Towards a new approach to Quantum Gravity Phenomenology

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Abstract

The idea that quantum gravity manifestations would be associated with a violation of Lorentz invariance is very strongly bounded and faces serious theoretical challenges. This leads us to consider an alternative line of thought for such phenomenological search. We discuss the underlying viewpoint and briefly mention its possible connections with current theoretical ideas. We also outline the challenges that the experimental search of the effects would seem to entail.

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I. INTRODUCTION

There has been recently a great deal of interest in possible phenomenological manifestations of quantum gravity effects \(^1\). These effects are thought to arise from the granularity of space-time at the Planck scale leading to a breakdown of Lorentz Invariance in its low energy limit and would generally imply, in contrast with one of the most cherished and useful principles of physics, the existence of a preferential frame; a new version of the XIX\(^{th}\) century Ether\(^1\). In fact a large collection of very tight bounds have been obtained by considering astrophysical observations and Laboratory experiments \(^1\). Moreover, a recent analysis of the way that such a preferred frame granularity would affect the radiative corrections in the standard model of particle physics, shows that the basic suppositions are in conflict with what we understand about quantum field theory together with even low accuracy tests of Lorentz Invariance in particle physics \(^1\).\(^2\).

The purpose of this paper is to explore what seems to be the next most natural assumption regarding the way quantum gravity might become manifest. We shall first motivate a proposal, starting with a plausibility argument constructed to reconcile our intuitions about quantum gravity, with the evidence against a Violation of Lorentz Invariance (VLI) of the sort that has been considered. We will then present the new possible ways in which an effective theory might be the low energy limit of certain quantum gravity theories, and finally we shall explore the possible phenomenological implications of this new proposal.

Let us try to motivate the need for a new approach to the subject. The idea is then that somehow the fact that the underlying symmetry of the fundamental structure is itself the Lorentz Symmetry, leads to a situation in which the large scale Lorentz Symmetry is protected by the symmetry of the fundamental granular structure. In other words, that, given the symmetric nature of the granular structure, the existence of a fundamental granularity might not show up as an observational brake-down of the symmetry, when the macroscopic physical entity (here the spacetime geometry) is itself fully symmetric. Thus a region of spacetime, normally considered as well approximated by Minkowski metric, would not manifests the granular structure of the quantum spacetime, through the breakdown of Lorentz Invariance. This line of thought would then explain naturally the previously mentioned empirical evidence. The point, however, is not the explanation itself, which admittedly is at best sketchy, but rather to motivate the next lines of thought. In view of the above, we note that the only interesting situation that would be left open to investigations is that in which the macroscopic space-time that is to be probed is not fully compatible with the symmetry of its basic constituents. The idea is to think in analogy to what happens when a large crystal has the same symmetry (say cubic) of the fundamental crystal, one could expect no deviations from fully cubic symmetry, as a result of the discrete nature of the fundamental building blocks. However if one wants to build a macroscopic crystal whose global form is not compatible with the structure of the fundamental crystals, say hexagonal, the surface will necessarily include some roughness, and thus a manifestation of the granular structure, would occur through a breakdown of the exact hexagonal symmetry.

This simple picture will be guiding our analysis, and in that respect we must keep in mind that we will be referring to the physical description of the situation at two levels. The

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\(^1\) Another possibility that has been considered in the literature are deformations of the Lorentz Algebra or their representations such as the so called Double Special Relativity (DSR) proposals \(^2\). We will not deal with these ideas in this manuscript.
first, the effective or macroscopic level of description would correspond in the example of the physics of solids, to a continuous description of physical objects, which we could envision as being expressed in terms of, say, a smooth metric and extrinsic curvatures of the surfaces of the solid, and smooth functions giving the mass density, pressures and viscosities in its inside, etc. In the case of gravitation it would correspond to general relativity. The second level would correspond to a fundamental quantum mechanical solid state description of both the interior and surface constituents in the case of our solid object, and a yet unknown theory of the underlying and somehow granular structure of spacetime. The connection between the two levels will be guided by symmetry arguments, and thus we will refer often using the first level of description to the situations in which the granular nature of the underlying or fundamental description would become manifest. We must keep this in mind for, otherwise, statements involving simultaneously the two levels of description would seem nonsensical.

Following with this line of thought and with the solid state physics analogy, we would expect that it might be precisely in the event of a failure of the space-time to be exactly Minkowski in an open domain, that the underlying granular structure of quantum gravity origin, would become manifest, affecting the propagation of the various matter fields. The effective description of such situation should thus involve the Riemann tensor, (which is known to precisely describe the failure of a space-time to be Minkowski over an open domain). This is, we know that in every point of spacetime we can construct “local inertial frames”, corresponding to the Riemann Normal coordinates at that point, and that the failure of such construction to provide an extended inertial frame is measured by the Riemann tensor. Thus the non-vanishing of Riemann would correspond to the macroscopic description of the situation where the microscopic structure of space-time might become manifest. Moreover, we can expect, due to the implicit correspondence of the macroscopic description with the more fundamental one, that the Riemann tensor would also indicate the space-time directions with which the sought effects would be associated. This would replace, in the current approach, the global selection of a preferential reference frame that was implicit on most schemes of –let us now refer to it as– the old approach towards Quantum Gravity Phenomenology (QGP).

In fact, when considering the phenomenology, it is important to recall that the Ricci tensor represents that part of the Riemann tensor which, at least on shell, is locally determined by the energy momentum of matter at the events of interest. Thus the coupling of matter to the Ricci tensor part of the Riemann tensor would, at the phenomenological level, reflect a sort of pointwise self interaction of matter that would amount to a locally defined renormalization of the usual phenomenological terms such as a mass or kinetic term in the Lagrangian. However we are interested in the underlying structure of space-time rather that the self interaction of matter. Thus we would need to ignore the aspects that are known to encode the latter, which in our case would correspond to all lagrangian terms containing only that part of the Riemann tensor proportional to the Ricci tensor, coupled to matter fields. The rest of the Riemann tensor can thus be thought to reflect the aspect of local structure of spacetime associated solely with the gravitational degrees of freedom. This local structure, which is codified in the macroscopic theory by the Weyl tensor, would in the microscopic theory reflect aspects of the quantum gravitational structure of spacetime in itself. The effects we are interested, which refer only to the gravitational aspects, and that would therefore constitute a probe into the quantum mechanical nature of spacetime, would thus be associated with the coupling of the Weyl tensor with the matter fields. In everyday situations (i.e. in the absence of gravitational waves) the Weyl tensor is also connected with the nearby “matter sources”
but such connection involves the propagation of their influence through the spacetime and thus the structure of the latter would be playing a central role in the way the influences become manifest. In this sense the Weyl tensor reflects the “nonlocal effects” of the matter in contrast with the Ricci tensor or curvature scalar that are determinable from the latter in a completely local way.

In this paper we will start the investigation of such ideas, in a rather heuristic form, firstly because we do not want at this point to commit ourselves to a specific proposal for the quantization of gravitation, and secondly, because our first aim is to outline the simplest available options for a more complex realm of possibilities regarding quantum gravity phenomenology. The main objective of this work is, therefore, to open the way to a new perspective of analyzing (and possible observing) the fundamental discreteness of the spacetime geometry.

The paper is organized as follows. In Section II we will study the most straightforward approach, showing that in this scenario the situation regarding the observability of the quantum gravity effects, is very pessimistic as the suppressions turn out to be bigger than expected at first sight. In Section III we will explore a more complicated approach, that, on the one hand looks as rather contrived, at least in the tensor language, which we must recognize, might not have much to do with the natural language that describes the quantum gravity realm, and on the other hand seems to yield relative large, and thus to a more promising scenario for the observability of such effects. In Section IV we shall give some arguments supporting our general view, but geared towards its realization in a particular approach to quantum gravity, the Loop Quantum Gravity Program. In Section V we will discuss the expected orders of magnitude and other issues that would confront the experimental investigation of these issues. We will end with a brief discussion of our analysis and with some conclusions in Section VI.

II. STRAIGHTFORWARD APPROACH

The fundamental fields of the standard model are boson and fermions, thus we start by considering all couplings of such fields to the Riemann tensor. The Riemann tensor has mass dimension 2, the fermions have mass dimension 3/2 and the bosons have mass dimension 1. Naturally the dimension $n$ Lagrangian terms would be suppressed by a factor $(1/M_{\text{Planck}})^{(n-4)}$. Furthermore we will as usual assume observer covariance and the absence of globally defined non-dynamical tensor fields. A careful examination will reveal that the least possible suppression corresponds to a unique term involving coupling of fermions and the Riemann tensor.

$$L_1' = \frac{\xi}{M_{\text{Pl}}} R_{\mu\nu\rho\sigma} \bar{\Psi} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \Psi,$$

where $\Psi$ stands for the various fundamental spinor fields in the standard model, $\gamma^\mu$ for the Dirac matrices, $R_{\mu\nu\rho\sigma}$ for the Riemann tensor, and $\xi$ a dimensionless number characterizing the geometrical aspects of the appropriate state of the quantum gravity theory and the fermions interaction with it. Note in particular that one can not write a similar dimension 5 operator involving boson fields. To proceed further we note that we can write the product of the four gamma matrices in terms of the symmetrized and anti-symmetrized products leading to an expansion containing only the matrices $\gamma^\mu, \gamma^5, \gamma^5 \gamma^\mu$, and $\Sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]$, together with the metric and the volume 4-form $\epsilon^{\mu\nu\rho\sigma}$. As already mentioned, we are not interested in probing the terms involving the Ricci tensor or the scalar curvature, as they
would be expressible using Einstein’s equations in terms of the local energy momentum tensor associated with the matter fields. In this event the sole term that would be left is

$$L' = \frac{\xi}{M_{Pl}} W_{\mu \nu \rho \sigma} \epsilon^{\mu \nu \rho \sigma} \Psi \gamma^\delta \Psi. \quad (2)$$

Where $W_{\mu \nu \rho \sigma}$ stands for the Weyl tensor.

However, as it is well known, the Riemann tensor, and thus also the Weyl tensor has a vanishing totally antisymmetric part, so $W_{\mu \nu \rho \sigma} \epsilon^{\mu \nu \rho \sigma} = 0$. We therefore conclude that there are no terms of this sort where the suppression factor is just $1/M_{Pl}$. Then we move to consider the terms suppressed by more powers of $M_{Pl}$ these are: In scalar sector we have a term,

$$L'_\phi = \frac{\xi}{M_{Pl}^4} W_{\mu \nu \rho \sigma} \text{Tr} \Phi \partial_\mu \partial_\nu \partial_\rho \partial_\sigma \Phi \quad (3)$$

In the fermion sector we have a term,

$$L'_\psi = \frac{\xi}{M_{Pl}^3} W_{\mu \nu \rho \sigma} \bar{\Psi} \gamma_\mu \gamma_\nu \partial_\rho \partial_\sigma \Psi. \quad (4)$$

Here in principle, we should have used covariant rather than partial derivatives, but we use this point to emphasize that we can choose at each point of space-time locally normal coordinates constructed so that the Christofell symbols vanish at that point. In a very small region of space-time which our probe could be consider to occupy, we would thus have essentially Minkowski coordinates, and would in normal circumstances declare that gravity has been turned off by using appropriately the free falling recipe to construct local inertial frames. In our scheme this turning off of gravitation would not be complete and there would be a remaining effect due to the fact that space-time was in some sense granular rather than continuous and smooth, and that in its bending it (due in the case of interest the effects of distant matter), the granular structure was forced to emerge. This is precisely what we seek to describe in this paper.

In the vector boson sector, taking into account the requirement of gauge invariance, we have a term of the form

$$L'_m = \frac{\xi}{M_{Pl}^2} W_{\mu \nu \rho \sigma} \text{Tr} (F_{\mu \nu} F_{\rho \sigma}) \quad (5)$$

The pattern seems very clear, the suppression decreases with increasing spin of the field. The minimum suppression given by the matter content of the standard model of particle physics is therefore associated with the vector boson sector term (5) and amongst these the most natural phenomenological arena would seem to be the one associated with the Maxwell field.

We finalize this section by pointing out that the introduction of these new lagrangian terms would lead to a change not only in the dynamics of matter fields in the presence of gravitation, but also to a change of the response of the metric to the presence of matter fields. However it is easy to see that the latter would be even more suppressed that the former. To see this let us write the total action as,

$$S = \int M_{Pl}^2 R(g) + L_{Mat}(\Psi) + \frac{1}{M_{Pl}^n} F(\Psi, W), \quad (6)$$

where $\Psi$ stands generically for the matter fields of the standard Model and $W$ stands for the Weyl tensor. The equations of motion for the matter fields will receive a contribution proportional to $M_{Pl}^{-n}$, while the Einstein tensor would receive extra contributions proportional to $M_{Pl}^{-n-2}$, and thus we will ignore the latter in the remainder of the manuscript.
III. AN ALTERNATIVE APPROACH

From the previous analysis we seem to conclude that there can be no effect of the sort we are interested in, and such that it is suppressed by the minimal amount that could be naturally associated with a quantum gravity effect. This is in sharp contrast with the situation prevailing in the standard Quantum Gravity Phenomenology where the Violation of Lorentz Symmetry could, at least at first sight, be associated with dimension five operators, naturally suppressed by one power of the Planck mass, and where radiative corrections would actually tend to transfer the violation to unsuppressed or even enhanced lower dimensional operators. Here we want to explore the possibility of effects of the type we have been discussing, with lower suppression, arising from alternative descriptions of the spacetime curvature.

We are interested, for phenomenological reasons, in schemes in which locally the gravitational degrees of freedom select preferential directions, planes or other subspaces of spacetime. This would present us with a scheme in which, in contrast with the old Quantum Gravity Phenomenology, there is no need to choose an ad hoc direction in spacetime, but where the gravitational environment would be making the selection of the locally preferred directions which could be naively considered as local violations of absolute Lorentz invariance. Clearly a situation much closer to the Machian spirit and that of G.R. than that of the old QGP. The phenomenological motivation is that the situations involving the breaking of symmetries afford in general a much more promising experimental scenario, than those that do not, specially dealing with what could be at most, extremely small effects. Needless is to say that this approach is less natural than the one we investigated in section II, and the only remark that we can make in this regard is to note that the degree of naturalness can be expected to depend on the language employed, and that is conceivable that if one were to use the language most appropriate to describe the quantum gravitational degrees of freedom – an issue that is still unknown as far as we are concerned – objects, that look unnatural in the tensorial language appropriate to sub-Planckian phenomena, might be rather natural, in that, still to be determined, quantum gravity language. As an illustration of this point, we recall that in Loop quantum gravity the fundamental degrees of freedom are associated with holonomies and fluxes, and thus are at some level fundamentally nonlocal, in contrast with the local degrees of freedom usually represented in terms of tensor fields.

The idea is then to search for tensors of lower type containing information about the spacetime curvature. Clearly these have to contain information already available in the Riemann tensor, but perhaps not all such information. We are thus driven to look at the Weyl tensor, the principal null vectors of the Weyl tensor and so forth. One approach that seems to yield the kind of terms we are interested is to consider the Weyl tensor viewed as a tensor of type (2, 2) as a mapping from the space of antisymmetric tensors of type (0, 2), $S$ into itself. As is well known the spacetime metric endows the six dimensional vector space $S$ with a pseudo-Riemannian metric of signature $(+ + + - - -)$ [7]. Then the Weyl tensor is a symmetric operator on this space $S$, which can therefore be diagonalized, and thus has a complete set of eigenvectors (which are however not necessarily orthogonal). Let us consider only the eigenvectors $\Xi^{(i)}$ corresponding to non-vanishing eigenvalues $\lambda^{(i)}$, by fixing the normalization of these eigenvectors to be $\pm 1$ (also drop the null eigenvectors)\(^2\). We will also assume for simplicity, and in order to avoid possible ambiguities, that all eigenvalues are

\(^2\) In spacetimes of astrophysical interest such as the Kerr metric, this decomposition of the Weyl tensor is indeed possible and can be explicitly done.
different. We can now use the antisymmetric tensors \( \Xi^{(i)}_{\mu\nu} \) and their associated eigenvalues \( \lambda^{(i)} \) to construct the types of Lagrangian terms we are interested in. In the same spirit as before, searching for terms linear in these objects, and recalling that the eigenvalues \( \lambda^{(i)} \) have the dimension of the Riemann tensor, we have the least possible suppressions in each sector as follows: In scalar sector we have a term,

\[
\mathcal{L}_\phi = \frac{\xi}{M_{\text{Pl}}} \sum_i \lambda^i \Xi^{(i)}_{\mu\nu} \text{Tr} \Phi \partial^\mu \partial^\nu \Phi .
\]

(7)

In the fermion sector we have a term,

\[
\mathcal{L}_\psi = \frac{\xi}{M_{\text{Pl}}} \sum_i \lambda^i \Xi^{(i)}_{\mu\nu} \bar{\Psi} \gamma^\mu \gamma^\nu \Psi .
\]

(8)

In vector boson sector, taking into account the requirements of gauge invariance, we are lead to a term

\[
\mathcal{L}_m = \frac{\xi}{M_{\text{Pl}}} \sum_i \lambda^i \Xi^{(i)}_{\mu\nu} \text{Tr} (F^\rho_{\mu} F^{\rho\nu}) .
\]

(9)

Thus the fermions provide the most promising probes, which seems a fortunate situation, in this scheme.

As it was pointed out to us, by a charitable soul, one could also consider coupling directly a scalar made out of the standard model fields to an appropriate power of a scalar constructed out of the Weyl tensor such as \((W_{\mu\nu\rho\sigma} W^{\mu\nu\rho\sigma})^{1/2}\). This proposal, while very reasonable, departs slightly from the spirit of our attempts to indicate that the space-time structure would naturally and locally select preferential directions, in a way that could be probed experimentally. Moreover, the lack of any such seemingly Lorentz invariance violating interactions would tend to make the effects much harder to detect experimentally. On the other hand this line opens the way to consider, despite their seeming unnaturalness, effects that would not be suppressed by any power of the Planck mass, such as

\[
\mathcal{L}_\psi = (W_{\mu\nu\rho\sigma} W^{\mu\nu\rho\sigma})^{1/4} \bar{\Psi} \Psi .
\]

(10)

We will not focus on this last proposal in this manuscript.

IV. SOME MOTIVATIONS FROM QUANTUM GRAVITY

In this section we shall give give some heuristic arguments to the effect that the basic variables and the strategy followed to get to an effective QFT (on a background) coming from loop quantum gravity \([6]\), and from String Theory, might allow for the type of terms that we have proposed before.

Let us first look at the issue from the LQG perspective. We start with the observation that LQG is based on a connection formulation of General Relativity, where one of the basic objects is an \( SO(3,1) \) connection \( A^B_{\mu C} \), whose curvature \( F^C_{\mu\nu B} \) is, on shell, equal to the Riemann tensor. The second observation is that there is a very close relationship between the algebraic structure of the Riemann tensor (or the Weyl tensor in vacuum) and the so called holonomy group of the spacetime. Basically the idea is that on a given point on spacetime, the holonomy along small closed curves, yielding elements of the gauge group (Lorentz) will belong to a specific subgroup of the Lorentz group \([8]\), depending on the algebraic
structure of the curvature tensor. Furthermore, the proper bivectors $\Xi^{(i)}$ appearing in the expansion [8] will have information precisely about the holonomies of the curvature tensor at that point. This is particularly relevant given that in the LQG formalism, both in the Hamiltonian approach (where the curvature is now only referring to the spatial part of the Lorentz group, namely local rotations), and in the still incomplete Lagrangian formulation (spin foams), the curvature tensor is always approximated by one of the fundamental objects in the theory, namely, the (quantum) holonomy.

One can imagine that a detailed treatment of semiclassical states for the geometry and the regularization of the matter fields on top of the quantum geometry (assuming that the subtleties and ambiguities already encountered in the discretization procedure, are resolved), might yield terms of the form (8). Let us now briefly discuss how this terms might arise. In the standard Hamiltonian for a spinor field one has a term of the form,

$$H = \int_{\Sigma} \frac{1}{\sqrt{\det q}} \left( i\pi^T \tau_i \mathcal{D}_a \varphi + \mathcal{D}_a (\pi^T \tau_i \varphi) + \cdots \right),$$

where $N$ is the lapse function, $\det q$ is the determinant of the spatial metric, $E_i^a$ is the triad field, $\mathcal{D}_a = \partial_a + [A_a, \cdot]$ is the covariant derivative, associated with the spatial connection $A_a$, $\varphi$ is the Weyl spinor corresponding to the fermion field, $\pi$ its canonical conjugate, and $\tau_i$ are the Pauli matrices. A standard trick is to bring this integral to the form,

$$H = \int d^3x N E_i^a \frac{1}{\sqrt{\det q}} \left( i\pi^T \tau_i \mathcal{D}_a \varphi + \mathcal{D}_a (\pi^T \tau_i \varphi) + \cdots \right),$$

where $V(x, \delta)$ is the volume element in a finite region. When the expression is turned into an operator, one replaces the Poisson brackets for commutators and the connection $A^i_a$ is approximated by holonomies. Finally, the strategy is to consider semi-classical states $|W, \xi\rangle$ of the geometry and the matter, and to compute the expectation value of the Hamiltonian operator $\hat{H}$ on this state to get an effective Hamiltonian for the spinor field. In the existing works on this subject (see [6]) some simple assumptions for the expectation values of certain operators in the semi-classical state are made, in particular in connection with the properties of the resulting geometry such as rotational symmetry of the macroscopic spacetime that corresponds to the state of the quantum geometry. Our observation is that, in describing at the fundamental level a region of spacetime which corresponds macroscopically to a given geometry, one would require a sufficiently detailed (and sophisticated) semiclassical state $|W, \xi\rangle$ that will contain, perhaps in a rather convoluted way, information about the extended space-time structure, and thus it should yield, subleading terms of the desired form (8), in the expectation values of complex operators.

It is, we believe, certainly worth pursuing this avenue, where the manifestation of the underlying discreteness would not be present as universal modifications of dispersion relations (closely related to LIV), but in the appearance of these new terms in the effective field theory, which would produce them locally. Needless to say, some work is needed in this direction to make these ideas precise.

From the String Theory outlook the situation is not clear because at this time there is no Nonperturbative formulation of the theory which includes a complete and clear understanding of the emergence of physical spacetime. However it seems safe to argue that any such scheme would at some level describe a mildly curved spacetime in terms of a sufficiently complex state involving many gravitons. As the spacetime curvature of the situation we envision is macroscopic, the gravitons would be in some sort of coherent state. It is well known
that the Weyl tensor is intimately connected with the polarization of a gravitational wave and thus it will be connected with the common polarization of the gravitons in the coherent state. In string theory the standard interaction of gravitons and other matter fields arises at the lowest order in perturbation theory, but other forms of interaction involving heavier modes are known to occur, however suppressed by the string length $\sqrt{\alpha'}$, in the perturbation expansion. These higher order interactions will couple the gravitons to matter and it is quite natural to expect that some of these interactions will be polarization dependent. Thus a mechanism to produce an effective coupling of the spacetime curvature (associated with the polarization of the gravitons) and suppressed by the string mass scale which we take to be of the order of $M_{\text{Pl}}$ seems to be in place.

Let us now consider the possible approaches for experimental tests for these type of theories.

V. PHENOMENOLOGY

The views presented here clearly call for a reassessment of the phenomenology of quantum gravity. To start with, we are called to concentrate clearly in the fermion sector as it is the one leading to the most promisingly observable effects.

Let us write again the corresponding Lagrangian term now taking into account possible flavor dependence;

$$\mathcal{L}^{(2)}_f = \sum_a \frac{\xi_a}{M_{\text{Pl}}} \sum_i \lambda^i \Xi_{\mu\nu}^{(i)} \bar{\Psi}_a \gamma^\mu \gamma^\nu \Psi_a .$$

(13)

where $a$ denotes flavor. Next we note that we have in principle the same types of effects that have been considered in the Standard Model Extension (SME) but only with terms of the form $-1/2 H_{\mu\nu} \bar{\Psi} \sigma^{\mu\nu} \Psi$. Moreover, here the tensor $H_{\mu\nu}$ must be identified with $-2\xi M_{\text{Pl}} \sum_i \lambda^i \Xi_{\mu\nu}^{(i)}$ has a predetermined space-time dependence dictated by the surrounding gravitational environment.

Thus different experiments at different sites could be compared only after taking into account the differences in the surrounding environment that leads to variable values of the relevant curvature related tensors.

The relevant experiments would thus be associated with both, relative large gravitational tidal effects (indicating large curvature) in the local environment together with either very high sensitivities in the probes. Furthermore it is clear that the probes would need to involve polarized matter as the explicit appearance of the Dirac matrix $[\gamma^\mu, \gamma^\nu]$ indicates. Naturally neutrinos crossing regions of large curvature such as supernova interiors come to mind. It is noteworthy that a term of the sort we are considering could lead to neutrino oscillations even if they are massless, in close analogy with the ideas exposed in [13].

Next we note that the term in question does not violate CPT so that that particular phenomenological avenue is closed. On the other hand other discrete symmetries, particularly CP could, depending on the environment and state of motion of the probes be open channels for investigation.

In the case of potentially flavor dependent effects, which would look as violations of the equivalence principle, we must recall that in the present scheme these are expected only in regions with large gravitational gradients. Thus the fifth force type tests such as the torsion balance experiments must be revised. The relevant non-relativistic hamiltonian for a particle with flavor $a$ can be directly read off from equation (13) using the formulation of
We note that the term proportional to $H_{l0}$ can only come from a non-stationary aspect of the source which in the case of ground based experimental setups case would seem to entail the Earth’s rotation, and would thus be further reduced in magnitude. The remaining part would seem to be the most promising one, and in this case we should clearly focus on the first term.

To do this we write this term as

$$\mathcal{H}_{NR} = \xi (1/M_P) \vec{C} \cdot \vec{\sigma}$$

where $C_i = (1/2)\epsilon_{ijk} \sum_l \lambda^l \Xi^{l}_{jk}$ is a sort of magnetic field, which is associated with the Weyl tensor. As such, in ordinary conditions (static matter sources) we can expect it to be of order $GM/r^3$, a feature that indicates that in contrast with the case of the ordinary Newtonian gravity, the effects of small and close-by sources will be of the same relative importance as those of large but relative distant sources. In the case of a spherical source, for instance the effect at its surface, will be determined solely by its density and not by its size $|C| \approx (4\pi/3)G\rho$. This is a serious impediment for constructing sources that can lead to large effects. From this perspective, the most attractive location for a test would be, the vicinity of a nucleus where tests such as those designed to look at a possible scale dependence of the gravitational constant[12] could be of use, and also the surface of neutron stars.

In the realm of more ordinary and Earth-based alternatives, one needs to note the need to use spin polarized matter in the probe, which normally makes the experiments difficult due to magnetic effects.

To estimate order of magnitude of the effects one would be seeking in an the experiment we compute the ratio of the contribution to the energy of the term in question to the ordinary potential gravitational energy of the probe. That is,

$$\frac{\delta E}{E} = \frac{\langle \sigma \rangle (\xi/M_P)(GM/r^3)}{(GMm/r)} = \xi (l_{\text{Compton}}/r^2)P = \xi P 10^{-25} (l_{\text{Compton}}/\text{cm})^2$$

Where, $r$ is the effective size of the source and $P$ stands for the mean polarization of matter, $l_{\text{Compton}}$ is the Compton length of the constitutive fermions.\footnote{We would need to model the contribution of quarks and electrons to the overall spin polarization of the probe, and weight their Compton lengths appropriately} Where we have taken as indicative of what one must look for, the value of $r$ to be of the order of the distances probed in recent Grenoble neutron experiments \footnote{r \approx 10^{-4}\text{cm.}} As for the Compton wavelength we should point out that, for instance, the neutral Kaon system has a Compton length associated to the mass difference of the order of 30 cm \footnote{30 cm}. One should then look for systems (like a solid) whose excitations have an effective mass and thus a Compton length that is large enough to have a sizable possibility of having observable effects.

Special attention should be directed into experiments with single polarized particles (so that $P = 1$), in the quantum regime, where one would look for unexpected phase changes associated with the polarization and with the presence of gradients of the Newtonian gravitational acceleration. These again can be expected to be extremely small, however we should point out that in the limited experimental evidence there is a report of a rather large
anomaly (one part in $10^3$ violation of the equivalence principle) seen in interference experiments probing the gravitational field with neutrons [17] while similar experiments using atoms do not observe anything despite a higher precision [18]. In this case the effect seems to be many orders of magnitude larger than what we could expect, and of course, in all such cases of reported anomalies these must be taken with great care, and therefore at this point and given its magnitude we are not taking it as indicative of evidence in favor of our proposal but rather just as an example of the kind of effects one might hope to investigate within this setting.

We end up emphasizing that although, one could think that unless $\xi$ is unexpectedly large, the outlook for detecting such effects is not particularly promising, however we should keep in mind the lack of relevant experimental results. In particular, one of the challenges that programs such as Loop Quantum Gravity should face in the near future is to construct suitable semiclassical states corresponding to situations in which large regions with specific but small curvatures are present. In that light, any experimental bounds found by a program like the one suggested here, would play a significant role in guiding the theoretical developments, much as the Eötvos and other early test of the equivalence principle, played in the construction of General Relativity.

VI. CONCLUSIONS

We have considered a new phenomenological scenario to search for signatures of quantum gravity. This new scheme starts by rejecting from the outset the notion of preferential frames, thus keeping intact the conceptual framework leading to special and general relativity.

We must emphasize at this point that for instance, loop quantum gravity, has nothing in its framework that necessitates the breakdown of Lorentz Invariance that is associated with the existence of a preferential reference frame. All that has been said in this regard up to this point are heuristic proposals for states of the theory [6], that would result in the types of effects discussed in [1]. Moreover, given any of such states, there is nothing in principle preventing the construction of new states by applying a kind of group averaging procedure by means of Lorentz boost (using an appropriate Loop quantum gravity operator) to the original state. In this way one could conceive a suitable ‘superposition’ of states which will not be associated with any preferential frame. Such type of scenario would be immune to the constraints being set by the previous explorations of Quantum Gravity Phenomenology. Furthermore, one might imagine that (in the case one could construct) a quantum state that satisfies the full set of constraints, being thus fully diffeomorphism invariant, would be in an appropriate sense necessarily devoid of the problem of emergence of preferential frames.

The proposal here is clearly beyond anything that has been considered so far, and the search for experiments that could provide relevant information seem from the onset to be very challenging indeed. We hope however that the ideas proposed here will motivate our theoretical and experimental colleagues to explore these intriguing possibilities, either through some of the directions we have mentioned here, or through some new and cleverly devised experimental set-ups.
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[1] G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, D.V. Nanopoulos and S. Sarkar, Nature (London) 393, 763 (1998); Nature (London) 400, 849 (1999); D.V. Ahluwalia, Nature (London) 398, 199 (1999); G. Amelino-Camelia, Lect. Notes Phys. 541, 1 (2000).

[2] G. Amelino-Camelia, “Doubly special relativity,” Nature 418, 34 (2002) arXiv:gr-qc/0207049. G. Amelino-Camelia, “Relativity in space-times with short-distance structure governed by an observer-independent (Planckian) length scale,” Int. J. Mod. Phys. D 11, 35 (2002) arXiv:gr-qc/0012051. J. Magueijo and L. Smolin, “Generalized Lorentz invariance with an invariant energy scale,” Phys. Rev. D 67, 044017 (2003), arXiv:gr-qc/0207085.

[3] G. Amelino-Camelia, J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos and S. Sarkar, “Potential Sensitivity of Gamma-Ray Burster Observations to Wave Dispersion in Vacuo,” Nature 393, 763 (1998); R.J. Gleiser and C.N. Kozameh, “Astrophysical limits on quantum gravity motivated birefringence,” Phys. Rev. D 64, 083007 (2001); D. Sudarsky, L. Urrutia and H. Vucetich, “New observational bounds to quantum gravity signals,” Phys. Rev. Lett. 89, 231301 (2002); T. Jacobson, S. Liberati and D. Mattingly, “Lorentz violation and Crab synchrotron emission: A new constraint far beyond the Planck scale,” Nature 424, 1019 (2003); D. Mattingly, “Modern tests of Lorentz invariance,” arXiv:gr-qc/0502097.

[4] A. Perez, and D. Sudarsky, Phys. Rev. Lett., 91 179101-1 (2003).

[5] J. Collins, A. Perez, D. Sudarsky, L. Urrutia, and H. Vucetich, Phys. Rev. Lett. 93, 191301 (2004).

[6] R. Gambini and J. Pullin, “Nonstandard optics from quantum spacetime,” Phys. Rev. D 59, 124021 (1999); J. Alfaro, H. A. Morales-Tecotl and L. F. Urrutia, “Quantum gravity and spin 1/2 particles effective dynamics,” Phys. Rev. D 66, 124006 (2002); J. Alfaro, H. Morales-Tecotl and L. Urrutia, “Loop quantum gravity and light propagation,” Phys. Rev. D 65, 103509 (2002); J. Alfaro, H. Morales-Tecotl and L. Urrutia, Phys. Rev. Lett. 84, 2318 (2000); H. Sahlmann and T. Thiemann, “Towards the QFT on curved spacetime limit of QGR. II: A concrete implementation,” arXiv:gr-qc/0207031. M. Bojowald, H. A. Morales-Tecotl and H. Sahlmann, “On loop quantum gravity phenomenology and the issue of Lorentz invariance,” arXiv:gr-qc/0411101.

[7] R. M. Wald, General Relativity, (Chicago Univ. Press, 1984) p. 179; H. Stephani, D. Kramer, M. MacCallum, C. Hoenselaers and E. Herlt, Exact solutions of Einstein’s field equations, (Cambridge U. Press, 2003).

[8] G. S. Hall and D. P. Lonie, “Holonomy groups and spacetimes,” Class. Quant. Grav. 17, 1369 (2000) arXiv:gr-qc/0310076.

[9] D. Colladay and V. Alan Kostelecky, “Lorentz Violating extension of the standard Model”, Phys. Rev. D 58, 116002 (1998).

[10] V. Alan Kostelecky and Charles D. Lane, “Nonrelativistic quantum Hamiltonian or Lorentz
Violation”, J. Math. Phys. 40, 6245 (1999).

[11] D. Sudarsky, L. Urrutia, and H. Vucetich, “New observational bounds to quantum gravity signals,” Phys. Rev. Lett., 89, 231301 (2002).

[12] A. Frank, P. van Isacker and J. Gomez-Camacho, “Probing additional dimensions in the universe with neutron experiments,” Phys. Lett. B 582, 15 (2004). [arXiv:nucl-th/0305029]

[13] M. Gasperini, “Testing The Principle Of Equivalence With Neutrino Oscillations,” Phys. Rev. D 38, 2635 (1988).

[14] E. Fishbach and C. L. Talmadge, “The Search for Non Newtonian Gravity”, (Springer Verlag, New York 1999).

[15] See H. Abele S. Bäßler and A. Westphal, “Quantum States of Neutrons in the Gravitational Field and Limits for Non Newtonian Interaction in the range between 1µm to 10µm” in Quantum Gravity From Theory to Experimental Search (Eds. D. Giulini, C. Kiefer, and C Lämmerzahl) (Springer Verlag, Berlin 2003).

[16] A. Alavi-Harati et al. [KTeV Collaboration], “Measurements of direct CP violation, CPT symmetry, and other parameters in the neutral kaon system,” Phys. Rev. D 67, 012005 (2003) [Erratum-ibid. D 70, 079904 (2004)] [arXiv:hep-ex/0208007].

[17] K. C. Littrel, B. E. Allman and S. A. Werner, Phys. Rev. A. 56, 1767 (1997).

[18] A. Peters, K. Y. Cheng, S. Chu, Nature 400, 849 (1999).