + b \rightarrow c + d\) particle-physics process gives

\[
E_a + E_b = E_c + E_d ,
\]

(4)
\[
p_a + p_b = p_c + p_d .
\]

(5)

Note that this framework breaks Lorentz symmetry, and it should therefore be properly studied in a “privileged” reference frame, such as the natural frame of CMB radiation. We may call this naïve Lorentz symmetry breaking or NLSB

Moreover, it should be stressed that there need be no dependence of the correction terms on helicity/polarization and hence, no birefringence for the propagation of light[1, 3]. For reasons that will be clear shortly, it turns out to be impossible to describe the effects of this scenario within the framework of effective low-energy field theory in a classical spacetime. This leads some theorists to be skeptical that this can be a realistic framework. Our view is that effective field theory can be an important theoretical guide, but its ultimate validity is itself an experimental question. Thus, theoretical expectations should not be the basis of closing off experimental searches, especially given the likelihood that new physical principles may come into play at the Planck scale.

2.2 Lorentz symmetry breaking within effective field theory

Soon after the first papers on the NLSB scenario, Gambini and Pullin produced [7] a first attempt of formalization within low-energy effective field theory. This led to scenarios we call lorentz-symmetry breaking in effective field theory, or (LSB-EFT). They showed that for correction terms that are only linearly suppressed by the Planck scale \((\alpha = 1)\) one would inevitably end up predicting birefringence for light waves.

Note that while Gambini and Pullin worked within the framework of loop quantum gravity [18, 19, 20, 21], their scenario depends on the assumption of a particular and non-physical ground state for that theory. Thus, their scenario should not be viewed as a

\[\text{This “sign parameter” } s_\pm = 1 \text{ was denoted by } \xi \text{ in Ref. [3].}\]

\[\text{This framework emerged primarily from the studies reported in Refs. [1, 2, 3, 5, 6].}\]
definite prediction of loop quantum gravity or more generally of other quantum theories of gravity.

Unfortunately, this is typical of the current state of the art, in which theories of quantum gravity suggest possible new phenomena that can be searched for experimentally, without so far making precise predictions for them [22]. At this phase in our understanding it makes sense to use semi-heuristic arguments based on the present understanding of the various approaches to the quantum-gravity problem to derive an intuition for the effects that could be expected, which are then to be modeled phenomenologically.

For the details of modelling Planck-scale dispersion within an effective-field-theory setup, a framework introduced by Myers and Pospelov[23] has proved very useful. It was shown there, assuming essentially only that the lorentz symmetry breaking effects are linear in $l_{\text{Planck}}$ and are characterized by an external four-vector, that one arrives at a single possible correction term for the Lagrangian density of electrodynamics:

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2M_{\text{Planck}}} n^\alpha F_{\alpha\delta} n^\sigma \partial_\sigma (n_\beta \varepsilon^{\beta\delta\gamma\lambda} F_{\gamma\lambda})
\]  

where the four-vector $n_\alpha$ parameterizes the effect.

The (dimensionless) components of $n_\alpha$ of course take different values in different reference frames, transforming indeed as the components of a four-vector. A comprehensive programme of investigations of this framework would require [24] a phenomenology of the Myers-Pospelov field theory exploring a four-dimensional parameter space, $n_\alpha$, and contemplating the characteristic frame dependence of the parameters $n_\alpha$. There is already a rather sizeable literature on this phenomenology (see, e.g., Refs. [22, 25, 26, 27] and references therein) but still fully focused on what turns out to be the simplest possibility for the Myers-Pospelov framework, which is the one of assuming to be in a reference frame where $n_\alpha$ only has a time component, $n_\alpha = (n_0, 0, 0, 0)$. Then, upon introducing the conventional parametrization in terms of a dimensionless parameter $\xi \equiv (n_0)^3$, one can rewrite (6) as

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\xi}{2M_{\text{Planck}}} \varepsilon^{jkl} F_{[wj} \partial_0 F_{kl]}, \tag{7}
\]

and in particular one can exploit the simplifications provided by spatial isotropy.

### 2.3 Doubly special relativity

The third option is doubly or deformed special relativity [11, 12, 13, 14, 28, 29, 30] which incorporates modifications or deformations of the Poincare transformations without giving up on the principle of the relativity of inertial frames. The principle of the universality of (the infrared limit of) the speed of light is joined by a principle of the universality of a second, dimensional scale, often taken to be the Planck energy. This scenario can be understood as the phenomenology arising from a quantum theory of gravity in the limit, $\hbar \to 0$ and $G_N \to 0$ with the ratio $M_{\text{Planck}} = \sqrt{\frac{\hbar}{G_N}}$ held fixed.
Over the last years it has been understood that this idea can be expressed in several different frameworks and theories, leading to a variety of phenomenologies. The most studied possibility is the description in terms of “Hopf algebras”, a generalization \[31,32\] of the concept of Lie algebra which appears to be relevant in some quantum pictures of spacetime, such as spacetime noncommutativity \[11,12,33\]. Significant progress has also been achieved by attempts to formulate DSR theories in terms of an energy-dependent “rainbow” metric \[34\].

At present DSR must be considered mainly a phenomenological framework as it has not yet been fully incorporated into realistic interacting quantum field theories. There have been several heuristic arguments that DSR follows from loop quantum gravity \[35,36,37\], but no rigorous proof. There are several results that indicate it is the case in models of spacetime with 2 + 1 dimensions \[35,38,39,40\]. There are presently only partial results towards the construction of interacting quantum field theories with DSR symmetry in 3 + 1 dimensions. It is not known whether DSR can be realized in string theory, although there is one positive result at the level of the free bosonic string\[41\].

While all these results should be still considered preliminary \[42\], the evidence available so far encourages us to assume that a dispersion relation of the type \[3\] could indeed be introduced in a DSR framework, with deformed laws of transformation between observers but no privileged class of observers (a “deformation” of Poincaré symmetry, but without breaking the symmetry).

For example, there has been a rather sizeable literature \[11,12,13\] considering the possibility that the dispersion relation be of the form

\[0 = 8M_{dsr}^2 \left[ \cosh \left( \frac{E}{2M_{dsr}} \right) - \cosh \left( \frac{m}{2M_{dsr}} \right) \right] - p^2 e^{s_{\pm} \frac{2E}{M_{dsr}}} \]  

which for \(E \ll M_{dsr}\) (of course also \(M_{dsr}\) is expected to have value close to the Planck scale) reproduces the dispersion relation \(3\) with \(\alpha = 1\):

\[E \simeq p + \frac{m^2}{2p} - s_{\pm} \frac{E^2}{2M_{dsr}}.\]  

Other forms of dispersion relations which have been explored include\[29\]

\[E^2 = \frac{p^2}{(1 + s_{\pm} \frac{E}{4M_{dsr}})^2} + m^2\]  

which also reduces at leading order to \(9\).

Note that there are DSR scenarios which give either sign of \(s_{\pm}\), giving rise respectively to sub-luminal or superluminal propagation. But a given DSR scenario generally predicts a parity even effect at leading order, so that one sign of \(s_{\pm}\) holds for all photons, independent of polarization. DSR frameworks with quadratic (\(\alpha = 2\)), rather than linear (\(\alpha = 1\)), leading modification of the dispersion relation have also been studied extensively (see,
e.g., Ref. [43] and references therein). It should also be emphasized that there are special choices of DSR deformations which leave the speed of light unchanged[44, 45].

The consistency of a DSR framework requires two further modifications of special relativistic physics that are not present in either NLSB or LSB-EFT scenarios. These are modifications of the Poincare transformations connecting observations made by different observers and modifications of the energy and momentum conservation laws. For example, the deformed laws of energy-momentum conservation, at leading order in $\frac{1}{M_{\text{dsr}}}$ take the form

$$E_a + E_b - \frac{s_\pm}{2M_{\text{dsr}}} p_a p_b - E_c - E_d + \frac{s_\pm}{2M_{\text{dsr}}} p_c p_d = 0 ,$$

(11)

$$p_a + p_b - \frac{s_\pm}{2M_{\text{dsr}}}(E_a p_b + E_b p_a) - p_c - p_d + \frac{s_\pm}{2M_{\text{dsr}}}(E_c p_d + E_d p_c) = 0 .$$

(12)

The deformations of transformation laws and energy-momentum conservation in DSR are extensively discussed in the literature. As these play no role in time of arrival experiments, they will not be further discussed here.

2.4 In-vacuo dispersion in the NLSB, LSB-EFT and DSR frameworks

From Eqs. (3) and (9) (respectively for the NLSB and DSR frameworks) one easily derives [1, 3, 11] that for two photons with energy difference $\Delta E$ simultaneously emitted by a source at relatively small redshift the times of arrival should differ by

$$\Delta t \big|_{\text{small } z} \simeq \frac{s_\pm}{M_{\text{QG}}} \frac{\Delta E}{L} ,$$

(13)

where $L = H_0 z$ is distance of the source from Earth given in terms of the Hubble expansion rate and the redshift. (In the DSR framework $M_{\text{QG}} \approx M_{\text{DSR}}$.) For the “subluminal” case, $s_\pm = 1$, one has positive $\Delta t$ whenever $\Delta E$ is positive, meaning that for simultaneously emitted particles the one of lowest energy is detected first. The opposite of course holds for the “superluminal” case, $s_\pm = -1$.

At large redshifts one should instead take into account the exact (non-linear) dependence on redshift encoded in the formula [46, 47, 48]: The basic formula for linear dependence

$$\Delta t = \frac{\Delta E}{M_{\text{QG}} H} \int_0^z dz \frac{1}{\sqrt{\Omega_\Lambda + (1+z^3)\Omega_{\text{Matter}}}}$$

(14)

assuming $\Lambda$CDM cosmology with parameters $\Omega_\Lambda$ and $\Omega_{\text{Matter}}$.

In the LSB-EFT framework there are similar effects of energy-dependent speed of photons, but the effect carries opposite sign for the two circular polarizations of light, i.e. it is a birefringence effect.

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4The exact form of these deformed laws of energy-momentum conservation is a rather messy combination of exponentials [43], but in the phenomenological applications we can foresee one only needs the form at leading order in $\frac{1}{M_{\text{dsr}}}$.
2.5 The situation before Fermi

There is a large literature [22, 27] on the phenomenology of lorentz symmetry breaking, both naive and within effective field theory, and a growing literature on the DSR phenomenology. Before Fermi, the bounds on the in-vacuo dispersion expected in the NLSB or DSR contexts were still two orders of magnitude below the Planck scale, even for the case of Planck-scale-linear effects on which we are here focusing. The best bound derived from GRB data before Fermi was $M_{QG} < 2 \cdot 10^{17}$ GeV from [49].

However, in the case of LSB-EFT, which has birefringent propagation, it has been established that very stringent bounds can be derived from observations of polarized radio galaxies. Assuming that the field-theoretic LSB-EFT setup is spatially isotropic in the natural frame of the CMB these bounds would exclude the entire range of values of $\xi$ that could be favoured from a quantum-gravity perspective. But, it has been very recently noticed [24] that these bounds become much weaker if one removes the assumption of isotropy in the CMB frame, and that this assumption of isotropy is not particularly preferred by the Myers-Pospelov setup. In light of this, we shall in the following prudently consider the LSB-EFT picture as still viable from a quantum-gravity perspective, but perceive it as an approach that does not naturally match the observations.

An important point is that so far as time of flight experiments are concerned the NLSB and DSR scenarios predict the same dispersion relations to leading order and hence make the same leading order predictions. Thus, to distinguish them one must take into account experiments where either or both of the modifications in transformation laws and energy momentum conservation arise. As these are modified in DSR, but not in NLSB, experiments that take them into account allow the NLSB and DSR scenarios to be distinguished.

Observations where this is the case are tests of threshold effects such as the GZK threshold predicted [5] for cosmic ray protons from their scattering off the cosmological microwave background. Similar predictions [6] hold for infrared photons scattering off the infrared background. Because DSR maintains the principle of relativity of inertial frames, the interactions involved can always be evaluated in the centre of mass frame, where the energies coming into the deformations from special relativity are smaller. Consequently, DSR makes, up to unobservably small corrections, the same predictions for threshold experiments as ordinary special relativity. However both lorentz symmetry breaking scenarios, NLSB and LSB-EFT predict, for suitable choices of parameters, order one modifications in the positions of these thresholds.

To the extent that recent observations by Auger confirm the standard special relativistic predictions for the GZK cutoff, the lorentz symmetry breaking scenarios are disconfirmed, while the DSR scenario remains unaffected. The only reservation that might be

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5 If the actual quantum-gravity scale is within a couple of orders of magnitude of the Planck one reaches a lowest estimate of $\xi$ of about $10^{-2}$ while, assuming that the field-theoretic LSB-EFT setup is spatially isotropic in the natural frame of the CMB, even the most conservative bounds [25] would imply $\xi < 10^{-4}$.

6 We should also mention that the possibility that quantum gravity dispersion competes with ordinary electromagnetic dispersion in the intergalactic medium has been considered [5], and it turns out that the latter is negligible compared to the possibilities of the former in the range of phenomena here of interest.
made is that it is possible to imagine that the parameters in the modified dispersion relation are not universal. The GZK analysis applied to protons, and as this is the only significant constraint for the NLSB scenario, it is possible to hold open, as an experimental possibility, that the photon and proton dispersion are governed by independent parameters.

However, in summary, it would be reasonable to say, with due caution, that we entered the Fermi era with two strikes against the LSB-EFT scenario, given by bifringence and GZK and one strike against the NLSB scenario, given by GZK.

3 First observations from Fermi relevant for quantum gravity phenomenology

At present there are reports [15,16,17] of \( \sim 200 \) GRBs observed at low energies by Fermi’s GBM, and for eight of these GRBs there are reports of associated observations by Fermi’s Large Area Telescope (LAT), with photons with energies on the order of or greater than 1GeV. With the exception of GRB080916C, which was thoroughly described in Ref. [15], most of the information on these bursts is presently only publicly available in resources, such as notices for the Gamma-ray burst Coordinates Network (GCN), that are not customarily in use in the quantum-gravity community, which is part of the target readership of this paper. Hence, for the convenience of theorists we summarize in Appendix A the information publicly available [15]-[17],[50]-[60] on these 8 GRBs. We list the information also in the following table.

| GRB     | redshift | duration | counts\(_{LAT}\) | \( E_{\text{max}} \) | \( t_{i}^{LAT} \) | \( t_{f}^{LAT} \) |
|---------|----------|----------|----------------|-------------------|----------------|----------------|
| 080916C | 4.35     | long     | strong         | 13 GeV            | 4.5s           | \( \geq 10^3s \) |
| 081024B |          | short    |                | 3 GeV             | 0.2s           |                |
| 090510  | 0.9      | short    | strong         | \( > 1 \text{GeV} \) | \( < 1s \)     | \( \geq 60s \)  |
| 090328  | 0.7      | long     |                | \( > 1 \text{GeV} \) | \( \approx 900s \) |                |
| 090323  | 4        | long     | strong         | \( > 1 \text{GeV} \) | \( > 10^4s \)  |                |
|         |          |          |                | \( \sim 1s \)     | \( \approx 20s \) |                |
| 080217  |          | long     | weak           | 0.6 GeV          | 3s             | \( \geq 40s \)  |
| 081215A |          | long     | weak           | 0.2 GeV          |                |                |

Table 1: GRBs seen by Fermi LAT with photon energies \( \geq 1 \text{GeV} \). \( t_{i}^{LAT} \) is the time after the initial burst that high energy photon seen by the LAT begin. \( t_{f}^{LAT} \) is the time after the initial burst the high energy signals extend to. For references see the appendix.
3.1 Discussion of features of the bursts

It is clear from the above table that there is a growing wealth of information being gathered by Fermi which will be relevant for testing the quantum gravity phenomenological scenarios we discussed above. It would be premature to draw rigorous conclusions at this stage, before most of the data has been analyzed and the results published by the Fermi collaboration. Our aim here is not to compete with the work of observers, instead we want only to draw attention to the potential inherent in what is publicly known about the growing catalogue of events to resolve a question at the heart of fundamental theoretical research. To this end we now briefly discuss some first conclusions which can be drawn from the public reports of these events.

3.1.1 GRB080916C

Among the 8 GRBs observed by the Fermi LAT GRB080916C is the one that has generated most interest from a quantum-gravity perspective. The feature on which these quantum-gravity discussion have focused is the 13.2GeV photon detected by the LAT 16.5s after the GBM trigger. This allowed \[15\] the Fermi collaboration to place a conservative bound on the parameter \(M_{\text{QG}}\) for pure dispersion in the “subluminal” case (with \(s_\perp = 1\)). This is a remarkable achievement of the Fermi collaboration, and we review it below.

There are other features that are relevant from the perspective of dispersion studies and may eventually prove even more valuable: For GRB080916C Fermi detected \(\sim 200\) high-energy (\(> 100\text{MeV}\)) photons, allowing time-resolved spectral studies. And there was a significant delay of \(\approx 4.5\text{s}\) between onset of \(> 100\text{MeV}\) and \(~ 100\text{keV}\) radiation. Also relevant is the fact that the time-resolved spectra for GRB080916C are well fitted \([15, 61]\) by an empirical broken-power-law function (the so-called Band function \([62]\)) in the entire energy range, from \(8\text{keV}\) to \(~ 10\text{GeV}\), leading to the conjecture that a single emission mechanism might have to describe what has been seen over this broad range of energies. Moreover the \(> 100\text{MeV}\) emission lasts at least \(1400\text{s}\), while photons with \(< 100\text{MeV}\) are not detected past \(200\text{s}\). And it is for us particularly significant that the time when the \(> 100\text{MeV}\) emission is detected (\(\approx 4.5\text{s}\) after the first \(< 5\text{MeV}\) pulse) roughly coincides with the onset of a second \(< 5\text{MeV}\) pulse, but most of the emission in this second (\([< 5\text{MeV}] \oplus [> 100\text{MeV}]\)) pulse shifts \([63]\) towards later times as higher energies are considered.

3.1.2 GRB081024B and GRB090510

Information that is somewhat complementary to the one provided by GRB080916C could come from the two “short” bursts in the sample, which are GRB081024B and GRB090510. For GRB081024B there was no redshift determination but preliminary reports indicate \([17, 51, 52]\) that the second peak in GBM was seen \(\approx 0.2\text{s}\) after the (first-peak) trigger and a few photons with energy \(\gtrsim 100\text{MeV}\) were observed in rough coincidence with the second GBM peak, including a \(3\text{GeV}\) photon. For GRB090510, according to preliminary
reports [60], several multiGeV photons were detected within the first second of the burst (whose inferred redshift is $\approx 0.9$).

This preliminary information on short GRBs is potentially very significant for the outlook of studies of in-vacuo dispersion. And it is to some extent unexpected [64], since before these Fermi observations it had been argued that high energy emission would be more likely for long GRBs. There are obvious advantages for in-vacuo-dispersion studies when the analysis can rely on sources of relatively short duration. And since it is expected that the astrophysics of short GRBs is significantly different [64, 65, 66] from the one of long GRBs, the fact that both types of GRBs are well observed at high energies could prove very valuable for efforts aimed at disentangling propagation effects from effects at the source.

### 3.1.3 Common features of the data

In addition to the three we have just discussed the Fermi-LAT has observed so far 5 other bursts. On some of these bursts there is still rather limited information, but preliminary reports suggest that some features noticed in GRB080916C may be generic. 1) typically the onset of LAT events coincides with a second peak in the GBM, a few seconds to fractions of a second, after the first peak; 2) high energy events last much longer than low energy events; 3) the number of LAT detections is often relatively large.

### 3.2 Constraints on subluminal in-vacuo dispersion

Now we turn to conclusions that can be drawn from the data at this early stage. The first thing to mention for those interested in possible measurement of $M_{QG}$ is that the data cannot be interpreted purely in terms of dispersion during travel. In that ideal situation there would be a simple linear relation between photon arrival time and energy and that is not the case. On the contrary it is typical that several lower-energy photons are detected both before and after the detection of the highest-energy photon in the burst. There is also evidence that the onset of arrival of higher energy photons comes in rough coincidence with a second peak in low-energy detections, and the presence of this feature for bursts at different redshift may (at least tentatively) encourage us to interpret it as an astrophysical effect.

The feature for which it appears most natural to invoke a role played by quantum-gravity effects is the fact that, as most clearly seen in GRB080916C (but supported also by the other LAT-observed bursts), the second peak in the signal (first peak in the LAT) shifts towards later times as higher energies are considered.

But in any case, in light of these considerations, it is clear that any extraction of a measurement of $M_{QG}$ requires some methodology which models or averages out astrophysical effects. This means that any fit to data relevant for measuring $M_{QG}$ is likely to involve additional parameters, the minimum would be a two parameter fit where the
second parameter controls the probability of emission of photons from the source as a function of time since the burst and their energy (both in the frame of the source).

It is far simpler to establish bounds on $M_{QG}$. We now turn to this, focusing (as for most parts of this paper) on the case $\alpha = 1$ in which the effects depend linearly on (the inverse of) the quantum-gravity scale.

### 3.2.1 Conservative bounds on subluminal propagation

We begin with the “subluminal case”, with $s_\pm = 1$. Here one can establish a lower bound on $M_{QG}$ by simply measuring a distance to the source and a delay time $\delta t$ for a certain high-energy photon. Assuming that the photon left the source at the time of the initial burst gives a value for $M_{QG}$. But given that we cannot know it left then, rather than a bit later, $\delta t$ is actually an upper bound on the quantum gravity caused time delay, and hence the corresponding $M_{QG}$ is a lower bound.

Using this methodology, the Fermi collaboration establishes a bound on $M_{QG}$ using the 13.6 GeV photon of GRB 080916C which arrived 16s after the initial burst \[ M_{QG} > 1.3 \cdot 10^{18} \text{GeV} \] (15)

\[ i.e. \text{ roughly } M_{QG} > 0.1 M_P. \]

### 3.2.2 Less conservative bounds on subluminal propagation using more structure in the data

We note that this is counting time from the initial peak (the “trigger” peak) of the burst. However, in light of the observations we made above, it appears reasonable to assume that at best quantum-gravity effects could have come into play in generating a delay with respect to the time of the second low-energy peak of GRB080916C (some 4.5s after the first low-energy peak), and this would then lead to a bound of

\[ M_{QG} > 1.8 \cdot 10^{18} \text{GeV} \] (16)

This of course cannot be considered as a conservative bound, but we feel it is robust enough to be used tentatively as guidance for further studies on the theory side (see below).

One might ask instead whether the delay in high energy photons arriving at the second peak can itself be considered a result of in vacuo dispersion. The problem is that the correspondence between the first peak of the LAT and the second peak of the GBM (the low energy detector) is particularly significant because the former is itself a peak that receives contributions from a broad range of energies. Thus, if the delay of the first peak of the LAT and the first peak of the GBM was due to dispersion then we should see even more dispersion of the former than the ”peak dispersion” between the first two peaks. (Notice that $\Delta E$ between 100 MeV and 5 MeV is of course smaller than $\Delta E$ between 1 GeV and 100 MeV)
We can illustrate this with a specific feature of GRB081024B. In this case preliminary analyses indicate [17, 51, 52] there was a small peak of photons with energy between 300 and 500 MeV which arrived in coincidence with the second low-energy peak, some 0.2s after the first low-energy peak. Then after another 0.2s a 3 GeV photon arrived. Even without the redshift, which was not measured in this case, we can use this to argue that it is impossible that the delay between the first and second peak could be a quantum-gravity effect. For any redshift, we can use the 3 GeV photon to put a bound on $M_{QG}$. This would then imply that any quantum-gravity delay acting on photons with a factor of ten less energy could lead to a delay of no more than 0.04s. Thus, quantum gravity cannot account for the 0.2 second delay between the first low energy peak and the arrival of 300 and 500 MeV photons coincident with the second low energy peak.

In the spirit of seeing what might be possible as the data improves, we can ask what kind of bound on $M_{QG}$ would be possible with a similar short burst, with the characteristics of GRB081024B but with a measured redshift. Suppose that the redshift of GRB081024B had been measured and found to be $z_{081024B} \gtrsim 0.35$. (This guess assumes that it is not smaller than half of the smallest among the redshifts of the other GRBs so far seen by the LAT). The result would have been a bound of $M_{QG} \gtrsim 2.2 \cdot 10^{18}$GeV.

To see that this is not unreasonable, let us consider a second hypothetical argument of this kind based on the preliminary information on GRB090510, which, has been announced [60] as a burst with several multiGeV photons within the first second after the low-energy trigger. A bound of $M_{QG} \gtrsim 2.2 \cdot 10^{18}$GeV would be confirmed by detecting a photon of, say, 2 GeV arriving from $z \approx 0.9$ within 0.4s of the onset of the LAT signal.

### 3.2.3 Comparison with previous analyses of Mk501 and PKS2155-304

Fermi has not been the only observatory making recent measurements relevant for in vacuo dispersion. The MAGIC and HESS detectors have reported interesting observations of TeV flares from the AGNs Mk501 and PKS2155-304, respectively. A study of spectral lags in these observations was found [47,48] to favour the “subluminal” case ($s_\perp = 1$) with an estimated measurement (rather than a bound) for $M_{QG} = (0.98^{+0.77}_{-0.30}) \cdot 10^{18}$GeV. We may note that this is on the “light side” of the range of values of $M_{QG}$ that could be considered from a quantum-gravity perspective, and it thus implies the effects of in vacuo dispersion are larger than they would be for heavier $M_{QG}$, at or above $M_{\text{Planck}}$. If this estimate turns out to be correct, it is good news as it means the discovery of quantum-gravity effects in Fermi’s GRB data should not be too challenging. In fact, with $M_{QG} \approx 10^{18}$GeV for typical GRB redshifts of $\sim 1$, and for observations of multi-GeV photons, the expected time delays would be of the order of tens of seconds. This time scale is safely larger than the typical variability time scales one expects for the astrophysics of GRBs.

It is then important to compare these measurements with the results being reported from Fermi. The first thing to note is that the conservative lower bound $M_{QG} > 1.3 \cdot 10^{18}$GeV established by the Fermi collaboration in Ref. [15] is compatible within one standard deviation with the mentioned estimate $M_{QG} = (0.98^{+0.77}_{-0.30}) \cdot 10^{18}$GeV based on pre-
vious observations of Mk501 and PKS2155-304. It is therefore legitimate to continue to investigate this estimate.

On the other hand the observations we discussed above, concerning the coincidence between the second peak of low-energy GRB signal and the first peak of the $> 100\,\text{MeV}$ GRB signal, appear to provide encouragement for a somewhat higher value of $M_{QG}$. Our “reasonably conservative” bound $M_{QG} > 1.8 \cdot 10^{18}\,\text{GeV}$ obtained from assuming the high energy photons started in coincidence with the second peak of GRB080916C is already more than one standard deviation away from $M_{QG} = (0.98^{+0.77}_{-0.30}) \cdot 10^{18}\,\text{GeV}$. And the remarks on GRB082014B offered at the end of the previous subsection appear to favour values of $M_{QG}$ that would be in significant disagreement with the estimate $M_{QG} = (0.98^{+0.77}_{-0.30}) \cdot 10^{18}\,\text{GeV}$.

It would not be surprising if this disagreement between Fermi’s observations of GRBs and previous analyses of Mk501 and PKS2155-304 was confirmed, since those results had been correctly reported [47, 48] as the outcome of “conditional analyses”, relying on simplifying assumptions about the behaviour of the sources. Still it is worth noticing that the evidence of redshift dependence of the spectral lags reported in Refs. [47, 48] was uncovered by considering average arrival times of particles in different energy intervals, while both here and in Ref. [15] the analysis is focused on single photons and their specific detection times. It is therefore plausible that analyses of Fermi’s GRBs done in the same spirit of the ones previously applied to Mk501 and PKS2155-304 (i.e. comparing average arrival times of several photons detected in different energy intervals) might uncover redshift-dependent effects consistent with the results from Mk501 and PKS2155-304, reported in Refs. [47, 48]. We will discuss in Section 5 their possible relevance for descriptions of quantum-gravity effects on propagation that go beyond the pure-dispersion picture.

### 3.3 Bounds on superluminal propagation

We now turn to discussion of putting possible bounds on superluminal propagation, which is the case $s_\pm = -1$. This is important to do as from a theoretical perspective there appears to be no compelling reason to prefer either of the two possibilities, $s_\pm = 1$ and $s_\pm = -1$. In the frameworks that are at the basis of the NLSB and DSR pictures there is so far no result that may favour one or the other sign choice. Furthermore, the leading-order parity-violation effect that arises in the LSB-EFT scenario automatically provides both “superluminal” and “subluminal” propagation, for the two circular polarizations of photons. Thus, in this case, one expects equal numbers of subliminal and superluminal photons.

There are roughly two ways one might go about establishing bounds on superluminal propagation: with photons that are detected and with photons that are not detected.
3.3.1 A bound from photons that are seen

The first approach, using the photons that are detected, is challenging because the high energy emissions are extended in time. So while there is a clear signal for the beginning of a burst from which retardation might be measured, there is not a clear point from where advancement over lower energy photons might be counted.

For example, on a first look at the data, particularly the data on GRB080916C, one might naively deduce that it must be possible to constrain the superluminal case rather tightly, since the data shows a tendency of high-energy particles to arrive, on average, later than low-energy ones. But this feature does not actually provide evidence in favour of subluminal propagation, since with our present, very limited, understanding of the sources, it is possible that it be fully of astrophysical origin. This it also does not amount to any evidence against superluminal propagation. The only safe assumption on which one can anchor a conservative bound on $M_{\text{QG}}$, that all high-energy particles were not emitted much before the low-energy particles that provide the GBM trigger, is clearly useless from the point of view of establishing a conservative bound on the case of superluminal propagation.

In the spirit of the type of considerations we offered in Subsection 3.2.2, for the case of subluminal propagation, we can look for arguments that allow to establish “reasonably conservative” (although not fully conservative) bounds on $M_{\text{QG}}$ for the case of superluminal propagation. Let us start by focusing our attention on the first two photons with energy $\gtrsim 1\text{GeV}$ that were detected by the Fermi-LAT [15] at $6.0 \pm 0.5$ seconds and at $7.0 \pm 0.5$ seconds after the trigger of GRB080916C. It appears reasonably safe to assume that these two photons were produced as part of a first main interval of activity of the bursters which, from the data, we associate to the time interval from the time of trigger to a time we conservatively estimate to be $\lesssim 12$ seconds later (see Fig. 1 of Ref. [15]). On the basis of these reasonably safe assumptions we deduce that a photon of energy of at least 1 GeV after travelling a distance of $z=4.3$ had not gained more than 5.5 seconds. From this we infer

$$M_{\text{QG}}^{[s_{\text{QG}}=1]} > 3.2 \cdot 10^{17}\text{GeV}. \quad (17)$$

One can arrive at a comparable bound by considering the first group of $>100\text{MeV}$ photons detected by LAT for GRB080916C. With the much higher total count one can clearly see [15] a reasonably smooth peak structure at $6.0 \pm 0.5$ seconds after the trigger, which (according to the observations on the structure of the second peak of GRB080916C discussed above) we must place in correspondence with a peak found at $5.3 \pm 0.7$ seconds after the trigger for photons detected with energy between $260\text{keV}$ and $5\text{MeV}$. On the basis of these observations we deduce that photons with energy $\gtrsim 100\text{MeV}$ do not gain more than 0.5 seconds after travelling a distance of $z=4.3$, and in turn from this we infer

$$M_{\text{QG}}^{[s_{\text{QG}}=1]} \gtrsim 3.5 \cdot 10^{17}\text{GeV}.$$  

It is interesting that almost the same bound is obtained from two independent “reasonably conservative” strategies, involving photons of different energies. This is also, so far as we are aware, presently the best bound on superluminal propagation in the litera-
ture. We may then suggest that (17) be treated as a conservative upper bound on the scale $M_{QG}^{[s_0 = -1]}$ of possible quantum-gravity-induced superluminal propagation (for the case of effects that depend linearly on the inverse of such a scale).

Note that we did not get beyond the level $\sim 3 \cdot 10^{17}\text{GeV}$ because we could not exclude some sort of “conspiracy” at the source such that the observed delays of high-energy particles be the result of even greater delays of emission at the source which would be partly eroded along the way to the telescope. For example, if $M_{QG}^{[s_0 = -1]} \approx 4 \cdot 10^{17}\text{GeV}$, which is a possibility not excluded by our conservative bound, a 13.2 GeV photons arriving from $z \simeq 4.3$ should have gained along the way some 65 seconds, and as a result it would have needed some tuning to achieve an arrival time which is 16s after the trigger, rather than some time before it. While such conspiracies cannot be excluded while attempting to establish a robust bound, for the purpose of orienting our theoretical intuitions we would argue that the data rather clearly encourage us to focus future work on superluminal in-vacuo dispersion on estimates that are significantly higher than $3 \cdot 10^{17}\text{GeV}$, perhaps already in some neighborhood of $M_{QG}^{[s_0 = -1]} \sim M_{\text{Planck}}$.

3.3.2 Implications of photons that are not seen

A different kind of strategy, employing reasoning concerning photons that are not seen, might be used to put stronger bounds, particularly on the LSB-EFT scenario. To do this one must assume that there are no features of the source that would result in the production of predominantly one helicity, so we expect equal numbers of subluminal and superluminal photons. Then, if from a given source we see $N$ high energy photons within a window in energy and time after the initial low energy burst, and no photons in the same energy window within the same time before the burst, one can set a limit on the probability that roughly $N$ photons of the opposite helicity which would be superluminal, were produced but not detected.

To see how this might work, pick a candidate value of $\bar{M}_{QG}$ and consider a set of photons in a range of time and energy, as follows. The photons must arrive within a time $t \leq t_0$ after the trigger with energies $E \geq E_0$ such that the minimum time delay $\delta t = \frac{E_0}{\bar{M}_{QG}} L \geq t_0$. These are chosen so that superluminal photons with the same characteristics should arrive before the trigger. Suppose that there are $N$ photons in this set. Then there are roughly $N$ missing photons, which should have arrived before the trigger if the LSB-EFT scenario is true with that value of $\bar{M}_{QG}$, and the source does not emit predominantly in one helicity.

Let $p_{\text{missed}}$ be, for each photon that was observed, the probability that it might have passed the detector and not been observed, and let $\bar{p}_{\text{missed}}$ be their average over incident energy. The probability that the $N$ photons were missed is then their product, or $p_{\text{total}} = p_{\text{missed}}^N$. This is roughly the probability that the LSB-EFT scenario is correct with the chosen $\bar{M}_{QG}$ in spite of the fact that $N$ of the superluminal photons it predicts should have been detected were not. That is, we can say that with a probability $1 - p_{\text{total}}$ that $M_{QG} > \bar{M}_{QG}$.
4 Prospects for measuring a quantum gravity scale

We now turn to the question of whether future experiments might make possible a measurement of $M_{QG}$ rather than a bound. As we have discussed, this is much harder because of the possibility of properties of the sources that mimic the effect of in-vacuo dispersion, by introducing some correlation between the time of emission and the energy of the particles. And, as we also stressed above, the fact that the first results of the Fermi telescope do not fit naturally within the most studied previous models of GRB sources is likely to create a sort of competition between postdiction of the observed features within accordingly tailored astrophysical pictures and the possibility of in-vacuo-dispersion effects. If the quantum-gravity dispersion effects turned out to be on the large side of the range of theory-favoured magnitudes, as initially suggested by the preliminary analyses of AGNs reported in Refs. [47, 48] the competition with model building on the astrophysics side might have been less challenging, since with $M_{QG} \approx 10^{18} GeV$ for typical GRB redshifts of $\sim 1$ and for observations of multi-GeV photons the expected time delays would be of the order of tens of seconds, a time scale that is safely larger than the typical variability time scales one expects for the astrophysics of GRBs. However, as we stressed in Subsection 3.2.3, the first observations reported by Fermi, while still in principle compatible with that estimate, provide the intuition that it is likely that we should orient our speculations toward values of $M_{QG}$ that are somewhat higher. This implies that the magnitude of quantum-gravity effects may be comparable or even smaller than the typical scales of time variability of GRBs.

It therefore appears that the best opportunities for discovering in-vacuo-dispersion effects will be based on their dependence on redshift. With correspondingly high statistics (number of strong GRBs observed at different redshifts) it should be possible to infer from analyses of this redshift dependence some evidence of even small in-vacuo-dispersion effects.

In this section we would like to contemplate the possibility of combining redshift-dependence analyses of Fermi data with unusual events detected by other observatories. In particular, we note that the preliminary evidence of redshift-dependent effects found in the analysis of Fermi data might acquire much greater significance if some of the GRBs used in the analysis were also observed by other telescopes, at energies higher than the ones accessible to Fermi.

This possibility finds some encouragement in the first few observations reported by Fermi. For GRB080916C there was positive identification of $\sim 200$ photons with energy $> 100 MeV$ and, among these, 14 photons with energy $> 1 GeV$, which might suggest that it is not unlikely that the signal is strong enough for detection at even higher energies.

It is also encouraging that the LAT signal tends to persist for relatively long times after the trigger, in some cases of the order of $10^3$ seconds. This means that some telescopes that need to be positioned in the direction of the burst (like MAGIC [67]) should have some chances of getting positioned in time.

Furthermore, attempts to find VHE counterparts to Fermi-LAT GRBs are particularly
valuable for searches of superluminal effects, as we shall stress rather forcefully in the last subsection.

### 4.1 Photons of a few TeV

The abundance of GeV photons detected by Fermi is encouraging for the idea of observing some Fermi-LAT bursts also at TeV-photon observatories. There is, however, an expectation (see, e.g., Ref. [68] and references therein) of significant absorption of TeV photons due to electron-positron pair production by IR background photons. However, our view is that, nonetheless, these searches should be conducted without reservations. In fact, the IR background is difficult to determine, as direct measurements are problematic, owing to the bright Galactic and Solar System foregrounds present. And in recent years there have been several reports (see, e.g., Ref. [68] and references therein) of spectra of some observed blazars that appear to be harder than anticipated, considering the expected IR-background absorption.

Moreover, the NLSB framework itself predicts a reduction of pair-production absorption of TeV photons [6, 69, 70, 71, 72] (while no such reduction is expected in DSR [11]), so this issue is mixed up with that of in-vacuo dispersion. That is, if an NLSB framework were true, there might be reduced absorption of TeV-scale photons to be observed from GRBs. This would be both indirect evidence evidence for that scenario and permit the observation of a TeV photons.

For \( M_{QG} \sim M_{Planck} \) a 10TeV photon should acquire a delay of about \( 10^3 \)s from \( z=4 \). This may be a manageable challenge for some of the observatories which need to be directed toward the burst. A detection of such a photon identified with a GRB would provide significant insight since \( 10^3 \)s is a time scale that appears to be safely larger than the variability scales observed for these GRBs. The insight gained would still be very significant (though subject to more subtle analysis) for time delays of, say, 10s, as for example in the case of a 3TeV photon from \( z=1 \) in the case of \( M_{QG} \sim 10M_{Planck} \). Delays of this magnitude however pose a challenge for observatories that need to be directed toward the burst.

### 4.2 Photons with energies between \( \sim 10^{14} \) and \( \sim 10^{17} \) eV

The abundance of GeV photons observed by Fermi may also give indirect encouragement to the idea of detecting photons with energy \( \gtrsim 10^{14}eV \) from Fermi-LAT-observed bursts. Moreover, while, as mentioned, some aspects of the spectral analysis of GRB080916C and other bursts remain mysterious from an astrophysics perspective, some authors find in these data further encouragement for the much-studied hypothesis that GRBs might be responsible for (at least some of) the UHE cosmic rays. In turn this would imply that GRBs are capable of producing UHE and VHE photons (e.g. through decays of UHE neutral pions).
For VHE photons one would as well expect absorption by the soft background photons, but for the same reasons mentioned in the previous subsection we feel this should not necessarily discourage such searches. In particular, we feel that such searches deserve significant priority at the Auger cosmic-ray observatory [73].

For such high-energy photons the expected delays are very large in the case of a linear quantum-gravity effect. For example for $M_{QG} \sim M_{Planck}$ a $10^{16} \text{eV}$ photon should acquire a delay of $\sim 10^6 \text{s}$ (\text{\sim a month!}) from $z=4$. The possibility of identifying such a long delayed photon from a GRB represents an extraordinary opportunity for attempts to discover quantum-gravity dispersion. But it also pose observational challenges having to do with correctly attributing such photons to a GRB that had triggered much earlier.

A key point is that even a single detection of this kind could provide crucial input. We can envisage a stage, possibly in the not too distant future, in which there are two competing interpretations of the data on arrival times versus energy of photons from GRBs, one from the quantum-gravity side and one from the astrophysics side. A single detection with such a huge time delay, but found to be in a time window compatible with the magnitude of the effects predicted by the quantum-gravity description of data at lower energies, could tilt the balance in favour of that description.

### 4.3 VHE neutrinos

It has long been recognized [74, 75, 76, 77, 78] that neutrinos can play a privileged role in the phenomenology of the study of quantum-gravity effects on the propagation of particles. This interest was centered mainly on the fact that neutrinos appear to be our best chance, in the long run, to test for dispersion effects suppressed quadratically by the Planck scale. The advantages of neutrinos from this perspective originate from the fact that it gets easier to observe them from distant sources as their energy increases, as a result of properties of the weak interactions. And they travel essentially undisturbed by all background fields in the universe.

But it is also possible that observatories such as ICECUBE [79] could give decisive contributions to the present effort of constraining or measuring quantum gravity effects suppressed linearly by the Planck scale. For reasons that are completely analogous to the ones discussed in the previous subsection for the case of VHE photons, even a single such detection could play such a decisive role, if it happened to corroborate an emerging quantum-gravity interpretation of data at lower energies.

While the working assumption that GRBs produce VHE cosmic rays leads us to expect that some VHE neutrinos are indeed produced by gamma-ray bursters (through processes such as $p + \gamma \rightarrow X + \pi^+ \rightarrow X + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$) all attempts of realistic estimates of rates[77], also in relation to the sensitivities of planned observatories, suggest that such searches of neutrinos from GRBs might at best detect very few neutrinos. It is therefore necessary to address concerns of a possible rejection of a genuine detection of a neutrino from a LAT-observed GRB, which could be missidentified as background/noise, especially if arriving with a delay of, say, a month from the GRB trigger when, without
the quantum-gravity motivation, such detections would be completely unexpected.

4.4 Forward and backward in time

We now turn from subluminal to superluminal propagation of very high energy photons and neutrinos. In the light of the observations we reported in Section 2 and Subsection 3.3, searches of VHE counterparts to LAT-observed GRBs are also very significant for scenarios with superluminal in-vacuo dispersion. And in this respect it is worth stressing that, while, as discussed in Subsection 3.3, placing bounds on superluminal effects is more challenging than for subluminal effects, robust evidence for superluminal propagation could be provided by simply establishing that there are some photons that arrive before the ones composing the low-energy trigger.

While in Subsection 3.3 the desire to derive an absolutely conservative bound led us to the prudent estimated bound of \( M_{QG}^{[\delta s= -1]} > 3.2 \cdot 10^{17} GeV \), we shall here adopt as working assumption (for reasons which we also discussed in Subsection 3.3) that our target should be at the level of \( M_{QG}^{[\delta s= -1]} \sim M_{Planck} \), or even one or two orders of magnitude greater. For such high values of the dispersion scale, and correspondingly small magnitude of the dispersion effect, one would expect little or no trace of it in data of the type of GRB080916C for energies \( \lesssim 10 GeV \). But dispersion effects of, say, 0.1 seconds for 10 GeV photons would imply dispersion effects of tens of seconds for multi-TeV photons. This specific numerical estimate is significant because the time interval between the first and the second peak of GRB080916C is \( \sim 4.5 s \), so in this scenario a multi-TeV photon emitted together with the second peak of GRB080916C would have been detected several seconds before the low-energy GRB trigger. And in the same scenario a photon or neutrino of, say, \( 10^{16} eV \) could have been detected \( 10^{5} s \) before the GRB080916C trigger.

The only observation we know of that could provide encouragement for these issues comes from the analysis reported in Ref. [80], which provided some (weak, 2.9 standard deviations) evidence of detection of photons with energy \( \sim 100 TeV \) from GRB910511 some 40 minutes before the trigger of GRB910511. If observations of this sort were established more robustly the interpretation would then be rather straightforward. But it might be challenging to establish the association with a GRB later seen at lower energies.

5 Models of the quantum gravity vacuum with more than one parameter

As we argued above it appears natural to expect that a full description of GRB data of the type of GRB080916C will require quite several parameters, most (if not all) of which needed to model the astrophysics of the system. Since such studies are in any case necessary it is legitimate to contemplate the possibility of uncovering scaling with redshift of more than one of the parameters, and in particular scaling that would not be consis-
tent with it parameterizing a property of the sources. It is therefore of interest to discuss whether the quantum-gravity literature can provide the basis for any positive expectations in this respect, and in this section we want to comment briefly on this.

5.1 Fuzzy dispersion

The idea that quantum gravity would imply modified dispersion relations is relatively new for quantum-gravity research; it started to be seriously discussed only in the second half of the 1990s. Before that discussions of possible effects of quantum gravity on particle propagation mainly concerned stochastic or so-called fuzzy effects. These were inspired by speculations that quantum spacetime was “foamy” so that spacetime structure would affect the average arrival time of a group of particles, but would instead contribute to the spreading of results of repeated measurements [81, 82]. One mechanism that was proposed for this was that light cones would fluctuate in quantum gravity, resulting in fluctuations in travel times of massless quanta. There were also studies of the idea that both dispersion and fuzziness could be characteristic of the quantum-gravity vacuum. [83, 84].

To motivate this possibility, consider an event that produces in a time $\Delta t^*$ a monochromatic burst of photons. Within classical mechanics, and without in-vacuo dispersion, there is no in-principle obstruction toward having such an event with arbitrarily small $\Delta t^*$. But consider the effect of turning on both quantum mechanics and in-vacuo dispersion of the signal.

Quantum mechanics implies that the energy spread of a signal produced in a time $\Delta t^*$ must necessarily be greater than $\hbar/\Delta t^*$, so the burst cannot be sharply monochromatic if it is emitted in a finite time interval $\Delta t^*$. Then in-vacuo dispersion acts on the resulting $\Delta E$ to increase the time spread of the signal seen at a distant telescope.

This conclusion is easily reached by describing the in-vacuo dispersion in terms of the formula

$$v(E) = 1 - \eta E/M_{\text{Planck}}$$

and observing that, since $\Delta E \gtrsim \hbar/\Delta t^*$, any burst which at the source had duration $\Delta t^*$ should be characterized by a spreading of speeds of the particles that compose it given by

$$v(E) \approx 1 - \eta E/M_{\text{Planck}} \pm \eta \hbar/(M_{\text{Planck}} \Delta t^*) .$$

As a result observations of such a burst performed at a arge distances $T$ from the source would not measure a spread of times of arrival over an interval $\Delta t^*$, but rather

$$\Delta t_{\text{meas}} \approx \eta T \hbar/(M_{\text{Planck}} \Delta t^*) ,$$

which can be much larger than the original $\Delta t^*$ if $T$ is correspondingly large.

From a purely phenomenological point of view, one might then contemplate an independent contribution to fuzziness of the type [83, 84]

$$v(E) \simeq 1 - \eta E/M_{\text{Planck}} \pm \eta/(M_{\text{Planck}} \Delta t^*) \pm \eta_f E/M_{\text{Planck}}$$

(21)
with \( \eta \) a phenomenological parameter to be determined experimentally but expected to be within one or two orders of magnitude of 1.

One advantage to this kind of scenario is that, in contrast to other Lorentz symmetry breaking scenarios, the GZK threshold remains essentially unaffected\(^{[84]}\).

From a pure-phenomenology perspective a “fuzzy dispersion” of the type (21) has some characteristic features. First, the predictions for the average arrival times of a collection of particles within a particular energy range are the same on average as in the pure-dispersion picture. Thus, when it comes to the prediction of averaged arrival times there is only one parameter, and it is the same as the one parameter models. This is significant because the emission mechanisms are messy and likely introduce randomness into the arrival times, thus the predictions of quantum gravity models for averaged arrival times with energy are more robust than predictions for individual arrival times.

On top of these, the fuzzy picture introduces randomness also in the quantum gravity predictions for arrival times of individual photons. This might make it possible to reconcile observations that contradict each other under the one parameter scenarios, and which also remain puzzling after astrophysical sources of randomness are taken into account. While this cannot be used to save scenarios that are cleanly ruled out, it might become necessary if, for example, measurements based on averaged arrival times, using many particles, lead robustly to measurements of values of \( M_{QG} \) that are ruled out by robust and conservative limits on \( M_{QG} \) based on arrival times of single photons (see discussion in Subsection 3.2.3).

### 5.2 Mixed parity dispersion

The second possibility for a two parameter fit from quantum gravity comes from the possibility that there is both an even and an odd parity effect in dispersion, coming perhaps from a fundamental chiral asymmetry in quantum gravity. Indeed, a chiral asymmetry is observed\(^{[85, 86]}\) in the formulation of loop quantum gravity, and is parameterized by a parameter called the Immirzi parameter. Now, it has definitely not been shown that this leads to a mixed parity dispersion of photon velocities but let us suppose it does.

Note that LSB-EFT predicts an odd parity effect in which \( \delta v = -\beta < s > \frac{E}{M_{QG}} \) where \( < s > \) is the expectation value of chirality, a number which ranges \(-1 \leq < s > \leq 1\), whereas NLSB and DSR predict an even parity effect \( \delta v = -\alpha \frac{E}{M_{QG}} \), independent of helicity. It is then possible to imagine that a quantum theory of gravity might predict a mixed effect

\[
\delta v = -(\alpha + \beta < s >) \frac{E}{M_{QG}} \tag{22}
\]

for parameters \( \alpha + \beta = 1 \). To the extent that the helicity of a photon can be treated as being essentially random in GRB observations, this would induce a stochastic element in the arrival times

\[
\delta t = (\alpha + \beta < s >) \frac{E}{M_{QG}} L \tag{23}
\]
6 Conclusions

When, about a decade ago, the possibility of this type of studies with Fermi (then known as GLAST) was first contemplated it appeared that reaching Planck-scale sensitivity and beyond would be plausible but challenging. It was reasonable to expect that this might require a large collection of GRB observations as well as sophisticated methodologies for data analyses.

However, after less than a year of Fermi observations we already have a robust bound at about $M_{QG} > 0.1 M_{P}$, from analysis of a single GRB. The quality and quantity of data with photons above $1 GeV$ makes it plausible that, with the large data sets we will have after several years of Fermi observations, the bounds may be pushed up to even a couple of orders of magnitude beyond the Planck scale. This would make it possible to fully explore the range of values that could be favoured from a quantum-gravity perspective, at least for a linear relation between energy and velocity.

Even with the present data it may be possible to obtain bounds on $M_{QG}$ that are significantly higher than the present conservative bound. This is because of some unexpected features of the GRB observations we briefly summarized above. One is the coincidence between the arrival of the first multiGeV photons and a second peak in the GBM. While this cannot be taken into account when establishing conservative bounds, it is possible to suggest that all the multiGeV photons originate at or after the second peak, so that the delays should not be computed with respect to the first GBM peak, but rather with respect to the second GBM peak, thereby strengthening the bounds. And in this respect it is noteworthy that, according to preliminary reports, for GRB081024B the LAT detected a $3 GeV$ photon with a delay of only $\approx 0.2 s$ with respect to the second GBM peak. It is unfortunate that there is no redshift in this case, but this suggests a way in which a very good bound might be possible with a short burst with known redshift.

To mention one scenario, it is entirely plausible that in a short time there might be observed, say, $20 GeV$ photon detected within, say, $0.1 s$ of the first LAT peak for a GRB at a redshift of 4.5. This could be used to establish a bound at the level $4 \cdot 10^{20} GeV$ in the case of subluminal propagation. The fact that placing bounds (at least for $s_{\perp} = 1$) is relatively easy is manifest in the fact that such a powerful result could be established even with the simple-minded strategies of analysis that we discussed so far and even without any further progress in the understanding of the astrophysics of GRBs.

Having emphasized the bright prospect for setting bounds on $M_{QG}$, we then turned our attention to the greater challenge of discovering quantum gravity effects by measuring a finite value of $M_{QG}$. As we emphasized above, the prospects for this are more challenging, in spite of there being several at least superficially encouraging signs, such as the general feature of time delays increasing with increasing energy. Indeed, if we take only the most energetic photons as data points, and assume there are no astrophysical contri-
butions to differential time delays, we could imagine naively making a measurement of $M_{QG}$ within an order of magnitude of $M_{Planck}$. The problems, as we emphasized above, are, first, that the data are not clean, so there is no simple linear relation between arrival times and energies for the high energy photons and second, because the time scales for plausible astrophysical effects and the hypothesized delays due to quantum gravity at these scales are comparable. It seems then that a discovery of a quantum gravity time delay will require a sophisticated methodology that deals with the astrophysical contributions to the time delays either by modeling them or by finding a way to subtract them out, also using redshift-dependence analyses.

It would have been ideal if Fermi had confirmed the predictions of one among the most studied emission mechanisms in the astrophysics literature. But we are in the opposite situation: some aspects of GRB080916C are “mysterious” \[61\] even for some of the leading experts. With a more reliable reference to a well-established astrophysical picture the discovery even of particularly small effects (such as in cases in which $M_{QG} \sim M_{Planck}$ or even one or two orders of magnitude bigger) could be achieved with relatively small samples of GRBs at different redshifts. In that ideal scenario both the redshift dependence and the comparison to the expectations of the reference astrophysical model could have been used in such searches. But already with these first few Fermi-LAT observations it is rather clear that attempts to make a discovery of a quantum gravity effect will have to be conducted in conditions that are significantly different from this ideal scenario.

Thus, it is possible that in the not too distant future we will be faced with a situation in which there is a competition and perhaps even a degeneracy between astrophysical and quantum gravity explanations of time delays seen in GRBs. It may very well be that Lorentz symmetry is not broken at linear order in $l_{Planck}$ so that astrophysical explanations suffice to explain the data from GRBs. But, given what is at stake for fundamental physics, it would be foolish to assume this while inventing astrophysical explanations for the time delays in the data, thus risking hiding what could be a fundamental experimental discovery of a breakdown or modification of special relativity theory.

It is then very important to search for ways to break this competition or degeneracy. To do this we turned in section 4 to the prospect of observing photons and neutrinos at higher energies above the range of Fermi’s LAT, up to $10^{17} ev$. The quantum gravity time delays in these cases would be hours to months, so there would be a clean separation of astrophysical and quantum gravity time scales. The prospect of making such observations is challenging, but we argued that the results would be very important. Moreover, as we emphasized above, the arguments sometimes given for not searching for $TeV$ scale photons from cosmological distances, because of absorption by the infrared background, cannot be relied on as it rests on assumptions about the applicability of special relativity which are being tested here. Indeed, the NLSB scenario predicts that the threshold for that absorption can be moved significantly to allow $TeV$ photons to reach us from cosmological distances.

We close with messages to both observers and theorists. To observers we would emphasize the opportunity for putting very significant bounds on some or all of the quantum
gravity scenarios for modifying or breaking Lorentz invariance. We would also emphasize the importance of experiments and analyses that could lift the degeneracy between astrophysical and quantum gravity explanations for a correlation between photon energy and delay in arrival times after initial bursts of GRBs. To quantum gravity theorists we suggest urgent attention be given to any possibility of deriving predictions for these observations from theories of quantum gravity, otherwise it may be only a matter of months to a year or two before we theorists are demoted to the role of postdictors of great experimental discoveries.

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A Appendix: The growing list of relevant GRB’s with GeV scale photons

For the convenience of theorists we summarize here the publicly available information on the GRBs discussed above.

1. **GRB 080916C**: We described in some detail this very strong long burst in Section 3. Photons were detected \[15\] by LAT up to \(\sim 13\, \text{GeV}\) (three photons above \(6\, \text{GeV}\)) and the overall strength of the LAT signal was such that time-resolved spectral studies could be performed \[15\]. Afterglow studies \[50\] allowed to determine a redshift of \(4.35 \pm 0.3\).

2. **GRB081024B**: This was the first short burst (described in Refs. \[15\] \[51\] \[52\]) with signal above \(1\, \text{GeV}\) (with maximum energy of \(3\, \text{GeV}\)), generating also some puzzlement \[64\] with respect to the characterization of short bursts that were fashionable before the Fermi era.

3. **GRB090510**: For this short burst (described in Ref. \[60\]), at a redshift of \(\approx 0.9\), the Fermi LAT detected more than 50 events above 100 MeV (at least 10 above 1 GeV) within 1 second of the low-energy trigger and more than 150 events above 100 MeV (at least 20 above 1 GeV) in the first minute after the trigger.
4. **GRB090328**: In this burst (described in Ref. [58]) the emission in the LAT lasts up around 900s after the trigger, with the highest energy events (some with > 1GeV) arriving hundreds of seconds late. Afterglow studies [59] allowed to determine a redshift of 0.7.

5. **GRB090323**: In this burst (described in Ref. [56]) the emission is observed in the LAT up to a few GeV, starting a few seconds after the GBM trigger time, and lasting $\sim 2 \cdot 10^3$ s. Afterglow studies [57] allowed to determine a redshift of $\sim 4$.

6. **GRB090217**: In this burst (described in Ref. [55]) the high-energy emission commences several seconds after the GBM trigger and continues for up to 20 seconds after the GBM trigger.

7. **GRB 080825C**: This was the first GRB seen by the Fermi LAT [15]. The LAT signal [53] was composed only of photons with energies below 1GeV. Even though the signal in the LAT is rather weak [53] it provides significant evidence that the high-energy component has a delayed onset [15] and persistence up to 35s after the trigger.

8. **GRB 081215A**: This burst (described in Ref. [54]) was at a large angle to the LAT boresight, and as a result neither directional nor energy information could be obtained with the standard analysis procedures. A preliminary analysis however provides evidence [54] of over 100 events above background, with energy presumably $\lesssim 200\,MeV$, detected within a 0.5 s interval in coincidence with the main GBM peak.

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