PHYSICAL REVIEW D **80,** 084017 (2009)

Prospects for constraining quantum gravity dispersion with near term observations

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(Received 25 June 2009; published 14 October 2009)

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 (GRBs) measured by the Fermi telescope. These prospects are brighter than might have been expected, as in the first ten months of operation, Fermi has so far reported eight events with photons over 100 MeV seen by its Large Area Telescope. We review features of these events which may bear on Planck-scale phenomenology, and we discuss the possible implications for alternative scenarios for in-vacua dispersion coming from breaking or deforming of Poincaré invariance. Among these are semiconservative 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 GRBs with energies in the range 10^{14}–10^{17} 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.

DOI: 10.1103/PhysRevD.80.084017 PACS numbers: 04.60.−m, 04.60.Bc

I. 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] $l_{\mathrm{QG}} = \frac{1}{M_{\mathrm{QG}}}$. Here M_{QG} may be expected to be within a few orders of magnitude of $M_{\mathrm{Planck}} = \frac{1}{\sqrt{G_N}}$. This leads to a variation in arrival time with energy, roughly given by (see below)

$$\Delta t \simeq \frac{\Delta E}{M_{\mathrm{QG}}} L, \tag{1}$$

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

Consequently, given the timing accuracy of Fermi it has been anticipated that after many events bounds could be put on M_{QG} on the order of M_{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 other papers, talks by collaboration members, and notices for the Gamma-Ray Burst Coordinates Network (GCN).

(i) There have already been, 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.
(ii) In at least one case (GRB080916C [15]) the number of events at high energy was abundant enough to allow spectral studies.
(iii) Some bursts are at high redshift, with two bursts with $z \approx 4$.
(iv) In these early events there are clear trends that more energetic photons arrive later, although the structure of the events is complex.
(v) Two short bursts have already 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 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 accumulate. Making such a measurement is much harder than setting a bound, because the structure of the bursts is complicated and there are astrophysical effects at the sources over time scales comparable to Δt'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 us prepare for facing this challenge, we do the following in this paper. First, in the next section we survey

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[1] We use units such that the Planck constant $\hbar$ and the speed-of-light scale c are set to 1. Since we are considering the possibility of in-vacuo dispersion, we are implicitly assuming as an operative definition of the speed-of-light scale the value of the speed of light in the infinite-wavelength limit.

the three basic possible scenarios which lead to effects of (1) coming from either breaking or deforming of Lorentz invariance. We also review some relevant experimental results that were obtained before Fermi.

In Sec. III 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 (roughly $M_{\rm QG} > 0.1 M_{\rm Planck}$) on subluminal propagation published so far [15] and propose new sets of assumptions that lead to new bounds, both on subluminal 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 Sec. IV we discuss whether the data may eventually allow a measurement of $M_{\rm QG}$ rather than a bound on $M_{\rm QG}$. We also explore 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, $M_{\rm QG}$. In Sec. V we discuss the possibility of models with two or more parameters and discuss how they may be constrained by observations.

Section VI contains our conclusions.

II. 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 as follows: *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 Poincaré group. It is then natural to ask whether the Poincaré 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, 1 Å 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.

A. 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

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

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

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 corrections in the ultrarelativistic ($E \gg m$) limit as follows:

$$E \simeq p + \frac{m^2}{2p} - s_{\pm}\frac{1}{2}\frac{E^{\alpha+1}}{M_{\rm QG}^{\alpha}}, \tag{3}$$

a parametrization which, in addition to $M_{\rm QG}$, also involves the power α, which is 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); $s_{\pm} \in \{-1, 1\}$, which specifies the sign[2] 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 ordinary (unmodified) law of energy-momentum conservation, and the resulting picture breaks [11] Lorentz symmetry so that it should be properly studied in a "privileged" reference frame, such as the natural frame of CMB

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[2] This "sign parameter" $s_{\pm} = 1$ was denoted by ξ in Ref. [3].

radiation. We may call this *naive 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.

B. Lorentz symmetry breaking within effective field theory

Soon after the first papers on the NLSB scenario, Gambini and Pullin made [7] a first attempt to formalize 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 [18–21], their scenario depends on the assumption of a particular and nonphysical ground state for that theory. Thus, their scenario should not be viewed as a definite prediction of loop quantum 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, so far without making precise predictions [22]. At this stage it makes sense to use semiheuristic 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 modeling 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 $1/M_{\text{Planck}}$ and are characterized by an external four-vector, that one arrives at a single possible correction term for the Lagrangian density of electrodynamics:

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

where the four-vector n_α parametrizes the effect.

The (dimensionless) components of n_α 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 Myers-Pospelov framework would require [24] a phenomenology exploring a four-dimensional parameter space, n_α, and contemplating the characteristic frame dependence of the parameters n_α. There is already a rather sizable amount of literature on this phenomenology (see, e.g., Refs. [22,25–27] and references therein) but still fully focused on what turns out to be the simplest possibility, which is the one of assuming to be in a reference frame where n_α only has a time component, $n_\alpha = (n_0, 0, 0, 0)$. Then, upon introducing the parameter $\xi \equiv (n_0)^3$, one can rewrite (4) as

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\xi}{2M_{\text{Planck}}}\varepsilon^{jkl}F_{0j}\partial_0 F_{kl}, \tag{5}$$

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

C. Doubly special relativity

The third option is doubly or deformed special relativity (DSR) [11–14,28–30], which incorporates modifications or deformations of the Poincaré 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 the 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 $\hbar \rightarrow 0$ and $G_N \rightarrow 0$ 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 well-studied possibility is the description in terms of "Hopf algebras" [31,32], which characterize the symmetries of certain 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 [35–37], but no rigorous proof. There are several results that indicate this is the case in spacetime models with $2 + 1$ dimensions [35,38–40]. 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 still be 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 sizable amount of literature [11–13] considering the possibility that the dispersion relation be of the form

$$0 = 8M_{\rm dsr}^2\left[\cosh\left(\frac{E}{2M_{\rm dsr}}\right) - \cosh\left(\frac{m}{2M_{\rm dsr}}\right)\right] - p^2 e^{s_\pm (E/2M_{\rm dsr})} \tag{6}$$

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

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

$$E^2 = \frac{p^2}{(1 + s_\pm \frac{E}{4M_{\rm dsr}})^2} + m^2, \tag{7}$$

which also reduces at leading order to (3) with $\alpha = 1$.

Note that there are DSR scenarios which give either sign of $s_\pm$, giving rise, respectively, to subluminal 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 modifications 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 Poincaré transformations connecting observations made by different observers and modifications of the energy and momentum conservation laws. These deformations of transformation laws and energy-momentum conservation in DSR are extensively discussed in the literature (see, e.g., Ref. [43] and references therein), but are not relevant for the in-vacuo-dispersion studies we focus on here (we shall only briefly comment on the implications of deformations of energy-momentum conservation for the possibility of absorption of gamma rays by the infrared background).

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

From Eqs. (3), both for the NLSB and the DSR frameworks ($M_{\rm QG} \rightarrow M_{\rm dsr}$ in the DSR case), one easily derives [1,3,11] that, for two photons with an energy difference ΔE simultaneously emitted by a source at relatively small redshift, the times of arrival differ by[3]

$$\Delta t|_{{\rm small}-z} \simeq s_\pm \frac{\Delta E}{M_{\rm QG}} L, \tag{8}$$

where $L = H_0 z$ is the distance of the source from Earth given in terms of the Hubble expansion rate and the redshift. For the subluminal case, $s_\pm = 1$, one has positive Δt whenever ΔE is positive, meaning that for simultaneously emitted particles the one with the lowest energy is detected first. The opposite holds for the superluminal case, $s_\pm = -1$.

At large redshifts one should instead take into account the exact (nonlinear) dependence on the redshift encoded in the formula [46–48]:

$$\Delta t = \frac{\Delta E}{M_{\rm QG}} \frac{1}{H} \int_0^z dz \frac{1 + z}{\sqrt{\Omega_\Lambda + (1 + z^3)\Omega_{\rm Matter}}}, \tag{9}$$

assuming ΛCDM cosmology with parameters Ω_Λ and $\Omega_{\rm Matter}$.

In the LSB-EFT framework there are similar effects from the energy-dependent speed of photons, but the effects carry opposite sign for the two circular polarizations of light; i.e. they are birefringence effects.

E. The situation before Fermi

There is a large amount of literature [22,27] on the phenomenology of Lorentz symmetry breaking, both naive and within effective field theory, and a growing amount of literature on the DSR phenomenology. Before Fermi, the bounds on the in-vacuo dispersion expected in the NLSB or DSR contexts were still 2 orders of magnitude below the Planck scale, even for the case $\alpha = 1$ on which we are focusing here. The best bound derived from GRB data before Fermi was $M_{\rm QG} > 2 \times 10^{17}$ GeV from Ref. [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 [25] the entire range of values of ξ that could be favored from a quantum gravity perspective. But, it has been noticed very recently [24] that these bounds become much weaker if one removes the assumption of isotropy in the CMB frame. 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.

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[3] We should also mention that the possibility that quantum gravity dispersion competes with ordinary electromagnetic dispersion in the intergalactic medium has been considered [3], and it turns out that the latter is negligible compared to the possibilities of the former in the range of phenomena of interest here.

An important point is that, as far as time-of-flight experiments are concerned, the NLSB and DSR scenarios can produce exactly the same leading-order effects. Thus, to distinguish them one must take into account experiments where either one or both of the modifications in transformation laws and energy-momentum conservation arise, since these are modified in DSR, but not in NLSB. 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 of the infrared background. Because DSR maintains the principle of relativity of inertial frames, the interactions involved can always be evaluated in the center-of-mass frame, where the energies coming into the deformations from special relativity are smaller. Consequently, DSR makes, up to unobservably small corrections [11], 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, sizable modifications to 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 disfavored, while the DSR scenario remains unaffected. The only reservation might be that the GZK analysis applies to protons, and as this is the only significant constraint for the NLSB scenario, it is experimentally possible that the photon and proton dispersions are governed by independent parameters.

III. FIRST OBSERVATIONS FROM FERMI RELEVANT FOR QUANTUM GRAVITY PHENOMENOLOGY

At present there are reports [15–17] of ~200 GRBs observed at low energies by Fermi's Gamma-ray Burst Monitor (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 1 GeV. 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 GCNs, 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 eight GRBs. We also summarize the information in Table I.

TABLE I. GRBs seen by Fermi LAT with photon energies $\gtrsim$ 1 GeV. $t_i^{\rm LAT}$ is the time after the initial burst that high-energy photons seen by the LAT begin. $t_f^{\rm LAT}$ is the time after the initial burst that the high-energy signals extend to. For references see the Appendix.

GRB	Redshift	Duration	$\text{counts}\vert_{\text{LAT}}$	$E_{\max}$	$t_i^{\rm LAT}$	$t_f^{\rm LAT}$
080916C	4.35	Long	Strong	13 GeV	4.5 s	$>10^3$ s
081024B		Short		3 GeV	0.2 s	
090510	0.9	Short	Strong	>1 GeV	<1 s	$\gtrsim 60$ s
090328	0.7	Long		>1 GeV		≈ 900 s
090323	4	Long	Strong	>1 GeV		$>10^3$ s
090217		Long			~1 s	≈ 20 s
080825C		Long	Weak	0.6 GeV	3 s	>40 s
081215A			Weak	0.2 GeV		

A. 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 have 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.

1. GRB080916C

Let us start by briefly summarizing the observation of GRB080916C, as reported by the Fermi Collaboration in Ref. [15]. For GRB080916C Fermi detected [15] ~200 high-energy (>100 MeV) photons, allowing time-resolved spectral studies. And there was a significant delay of $\simeq 4.5$ s between the onset of >100 MeV and ~100 keV radiation. The most energetic photon, with an energy of $\approx$ 13.2 GeV, was detected by the LAT 16.5 s after the GBM trigger. Also noteworthy 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 keV to ~10 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 MeV emission lasts at least 1400 s, while photons with <100 MeV are not detected past 200 s. And for us it is particularly significant that the time when the >100 MeV emission is detected ($\simeq 4.5$ s after the first <5 MeV pulse) roughly coincides with the onset of a second <5 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.

2. GRB081024B and GRB090510

Information that is somewhat complementary to the information 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 $\simeq 0.2$ s after the (first-peak) trigger and a few photons with energy $\gtrsim 100$ MeV were observed in rough coincidence with the second GBM peak, including a 3 GeV photon. For GRB090510, according to preliminary reports [60], several multi-GeV photons were detected within the first second of the burst (whose inferred redshift is ≈ 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 [64–66] 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. Common features of the data

In addition to the three bursts we have just discussed, the Fermi LAT has observed five other bursts so far. On some of these bursts there is still rather limited information, but preliminary reports suggest that some features noticed in GRB080916C may be generic. In particular, one finds frequently that 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, and that high-energy events last much longer than low-energy events.

B. 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 the possible measurement of $M_{\rm QG}$ is that the data cannot be interpreted purely in terms of dispersion during travel. In that ideal situation there would be a simple monotonic 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 the 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 redshifts 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 $M_{\rm QG}$ requires some methodology which models or averages out astrophysical effects. It is far simpler to establish bounds on $M_{\rm QG}$. We now turn to this, focusing (as in most parts of this paper) on the case $\alpha = 1$ in which the effects depend linearly on (the inverse of) the quantum gravity scale.

1. Conservative bounds on subluminal propagation

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

Using this methodology, the Fermi Collaboration established [15] a bound on $M_{\rm QG}$ using the 13.2 GeV photon of GRB080916C which arrived 16.5 s after the initial burst,

$$M_{\rm QG} > 1.3 \times 10^{18}\ {\rm GeV}, \tag{10}$$

i.e. roughly $M_{\rm QG} > 0.1 M_{\rm Planck}$.

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 4.5 s after the first low-energy peak), and this would then lead to a bound of

$$M_{\rm QG} > 1.8 \times 10^{18}\ {\rm GeV}. \tag{11}$$

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 ΔE between

100 MeV and 5 MeV is of course smaller than ΔE 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 0.2 s after the first low-energy peak. Then after another 0.2 s, 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 peaks 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 10 less energy could lead to a delay of no more than 0.04 s. Thus, quantum gravity cannot account for the 0.2 s 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 improve, 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 seen by the LAT so far.) The result would have been a bound of $M_{\mathrm{QG}} \gtrsim 2.2 \times 10^{18}$ 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 multi-GeV photons within the first second after the low-energy trigger. A bound of $M_{\mathrm{QG}} \gtrsim 2.2 \times 10^{18}$ GeV would be confirmed by detecting a photon of, say, 2 GeV arriving from $z \approx 0.9$ within 0.4 s of the onset of the LAT signal.

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 active galactic nuclei Mk501 and PKS2155-304, respectively. A study of spectral lags in these observations was found [47,48] to favor the subluminal case ($s_{\pm} = 1$) with an estimated measurement (rather than a bound) for $M_{\mathrm{QG}} = (0.98^{+0.77}_{-0.30}) \times 10^{18}$ 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 that the effects of in-vacuo dispersion are larger than they would be for heavier M_{QG}, at or above M_{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 $M_{\mathrm{QG}} \approx 10^{18}$ GeV for typical GRB redshifts of ~ 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 $M_{\mathrm{QG}} > 1.3 \times 10^{18}$ GeV established by the Fermi Collaboration in Ref. [15] is compatible within 1 standard deviation with the mentioned estimate $M_{\mathrm{QG}} = (0.98^{+0.77}_{-0.30}) \times 10^{18}$ GeV based on previous 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 the low-energy GRB signal and the first peak of the >100 MeV GRB signal, appear to provide encouragement for a somewhat higher value of M_{QG}. Our "reasonably conservative" bound $M_{\mathrm{QG}} > 1.8 \times 10^{18}$ GeV, obtained from assuming the high-energy photons started in coincidence with the second peak of GRB080916C, is already more than 1 standard deviation away from $M_{\mathrm{QG}} = (0.98^{+0.77}_{-0.30}) \times 10^{18}$ GeV. And the remarks on GRB082014B offered at the end of the previous subsection appear to favor values of M_{QG} that would be in significant disagreement with the estimate $M_{\mathrm{QG}} = (0.98^{+0.77}_{-0.30}) \times 10^{18}$ 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 behavior of the sources. Still it is worth noticing that the evidence of the 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 as 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 Sec. V their possible relevance for descriptions of quantum gravity effects on propagation that go beyond the pure-dispersion picture.

C. Bounds on superluminal propagation

We now turn to the discussion of 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 $s_\pm = -1$. 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 subluminal 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.

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 show a tendency of high-energy particles to arrive, on average, later than low-energy ones. But this feature does not actually provide evidence in favor of subluminal propagation, since with our present, very limited, understanding of the sources, it is possible that it is fully of astrophysical origin. Thus it does not amount to any evidence against superluminal propagation either.

In the spirit of the type of considerations we offered in Sec. III B 2, for the case of subluminal propagation, we can look for arguments that allow us to establish reasonably conservative (although not fully conservative) bounds on $M_{\rm QG}$ for the case of superluminal propagation. Let us start by focusing our attention on the first two photons with energy $\gtrsim 1$ GeV that were detected by the Fermi LAT [15] at 6.0 ± 0.5 s and at 7.0 ± 0.5 s 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 which, from the data, we associate with the time interval from the time of trigger to a time we conservatively estimate to be $\lesssim 12$ s 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 traveling a distance of $z = 4.3$ had not gained more than 5.5 s. From this we infer

$$M_{\rm QG}^{[s_\pm=-1]} > 3.2 \times 10^{17}\ \text{GeV}. \qquad (12)$$

One can arrive at a comparable bound by considering the first group of >100 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 ± 0.5 s after the trigger, which (according to the observations on the second peak of GRB080916C discussed above) we must place in correspondence with a peak found at 5.3 ± 0.7 s after the trigger for photons with energy between 260 keV and 5 MeV. From this we deduce that photons with energy $\gtrsim 100$ MeV do not gain more than 0.5 s after traveling a distance of $z = 4.3$, and in turn from this we infer $M_{\rm QG}^{[s_\pm=-1]} \gtrsim 3.5 \times 10^{17}$ 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 literature. We may then suggest that (12) be treated as a conservative upper bound on the scale $M_{\rm QG}^{[s_\pm=-1]}$ 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 $\sim 3 \times 10^{17}$ 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 on the way to the telescope. For example, if $M_{\rm QG}^{[s_\pm=-1]} \approx 4 \times 10^{17}$ GeV, which is a possibility not excluded by our conservative bound, a 13.2 GeV photon arriving from $z \simeq 4.3$ should have gained, along the way, some 65 s, and as a result it would have needed some tuning to achieve an arrival time which is 16 s *after* the trigger, rather than some time before it. Although 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 studies of superluminal in-vacuo dispersion on estimates that are significantly higher than 3×10^{17} GeV, perhaps already in some neighborhood of $M_{\rm QG}^{[s_\pm=-1]} \sim M_{\rm Planck}$.

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 opposite helicity, which would be superluminal, were produced but not detected.

To see how this might work, pick a candidate value of $M_{\rm QG}^{[s_\pm=-1]}$, $M_{\rm QG}^{[s_\pm=-1]} = \bar{M}$, and consider a set of photons in a range of time and energy, as follows. The photons must arrive within a time $t \le t_0$ after the trigger with energies $E \ge E_0$ such that the minimum time delay $\delta t = \frac{E_0}{\bar{M}} L \ge t_0$. 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 $\bar{M}$, and the source does not emit predominantly in one helicity.

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

IV. PROSPECTS FOR MEASURING A QUANTUM GRAVITY SCALE

We now turn to the question of whether future experiments might make possible a measurement of $M_{\rm QG}$ 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 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 turn out to be on the large side of the range of theory-favored magnitudes, as initially suggested by the preliminary analyses of active galactic nuclei reported in Refs. [47,48], the competition with model building on the astrophysics side might be less challenging, since with $M_{\rm QG} \approx 10^{18}$ GeV for typical GRB redshifts of ~ 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 Sec. III B 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 $M_{\rm QG}$ 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 redshifts. With correspondingly high statistics (the 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.

We note that these redshift-dependence analyses of Fermi data might acquire much greater significance if some of the GRBs used in the analysis are also observed by other telescopes, at energies higher than the ones accessible to Fermi. In this section we discuss some possibilities for such observations at higher energies.

A. Photons

Let us first consider the possibility of observing Fermi LAT bursts also at TeV-photon observatories. The advantages would be significant, since the time lags for photons of, say, ~ 1 TeV should be, within the in-vacuo-dispersion picture, at least an order of magnitude greater than for photons of <100 GeV. One concern for these searches is the expectation (see, e.g., Ref. [67] 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. [67] 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 [6,68–71] (while no such reduction is expected in DSR [11]), so this issue is mixed up with that of in-vacuo dispersion. That is, if a NLSB framework were true, there might be reduced absorption of TeV-scale photons to be observed from GRBs. This would be indirect evidence for that scenario and it would permit the observation of TeV photons.

The first Fermi observations, by showing that the LAT signal tends to persist for a relatively long time after the trigger, in some cases of the order of 10^3 s, provide encouragement for the possibility that such studies could also involve telescopes that need to be positioned in the direction of the burst (like MAGIC [72]).

Of course, the advantages for in-vacuo-dispersion studies would be even greater if photons of even higher energies (say, $>10^{13}$ eV) were detected for some Fermi LAT bursts. Also, for these very high-energy (VHE) photons absorption by soft background photons is expected, but for

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[4] This probability that a photon of a certain energy might have passed the detector at a certain time without being observed is not exclusively of interest for strategies aimed at placing limits on superluminal propagation. Also for subluminal propagation, this missed-photon probability can significantly affect the outcome of the analyses. We will investigate this issue when more information becomes available for the Fermi-LAT-detected bursts.

the same reasons mentioned above, we feel this should not necessarily discourage such searches. In particular, we believe that such searches deserve significant priority at the Auger cosmic-ray observatory [73].

A challenge (but possibly an opportunity) for such VHE-photon observations originates from the fact that the expected delays are very large in the case of a linear quantum gravity effect. For example, for $M_{\rm QG} \sim M_{\rm Planck}$ a 10^{16} eV photon should acquire a delay of $\sim 10^6$ s ($\sim$ 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 poses observational challenges having to do with correctly attributing such photons to a GRB that had triggered much earlier.

B. VHE neutrinos

It has long been recognized [74–78] 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, for reasons that are completely analogous to the ones discussed in the previous subsection for the case of VHE photons, 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.

While the working assumption that GRBs produce VHE cosmic rays leads us to expect that some VHE neutrinos are indeed produced [80] 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 misidentified as background/noise, especially if arriving with a delay of, say, a month from the GRB trigger.

C. Forward and backward in time

We now turn from subluminal to superluminal propagation of very high-energy photons and neutrinos. We stress that, while, as discussed in Sec. III B, 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.

It is intriguing that dispersion effects of, say, 0.1 s 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 ~ 4.5 s, so in this scenario a multi-TeV photon emitted together with the second peak of GRB080916C could be 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.

Preliminary encouragement for these issues comes from the analysis reported in Ref. [81], which provided some (weak, 2.9 standard deviations) evidence of detection of photons with energy ~ 100 TeV from GRB910511 some 40 min before the trigger of GRB910511.

V. 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 several parameters, most (if not all) of which are 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 consistent with it parametrizing 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.

A. Fuzzy dispersion

The idea that quantum gravity would imply modified dispersion relations is relatively new for quantum gravity research; a serious discussion of this idea began 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 not affect the average arrival time of a group of particles, but would instead contribute to the spreading of results of repeated measurements [82,83]. 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 [84,85], and we would like to underline that the quality of the data being reported by Fermi is such that even this more structured intuition about the quantum gravity vacuum could be investigated. In particular, one can consider the picture introduced in Refs. [84,85], which implies the following description of the relationship between the energy and speed of a particle:

$$v(E) \simeq 1 - \eta E/M_{\mathrm{Planck}} \pm \eta/(M_{\mathrm{Planck}}\Delta t^*) \pm \eta_f E/M_{\mathrm{Planck}}, \qquad (13)$$

where η parametrizes the type of "systematic" effect we already considered in the previous section, while η_f parametrizes the fuzziness of the relationship between the energy and speed.

One advantage to this kind of scenario is that, in contrast to other Lorentz symmetry breaking scenarios, the GZK threshold remains essentially unaffected [85]. As far as time lags are concerned, a "fuzzy dispersion" of the type (13) would predict that 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 they 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. In addition, the fuzzy picture also introduces randomness 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 Sec. III B 3).

B. 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 [86,87] in the formulation of loop quantum gravity, and is parametrized 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 $\delta v = -\beta\langle s\rangle \frac{E}{M_{\mathrm{QG}}}$, where $\langle s\rangle$ is the expectation value of chirality, a number in the range $-1 \leq \langle s\rangle \leq 1$, whereas NLSB and DSR predict an even parity effect $\delta v = -\alpha \frac{E}{M_{\mathrm{QG}}}$, independent of helicity. It is then possible to imagine that a quantum theory of gravity might predict a mixed effect,

$$\delta v = -(\alpha + \beta\langle s\rangle)\frac{E}{M_{\mathrm{QG}}}, \qquad (14)$$

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,

$$\delta t = (\alpha + \beta\langle s\rangle)\frac{E}{M_{\mathrm{QG}}}L \qquad (15)$$

in the small z approximation.

VI. CONCLUSIONS

When, about a decade ago, the possibility of this type of study with Fermi (then known as GLAST) was first contemplated, it appeared that reaching Planck-scale sensitivity 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. After less than a year of Fermi observations, it is clear that, for linear quantum gravity effects, the full range of values of M_{QG} that are of interest from a theory perspective, down to a couple of orders of magnitude beyond the Planck scale, can be studied.

Having emphasized the bright prospect for setting bounds on M_{QG}, we turned our attention to the greater challenge of discovering quantum gravity effects by measuring a finite value of M_{QG}. It seems 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 of 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 of even particularly small effects (such as in cases in which $M_{\mathrm{QG}} \sim M_{\mathrm{Planck}}$, or even 1 or 2 orders of magnitude bigger) could be achieved with relatively small samples of GRBs at different redshifts. 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. And, 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 $1/M_{\mathrm{QG}}$, so that astrophysical explanations suffice to describe the data from GRBs. But, given what is at stake for fundamental physics, it would be foolish to assume this, 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 Sec. IV 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.

ACKNOWLEDGMENTS

We are thankful to Antonio Capone, Sabine Hossenfelder, and Flavio Mercati for discussions during the preparation of this paper. We are also grateful to Camilla and Edoardo Amelino-Camelia and Kai Smolin for inspiration, particularly regarding the superluminal case. Research at Perimeter Institute for Theoretical Physics is supported in part by the Government of Canada through NSERC and by the Province of Ontario through MRI. G. A.-C. is supported in part by Grant No. RFP2-08-02 from The Foundational Questions Institute (fqxi.org).

APPENDIX: FERMI-OBSERVED GRBS WITH GEV PHOTONS

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

(1) *GRB080916C*.—We described in some detail this very strong, long burst in Sec. III. Photons were detected [15] by LAT up to ~13 GeV (three photons above 6 GeV), and the overall strength of the LAT signal allowed time-resolved spectral studies [15]. Afterglow studies [50] allowed one to determine a redshift of 4.35 ± 0.3.

(2) *GRB081024B*.—This was the first short burst, described in Refs. [15,51,52], with a signal above 1 GeV (with a maximum energy of 3 GeV).

(3) *GRB090510*.—For this short burst (described in Ref. [60]), at a redshift of ≈ 0.9, the Fermi LAT detected more than 50 events above 100 MeV (at least 10 above 1 GeV) within 1 s 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 high-energy emission (including some photons with >1 GeV) lasts up to around 900 s after the trigger. Afterglow studies [59] allowed one 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 $\sim 2 \times 10^3$ s. Afterglow studies [57] allowed one to determine a redshift of ~ 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 s 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 1 GeV. The LAT signal was rather weak [53] but still provided significant evidence of a delayed onset [15] of the high-energy component and persistence up to 35 s 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, provided 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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