Quantum Gravity Phenomenology in the Multi-Messenger Approach: COST Action CA18108 White Paper

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Contents

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1. Introduction

2. What effects are we looking for?

2.1. Time delays

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Time delays emerge already from the classical interaction between gravity, described by the geometry of spacetime, and particles and fields. We briefly recall the classical effect before we discuss additional time delays which are widely discussed in the literature on quantum gravity phenomenology. Then, we discuss the main challenges and difficulties in the search for quantum gravity induced time delays.

2.1.1. Time delays in classical and quantum gravity The gravitational interaction causes time delays for the propagation of light. The most famous instance of this fact is the Shapiro delay [1]: the observation that the travel time of a light signal between two points in the vicinity of a gravitating object is increased compared to the travel time in the absence of the object. We gather plentiful information about the gravitational interaction based on the observation of light propagating through spacetime. Thus, in our data analysis, it is of utmost importance to take into account the time delay effects.

Explicit famous examples are pulsar timing observations [2] and cosmological redshift and distance observations [3]. Pictorially, time delay effects can be understood in the sense that gravity acts as a certain effective medium for light propagation, introducing a refractive index [4]. On the basis of Maxwell electrodynamics and general relativity, the predictions for time delays are independent of the energy or frequency of the photons, due to the local Lorentz invariance of the theories. However, gravitationally induced time delays do not only affect the propagation of light, but also that of neutrinos and gravitational waves, given that gravity acts universally on all particles.

These examples from classical gravity clearly demonstrate that time delays are an important prediction of general relativity, which on the one hand, allow us to test the theory, and on the other hand, give us important information about the nature of the gravitational interaction, which is modeled through the geometry of spacetime.

For quantum gravity, the pictorial idea of spacetime as an effective medium has been developed further. The vacuum fluctuations of gravity create an environment with which highly energetic particles and fields interact, and thus their propagation through spacetime is affected. It is expected that the smaller the length scale which the particles and fields probe, i.e. the higher their energy, the more the fields are affected by this expected quantum structure of spacetime.

Effectively, such an interaction can mathematically be described by modified dispersion relations (MDRs), which the point particle excitations of the fields must satisfy, as a result of the interaction with the quantum gravity "environment". This effect can be determined from fundamental approaches to quantum gravity by studying the propagation of light in, for example, String Theory, Loop Quantum Gravity or non-commutative geometry, or they can be implemented phenomenologically. A detailed discussion of the emergence of such time delays from quantum gravity phenomenology can be found in the review [5, Sec. 5.1].

The additional effect to the general relativistic, local Lorentz invariant, frequency independent time delays mentioned in the beginning, are time delays which depend on the energy of the fields (or frequency of their waves/particles) involved. A most famous example is the delay in the time of arrival in the local observatory of gamma rays of different energies, which are emitted at the same spacetime point, the same time and the same location. As in the classical case, such energy or frequency dependent time delays are expected also for neutrinos and gravitational waves.

So far, such quantum gravity induced time delays have not been found. However, there also do not exist any dedicated experimental setups which are optimized to specifically search for such a time delay. In what follows we pinpoint the difficulties and challenges for such a detection.

2.1.2. Challenges and difficulties Challenges and difficulties to detect and interpret time delays correctly come from theoretical as well as experimental sides.

On the theoretical side, understanding frequency and energy dependent time delays leads to the emergence of deviations from local Lorentz invariance. This implies a modification of the causal structure of spacetime together with possible alteration of the notion of light-cone. Each of these modifications or the conjunction of both may drastically impact the observability of time delays linked to quantum regime of gravity.

A particular important challenge is the distinction between violation or the deformation of local Lorentz invariance (the replacement of the Lorentz group by a different notion of symmetry). Either the absence or the detection of time delays can be used as a guiding principle to identify the scale and the type of deviations from local Lorentz symmetry in nature. Whether this happens effectively at an intermediate scale or at the fundamental level is unclear and depends on the theoretical approach under consideration.

Often it is assumed that the quantum gravity scale, at which such time delay effects become important, is the Planck scale. However, it is important to stress that conclusions about the exclusion or impossibility to detect such effects are premature, even though some experiments exhibit sensitivities that in some special processes exceed the Planck energy scale. In many models the effective energy scale governing the time delays is characterized by a combination of the Planck scale and further parameters of the theory. This has for example been pointed out in [6, 7] for certain models of space-time foam stemming from string/brane theory (see Sec. 2.3). There, the effective energy scale which characterizes such delays is a combination of the quantum gravity (or string) mass scale multiplied by the inverse of the linear (possibly redshift dependent) density of the spacetime defects encountered by the particle during its propagation. The observed time delays will also depend on the location of the source and one should consider combination of searches at various redshifts, in order to constrain properly the effect.

An additional complication in interpreting time delays is their systematic errors which might be related to the underlying cosmological model, which the propagation of the particle probe strongly depends upon. For instance, in modified gravity models characterised by cosmic-time-varying dark energy (varying Λ cosmologies), time delays are subject to systematic deviations from ΛCDM which may affect high-redshift objects such as gamma-ray bursts gamma-ray bursts (GRBs), strong lensing and active galactic nuclei phenomena due to the time varying cosmic dark energy component.

Moreover, time delays of gravitational waves may be considered as indirect probes of dark matter. They can be sourced by the interference of the waves due to their scattering with primordial black holes (pBH) of masses in the range $10 - 100\,M_\odot$ or planet-size pBH, which can play the rôle of a dark matter component.

The interpretation of a detection or the absence of a time delay signal in gamma-rays, gravitational lensing images, pulsar timing, neutrinos or gravitational waves from an astrophysical event of interest, relies on the assumption that the messengers with different energies are emitted simultaneously. If that is not the case, the intrinsic time delay in their production must be known and incorporated in the data analysis.

There exist various competing models for the production of the different messengers. Additionally, classical propagation effects and time delays need to be taken into account. All of them depend on the underlying theory of gravity and the resulting cosmological model. These uncertainties about the source-intrinsic and classical propagation effects translates to less stringent constraints on the quantum gravitationally induced time delay of interest and pose a major challenge in the identification of a signal. However, a smoking gun which is capable to disentangle source-specific intrinsic delays from propagation delays is a linear redshift dependence of the expected delays that is predicted in some models. These cannot be mimicked by source-dependent delays.

Practically, the time delays of gamma-rays are determined from a mathematical representation of their spectral distribution. These light curves are then propagated to the point of detection by a theoretical model and compared with the detected light curve. Generically, these light curves are very complex and possess many features, so that a thorough statistical analysis and a very good parametric equation is needed, to identify all effects influencing the light curve. GRBs and active galactic nuclei are invaluable test-beds of energy-dependent time delays due to their high brightness and redshift and wide energy range. A limiting factor is the modest understanding of the emission mechanism at the source and the ensuing difficulty in isolating the propagation effects. On the data analysis front, simple time-profile studies based on energy bands are fast yet of limited sensitivity. On the other hand, likelihood techniques imply long computation times, however, leading to better sensitivity.

If the time delays exist, they will not only manifest themselves in the observation of astrophysical sources but also in the interaction between gravity and quantum systems, such as Bose–Einstein condensates. The advantage in the use of laboratory sized quantum systems as sensors for quantum gravity effects lies in the fact that they are highly controllable and extremely sensitive over a long time. Such control is a qualitative improvement and contrast to the extraterrestrial cosmic observations with their inherited uncontrollable uncertainties regarding the state of the physical system which is observed.

The challenge for the quantum system based detection is to amplify the quantum gravitational effect over the time span of the experiment, such that it becomes detectable, or to increase the measurement sensitivity, in order to probe the desired effect.

In summary, it is known that gravity causes a certain type of time delays. The search for additional, yet undetected energy-dependent time delays caused by potentially quantum gravity effects can be an important step in finding evidences of a theory of quantum gravity. Thus it is important to devise future dedicated experiments to address such a possibility both in astrophysical context and in the more controllable local context.

2.2. Anomalous threshold effects or new interaction effects

MDRs of elementary particles could bring changes in the kinematics of processes, so that a reaction that would otherwise violate conservation of momentum-energy in a given energy range (or be forbidden at all energies) is allowed. One could also have the opposite effect, in which the dispersion relation disfavours the process in a certain range of energies, or even the combination of both, a lower and an upper threshold which delimit a specific range of energies in which the process is allowed [8]. The study of the appearance, disappearance, or shifting of the threshold energies of processes with respect to special relativity (SR) is called the study of anomalous thresholds.

Threshold anomalies in a Lorentz invariance violation (LIV) scenario are very different from those in a scenario with a relativistic principle (doubly special relativity (DSR)). While LIV is normally introduced at the level of in-vacuo dispersion relations, modified by a high-energy scale Λ (usually taken as the Planck scale), fully relativistic scenarios equipped with such modifications also require a deformation of the relativistic symmetries, hence the energy-momentum conservation laws have to be modified to guarantee covariance under the deformed symmetries. For example, the kinematics of a process $A + B \to C + D$ is characterized by

$$m_I^2 = E^2 - \mathbf{p}^2 + f(E, \mathbf{p}, m_I, \Lambda), \tag{1}$$

$$\mathbf{p}_A \oplus \mathbf{p}_B = \mathbf{p}_C \oplus \mathbf{p}_D, \tag{2}$$

where the function f specifies the modified in-vacuo dispersion and the $\oplus$ symbol describes the deformed composition for energy-momentum. These deformations disappear when the quantum gravity (QG) scale Λ goes to infinity. A relevant example for phenomenological applications is electron–positron pair production from the interaction of very high-energy photons with low-energy photons such as those from the cosmic microwave background (CMB). At leading order, modifications for the special-relativistic threshold $E_{\rm th}^{\rm SR}$ of the process in the LIV and DSR scenarios can be written as [9]

$$E_{\rm th}^{\rm LIV} \approx \frac{m_e^2}{\epsilon}\left(1 + \alpha\frac{m_e^4}{\epsilon^3\Lambda}\right) = \left(1 + \alpha\frac{m_e^2}{\epsilon^2}\frac{E_{\rm th}^{\rm SR}}{\Lambda}\right)E_{\rm th}^{\rm SR}, \tag{3}$$

$$E_{\rm th}^{\rm DSR} \approx \frac{m_e^2}{\epsilon}\left(1 + \beta\frac{m_e^2}{\epsilon\Lambda}\right) = \left(1 + \beta\frac{E_{\rm th}^{\rm SR}}{\Lambda}\right)E_{\rm th}^{\rm SR}, \tag{4}$$

where α and β are real parameters characterizing the deformations and ϵ is the energy of the CMB photon. When the parameters are positive, the threshold is higher, so the Universe is more transparent to high-energy radiation, while the converse happens for negative values of the parameters. We notice that the parameter m_e/ϵ is an amplifier for the new physics effect, which is much stronger in the LIV case; therefore, while in the DSR case the modification of the threshold is only appreciable when the energy is close to the high-energy scale characterizing the correction to the kinematics, in the LIV case, the correction can be substantial at much lower energies. For this reason, threshold anomalies are usually analyzed in the LIV framework, except for the case of DSR parametrized by a high-energy scale much lower than the Planck mass [10].

Threshold anomalies can be seen as the kinematical modification of the special-relativistic description of interactions, and indeed, it is usually the only effect that is modelled to estimate the phenomenological consequences of LIV or DSR [11, 12]. However, in some cases, such as the possible modification of the transparency of the universe to high-energy gamma rays, it may be necessary to adequately control the relative importance between dynamic and kinematic effects. The LIV scenario has been previously explored, but the availability of results for cross sections or decay rates is limited [13]. For the DSR scenario, dynamical effects may only play a role in the case of an energy scale of DSR not much higher than the energies we can have access to. This is a mostly unexplored case, for which it will be necessary to develop new approaches and techniques.

2.2.1. Types of processes

Hadronic sector The impact of LIV in the hadronic sector can be in principle tested with ultra-high-energy cosmic rays (UHECRs); in fact, LIV can lead to an increase of the energy loss length of cosmic rays regarding the main interaction types at the highest energies, such as the photo-pion production and (if nuclei heavier than hydrogen are taken into account, as suggested by experimental evidences about UHECR mass composition at Earth) the photo-disintegration. The interpretation of the UHECR spectrum and mass composition data in terms of astrophysical scenario however suggests that the energy with which cosmic rays escape their sources is at the threshold, or smaller, for triggering the photo-pion production processes, therefore reducing the sensitivity to constraint LIV effects. The presence of a proton fraction at the highest energies, which is allowed by the most recent data, could be tested in the future to the aim of increasing the constraining power of the UHECR spectrum and composition data. Another aspect to be explored regarding the hadronic sector is the development of the cascade of particles in the atmosphere after the first cosmic-ray interaction (extensive air shower). The decay versus interaction probability of pions can be altered if LIV exist, with some effects expected in the reconstruction of the energy and of the nuclear species of the primary cosmic ray. In particular, observables sensitive to the number of muons in the shower and to its fluctuations can be successfully exploited to test LIV.

Electromagnetic sector In a superluminal LIV scenario, photon decay in vacuum leads to very restrictive constraints on the LIV high-energy scale. A subluminal scenario can lead to an increase of the energy threshold of the photon–photon interaction $\gamma\gamma \to e^- e^+$ [11], and hence of the transparency of the universe to gamma rays (especially at energies $\gtrsim 10$ TeV), thus potentially allowing high-energy gamma rays from sources at cosmological distances to avoid absorption (see, e.g., [14, 15]). However, using the current imaging air Cherenkov telescopes (IACTs) no evidence for such LIV effects could be detected. Such effects may be within reach of the future Cherenkov Telescope Array (CTA), with its significantly improved sensitivity and extended energy range, providing therefore unique tests of QG.

The constraints from photon decay do not apply, as such a process is not allowed, in a DSR scenario. However, a more complex behaviour in the interaction of high-energy photons with the background can arise. For instance, one can find an increase of the flux at lower energies but a decrease in the expectation at higher energies [10].

The investigation of possible imprints of LIV extensions of the standard model on the Compton scattering effect, which is likely to be of paramount importance for the production of non-thermal gamma-rays in the GeV–TeV range in many astrophysical sources, including GRBs and blazars, shows that such effects are plausibly only becoming discernible at $\sim$ PeV energies (in the electron rest frame), where it could possibly lead to a suppression of Klein–Nishina effects [15]. However, since at such energies, the Compton cross-section is already heavily reduced compared to the Thomson limit, the effect is unlikely to show any measurable signatures in astrophysical gamma-ray sources.

Neutrinos Besides new or modified kinematic thresholds, LIV may introduce such strong energy dependencies that by changing the energy one can cross from one range of energies in which the reaction is very favourable to another range in which it is almost negligible. This fact provokes the apparition of a new effective threshold of dynamical origin, which may be the relevant one for the study of a particle reaction or a decay process, depending on its relative position with respect to the kinematical threshold.

Such a situation arises in the weak decays of neutrinos with emission of an electron–positron or a neutrino–antineutrino pair in a superluminal LIV scenario [16, 17]. While the electron–positron emission by a superluminal neutrino ($\nu \to \nu e^- e^+$) has the (kinematical) threshold energy

$$E_{\rm th} = (2m_e^2 \Lambda^n)^{1/(2+n)}\,, \tag{5}$$

where Λ is the high-energy scale that parametrizes the LIV correction, of order $\mathcal{O}(E/\Lambda)$ for an energy E, the neutrino–antineutrino pair emission ($\nu \to \nu\nu\bar{\nu}$) has a negligible threshold (zero in the case of a massless neutrino).

However, the general expression of the decay width for these processes [17]

$$\Gamma_{\nu_{\rm f}\to A}(E) \,\propto\, E^5 \left(\frac{E}{\Lambda}\right)^{3n}\,, \tag{6}$$

(where the proportionality coefficient depends on the flavour of the initial neutrino ($\nu_{\rm f}$), the particles of the final state (A), the order n of the correction, and on the Fermi constant and the Weinberg angle), allows one to define an energy scale $E_{\rm th}^{\rm eff}$ (different for each process, initial neutrino flavour, and order of the correction) such that

$$\Gamma = H_0 \left(\frac{E}{E_{\rm th}^{\rm eff}}\right)^{(5+3n)}\,. \tag{7}$$

Owing to the large value of the exponent $(5+3n)$, $\Gamma \gg H_0$ above this energy scale, and $\Gamma \ll H_0$ below it, which is the reason why it acts as an effective dynamical threshold for the reaction to proceed. While this dynamical threshold is very relevant for the neutrino–antineutrino emission, in the case of the electron–positron emission the kinematical threshold is the most relevant one for values of the scale of the deformation below the Planck scale [18].

In contrast, in the subluminal LIV scenario, as well as in a DSR scenario, there are no propagation effects, but one will still have effects in the production of the neutrinos, like in the pion decay.

2.3. Spacetime foam

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Despite the absence of a generally accepted framework of QG, various candidate models seem to converge on the idea that, due to fundamental quantum uncertainties, the microstructure of the spacetime should be viewed as a dynamical entity fluctuating over distances of the order of Planck length $\ell_{\rm P}$ and time scales of the order of Planck time $t_{\rm P}$. This idea, originally introduced by Wheeler [19], further developed by Hawking [20], and popularized in [21], implies that, if such fluctuations are large enough to induce non-trivial deformations of the classical, smooth spacetime, the latter would develop a "foamy" structure at the microscopic level, with all manners of geometrically and topologically nontrivial structures being formed (e.g. via quantum tunnelling [22]), interacting with each other, and finally annihilating. Closely related to this *spacetime foam* is the idea of *emergent gravity*, by which the classical continuous gravitational field is not fundamental, but instead emerges as a sort of collective effect (valid at low-enough energies) from this spacetime foam discrete structure [23]. The natural questions thus arise as to how such a transition may take place and whether there might be any observable signatures of this foamy micro-structure. Indeed, most signatures that might be potentially realized in the forthcoming future [24] are but a low-energy manifestation recovered by most theoretical schemes that simultaneously describe quantum and gravitational effects, while a full implementation is still missing [25].

2.3.1. Specific implementations. Condensed matter systems provide valuable lessons about such a question, where metric and affine connection would be the collective variables of the microscopic theory in the continuum, the latter featuring curvature, torsion, and nonmetricity. These geometric objects are crucial to capture the existence of microscopic defects [26], which endow such systems with nontrivial topologies. Indeed, materials with a discrete microstructure, such as graphene, may behave in the continuum limit as emergent geometries, allowing the propagation of quantum fields on top of them [27]. Gravitational theories with independent metric and affine structures naturally accommodate underlying foam-like structures and they can be excited via gravitational collapse to form large wormholes [28]. Furthermore, based on the curvature/torsion/nonmetricity trio, one could build new gravitational theories such as $f(R)$ [29], $f(T)$ [30] and $f(Q)$ [31], connecting different implementations of this transition from the foamy microworld to observational signatures in the macroworld.

There are two other key influential concepts developed in the literature: the holographic conjecture [32], by the deep link it provides between quantum entanglement and emergent spacetime [33] further developed with its Ricci flows [34] including its stochastic version [35]; and Verlinde's entropic interpretation of emergent gravity [36]. Other examples of continuous emergent microstructure are the ones studied by MacDowell–Mansouri [37], which realized gravity emerging from the symmetry breaking over a principal bundle only equipped with Minkowskian metric, and the one in which gravity emerges from a complex system of N interacting particles with $O(N)$ symmetry, which is governed by quantum mechanics [38] or from gauge symmetry principles [39]. Spin foams [40] and fractal-based [41] ideas also have their share in this foamy discussions.

In minimal-length models foamy effects come from the presence of a minimal accessible length [42], which modify the Heisenberg algebra to accommodate a minimal uncertainty in position at the Planck scale. In phenomenological models of quantum mechanics the minimal length appears as a kinematic feature [43], while the shape itself of the Hamiltonian may be deformed from the combined action of a modified position-momentum algebra and the choice of a relativity principle [44]. Recently, the possibility to connect the minimal length prescription to non-Gaussian statistics has been explored [45]. On the other hand, by equipping this framework to the standard quantum mechanical scenario with a stochastic nature, it is possible to mimic the foamy structure of spacetime in the non-relativistic regime and analyze potential experimental implications [46].

Foamy effects can also modify the dispersion relations via generalized uncertainly principles as [47]

$$E^2 = p^2 \pm \epsilon \left(\frac{E}{M_{\rm P}} \right)^{\alpha} \tag{8}$$

where ϵ is a parameter of order unity, $M_{\rm P}$ is the Planck mass, and the value of α is fixed according to the different implementations of the foam idea. This represents a spontaneous breaking of the Lorentz symmetry by the ground state of foamy models. A neat prediction is a nontrivial subluminical vacuum refractive index suppressed by inverse Planck-scale mass which can be searched for using gamma-ray telescopes [48].

2.3.2. Specific effects.. Given the large variety of conceptual implementations of the transition of the space-time foam to the macroscopic world, specific effects come in many shapes:

- Alternatives to particle dark matter models in emergent gravity induced by modifications to the gravitational law via entanglement entropy [49].
- Consistence of Verlinde's emergent gravity with weak gravitational lensing of low-redshifted galaxies due to the displacement of dark energy by baryonic matter using KiDS and GAMA surveys [50].
- Light speed variation with energy (suppressed by a power of the string mass scale) in stringy supersymmetric spacetime foam via modified dispersion relations of the form (8) [51] and nontrivial reflective index [6] can be constrained using high energy gamma-ray burst photons [52]; constraints from birefringent effects and photon decays are consistent with this foamy scenario.
- Decoherence and breakdown of unitarity effects, particularly those leading to CPT violations [53] and neutrino decoherence from light-cone fluctuations [54].
- Broadening of spectral lines from foamy spacetime fluctuations [55].
- Null tests on foamy effects based on cumulative effects over distant sources from X-ray and gamma-ray burst observations [56].
- Implementation of stringy foam-like structures involving spacetime D-particle defects to modify estimates on the dark matter budget due to their quantum fluctuations on the space-time metric [57].
- Modification of the waveform and the dispersion relation of gravitational waves due to polymer quantization, leading to the dependence of the speed of the propagation of the waves on their frequency [58].
- Interferometric search for foamy effects, allowing to place constraints on specific implementations [59, 60].
- Local effective spacetime metric distorsions D-brane models with bosons [61] and fermions [62] induces a variation of the light velocity of order the energy of the scattering particle of the putative quantum fluctuations scale, $\delta c/c \sim -E/M_s$ [61], leading to different dispersion relations between particles/anti-particles which generate a matter-antimatter lepton symmetry. Bounds in the baryon asymmetry parameter $\eta = \Delta n_\nu/n_\gamma$ can be obtained from observations of the CMB radiation [63] and the predictions of BBN [64] to $\eta = (6.04 \pm 0.08) \times 10^{-10}$, while those from deuterium ^{4}He, Helium ^{2}H and Lithium ^{7}Li [65] result in an estimate $\eta \sim 5.9 \times 10^{-10}$. For specific such D-brane models this is translated into bounds on the dimensionless stochastic variable σ^2 expressing the fluctuations of the recoil velocity of the D-branes as [66]. Furthermore, such D-brane foamy models can induce other defects such as flavour-oscillating neutrinos [67].
- Quantum gravity and foamy effects affect relativistic stars' observables such as masses, radii and moment of inertia [68], among others.

In summary, the space-time foam idea, being a subset of the larger field of quantum gravity phenomenology, suffers from the same fundamental difficulty, namely, the impossibility to directly test its effects at the Planck scale. In this sense, the most plausible ideas revolve around cumulative effects that may average over large distances/scales, and which we could have any hope to detect via several means, e.g. interferometric technology; the (non-exhaustive) list above covers some proposals in the field.

3. Experimental requirements for QG research

In this section, we discuss the experimental requirements for searches of traces of QG in astrophysical observations. A definitive feature of research using astrophysical observations is its inability to control the source of the signal and the medium between the source and the detector. Limited knowledge of these is an important source of systematic uncertainties. The other essential ingredient is improvement of experimental facilities.

3.1. Astrophysical modelling

Improving our ability to model the processes within the sources of cosmic messengers, as well as the processes affecting the propagation of messengers, is paramount for improving the sensitivity of QG research. Ideally, we would need to know the energy and emission time of every single particle form the source. This is, of course, utopian; however, a precise multiwavelength modelling of the source-intrinsic flux, including its polarization properties and its flavour content, as well as emission time lags between different energy bands, could significantly increase the sensitivity to quantum gravity energy scale.

To investigate the potential effects of QG using cosmic messengers, it is crucial to understand how they propagate. This entails considering various matter and radiation fields that could act as targets, including the CMB, extragalactic background light (EBL), and interstellar radiation field (ISRF). Uncertainties in the EBL spectrum can significantly influence the propagation of gamma rays [69, 70, 71] and UHECRs [72, 73], thereby impacting the observables relevant to any potential QG signals. Studies taking into account the UHECR propagation through the extragalactic space for reproducing the measured energy spectrum and mass composition at Earth show differences up to 3.5σ between scenarios involving different EBL models, if the standard propagation is considered [74], and up to 3σ if modifications from LIV are considered, as shown in [75]. The spatial distribution of the EBL, despite being fairly homogeneous and leading to discrepancies of $\lesssim 1\%$ in the propagation of gamma rays [76], could also represent another source of uncertainty. Fortunately, with advancements in observational techniques across different wavelengths and the employment of multiple strategies, it is anticipated that the uncertainties associated with the EBL will be mitigated in the near- and mid-future, even for higher redshifts ($z \sim 6$) [71]. Upcoming IACTs such as CTA [77] will certainly contribute to improve this picture [78].

The cross sections for the corresponding interactions with various astrophysical targets also have to be known. This is particularly problematic for UHECRs, since photonuclear cross sections are poorly known [79, 72, 80, 81] and can lead to discrepant interpretations of the observations [82, 74, 83, 84]. In [74] the changes in the spectral parameters for UHECRs at the escape from the sources due to the different cross section models can produce differences at the level of 1σ in the fit of the UHECR spectrum and composition at Earth. These cross sections are the ones that change in the presence of LIV, for instance, both for CRs [85, 86, 87] and gamma rays [11, 12]. Therefore, accurate knowledge of this essential modelling ingredient is essential to properly identify QG signatures using high-energy messengers. It is relevant to notice that if LIV modifications in the propagation are considered for UHECRs, the fit of the UHECR spectrum and composition at Earth shows differences up to 5σ (for small deviations from the standard physics, while if the modification is very strong the difference becomes smaller) depending on different cross section models used for the propagation [75].

Magnetic fields present in the Milky Way and beyond can alter the trajectories of these particles. While UHECRs are particularly susceptible to these effects [88, 89], neutrinos are not, making them reliable messengers for studies requiring directional accuracy. Gamma rays are not directly affected by magnetic fields, but the charged component of the electromagnetic cascades they induce might be [90, 91, 92]. Although some constraints exist regarding the distribution of cosmic magnetic fields in regions such as galaxies and galaxy clusters, their characteristics in the filaments connecting clusters are less well-known [93, 94]. In cosmic voids, which dominates most of the volume of the universe, knowledge about magnetic fields is even more limited [95]. This directly translates into uncertainties in spectral, temporal, and directional observables. Future polarisation surveys such as SKA [96] and ngVLA [97] will reduce these uncertainties considerably. The Galactic magnetic field, in particular, will likely be much better modelled using the upcoming data and new computational tools such as IMAGINE [98]. Fields in cosmic voids, however, will hardly be measured in this way, but gamma-ray measurements are expected to deliver better constraints [78]. If they are weak ($\lesssim 10^{-17}$ G), their impact on time delays and arrival directions of astroparticles should be small; if they are strong ($\gtrsim 10^{-14}$ G), this might compromise time-delay studies, for example. In the case of gamma-ray observations, these uncertainties could effectively dilute the flux from a short-duration burst over much larger time scales.

Other conventional phenomena might also be at play and affect the propagation of cosmic messengers. A potentially important one that might affect gamma-ray–induced electromagnetic cascades are plasma instabilities, stemming from the interaction of the electrons with the medium. The role of this effect is far from clear [99, 100, 101] and can hardly be assessed without detailed particle-in-cell (PIC) simulations, which is not feasible for low-density environments such as the intergalactic medium. This could compromise the interpretation of gamma-ray observations and change the ratio between the fluxes of UHECRs and the corresponding cosmogenic photons.

UHECRs produce neutrinos and photons of cosmogenic origin during intergalactic propagation [102, 83, 84], which can act as backgrounds when studying individual astrophysical objects. Similarly, uncertainties inherent to the production of neutrinos and photons through CR interactions the large-scale structure of the universe such as galaxy clusters can act likewise [103, 104, 105, 106]. Evidently, this can be mitigated by reducing uncertainties related to their progenitor CRs, which is expected to happen with future UHE facilities [107].

All the modelling uncertainties listed above have to be accounted for in searches for QG phenomena. This is, however, computationally challenging, and requires advanced computational tools to scan the complete parameter space efficiently, including both conventional phenomena and QG-related ones. Existing computational tools, such as CRPropa [108, 109] (CRs, gamma rays, neutrinos), SimProp [110] (CRs), Elmag [111] (gamma rays), among others, can be adapted for this purpose ultimately leading to better models for interpreting observations.

3.2. Experimental requirements

In what follows, we discuss the experimental requirements for improving sensitivity to effects of QG in particular tests.

3.2.1. Photon time delays Since the exact emission time of individual particles is not known, testing the energy dependence of the speed of photons relies on comparison of detection time of individual highly energetic photons with arrival time of photons with lower energies. The influence of QG effects on low-energy photons is considered to be negligible. Therefore, their distribution at the detection remains the same as at the emission. The distribution of high-energy photons, on the other hand, is modified by the effects of QG. The detection time of individual photons (regardless of their energy) is usually measured at the µs level by the usage of Global Positioning System time/ Coordinated Universal Time (GPS/UTC), and introduces a negligible systematic uncertainty. The temporal distribution of emitted particles is usually described with a light curve template defined by several parameters. The magnitude of uncertainties of these parameters varies from case to case, and is a matter of concession between several factors. Faster and more pronounced flux variability puts stronger constraints on the emission time. The sensitivity to QG energy scale is directly proportional to the inverse of the variability time scale for $n = 1$, while for $n = 2$ it depends as a square root of inverse of the variability time scale (see Table 1 of [12]). This, however, requires using shorter time bins, which results in relatively smaller number of events per bin, and, consequently, larger uncertainties. For this reason, brighter, more variable emissions are selected to study time delays. Improvement of instrumental sensitivity‡ will directly reflect on the ability to model the emission light curves, and on the sensitivity to QG energy scale.

Note: The following paragraph is perhaps better suited for another section. Another important factor for sensitivity to the QG energy scale, which is

‡ Instrumental sensitivity in astroparticle experiments is defined as the faintest flux an instrument can detect with 5σ significance in a certain time.

related to instrumental sensitivity is the source distance. In [12], the sensitivity to QG energy scale depends linearly on the redshift of the source (for extragalactic sources) for $n = 1$, and is proportional to the redshift to the power of 2/3 for $n = 2$. However, gamma rays with energy higher than $\sim 100\,\mathrm{GeV}$ can be absorbed on background electromagnetic radiation, decreasing the total number of gamma rays reaching the detectors. Improving instrumental sensitivity cannot affect absorption on background radiation, but it can increase the rate of gamma rays detected among the ones that survive.

According to [112], systematic effects related to the light curve uncertainty spoil the sensitivity to QG energy scale by a factor of ~ 2.3 for linear or ~ 1.5 for quadratic correction of the dispersion relation. In most cases for $n = 1$, the dominant systematic effect comes from the uncertainty of the light curve template parameters. This is true for most of the individual sources considered, as well as for certain type of sources combined or combination of all sources used in the study. Indeed, the variance of the template statistics constitutes more than 50% of the total systematic variance. For $n = 2$ this falls down to about 20%, and the contribution of the template statistics to the total systematic variance is somewhat less, but still comparable to some other sources of systematic uncertainty, such as energy scale uncertainty.

Additionally, the assumption that the emission times in different energy ranges have the same distribution is a rather strong one, especially considering that intrinsic energy-dependent time delays have already been unambiguously detected in some GRBs (see, e.g., [113] and references therein). In [114], a detailed study of intrinsic spectral lags in flaring AGNs above 100 GeV was conducted in order to investigate whether these can be distinguished from LIV induced time delay. The authors concluded that, while certain intrinsic spectral lags are to be expected, their magnitude can vary in time. Meaning that, time delay between two photons of energies E_h and E_l is modelled as

$$\Delta t \propto (E_h^\alpha - E_l^\alpha) \times \kappa, \tag{9}$$

the exponent α will not be constant in time, which is contrary to the expected QG induced effects. Moreover, source intrinsic time delays should not depend on the source distance from Earth. One the other hand, if time delays are a consequence of the spacetime structure, the factor κ is a function of distance, which serves as an amplifier of the effect. Therefore, considering sources at different distances is another way of distinguishing source-intrinsic from QG-induced time delays. Ideally, in order to completely eliminate this source of uncertainty, we would need to know the energy and emission time of every single particle form the source. This is, of course, utopian; however, a precise broadband modelling of the source-intrinsic flux, including emission time lags between different energy bands, could significantly increase the sensitivity to quantum gravity energy scale.

A specific implementation of a likelihood fit has been used so far to measure energy-dependent time lags. This very sensitive (unbinned) technique has a drawback: it requires a parameterization of the (binned) low energy light curve. This parameterization is the biggest source of systematic errors. An improvement would be to find a way to implement a likelihood method directly from energies and times of detected photons. **comment on other statistical methods: likelihood vs "ecf"**

3.2.2. Neutrino time delays Neutrinos are potentially the most sensitive messengers for time delay studies, given the large travel distance and their higher energy with respect to photons. Moreover, given the large time delay effect associated to the high energies of astrophysical neutrino, source intrinsic effects are not expected to be important.

Currently, the largest and most sensitive neutrino telescope is IceCube [**?**], which has observed neutrinos of extragalactic origin in the energy range from 60 TeV to a few PeV [115, 116, 117, 118]. This lower bound on the energy comes from the need to disentangle the neutrino signal of astrophysical origin from background signal, such as atmospheric neutrinos [**?**]. The rate of these events is around 15 candidate astrophysical neutrinos per year [119]. **comment on improved background rejection** Being so low, it is extremely unlikely to detect more than one neutrino from a single emission event. Therefore, time delay studies cannot rely on the comparison of the time of flight of neutrinos with different energies. Rather, they rely on the comparison of the time of flight of one neutrino with a low-energy electromagnetic counterpart. So far, studies have focussed on the association of neutrino signal with GRBs, given that the latter have a time span smaller than the expected time delay effect. The identification of the electromagnetic counterpart of the neutrino signal is done by means of a directional correlation criterion. Note that one cannot associate unambiguously a given source to individual neutrino events, due to the directional uncertainty and the large neutrino energy, resulting in a large time delay expected between the neutrino and the lower energy photons. Therefore, the association is done statistically over the whole population. Reasonable angular resolution is required, both on the neutrino direction and the gamma-ray direction. Concerning the angular resolution of the gamma-ray, similar considerations as for the photon time delay effects apply (see section **??**). Concerning the angular resolution of the neutrino, there is a trade off between energy and angular resolution, as described below.

The energy measurement requires a reconstruction of the neutrino energy based on the deposited energy in the detector. Neutrino events are usually classified depending on the topology of the interaction vertex inside the detector. *Track events* are generated by the interaction of a neutrino with the ice outside of the instrumented volume, so that the resulting muon produces a track only partially inside of the detector. These kinds of events have a good angular resolution (less than 0.1° above TeV energies [**?**]), however the neutrino energy reconstruction is affected by large uncertainties [**?**], given that an unknown amount of energy is deposited in the ice outside of the detector. For *cascade events* the interaction does not produce visible muon tracks. Their energy is contained completely in the "instrumented volume", so that the energy reconstruction of the neutrino is very accurate, giving an energy uncertainty of about 10% [**?**]. However, the topology of the interaction makes it harder to determine the incoming direction of the neutrino, so the angular resolution of these events is much lower with respect to tracks (of the order of 10°). It is then clear that there is a trade off between energy and angular resolution: shower events optimise energy resolution at the expense of angular resolution, while the converse holds for track events.

Identification of the electromagnetic counterpart of the neutrino signal is also needed in order to pinpoint the redshift of the source, and thus estimate the distance traveled. The redshift measurement is currently the main source of uncertainty in these time of flight studies, due to the fact that for most of the GRBs the redshift is unknown. Here, the same difficulties arising in the distance determination of photon time of flight studies apply. To identify the distance of the source, see the techniques and considerations discussed for the photon time delays measurements. Alternatively, over a large population, redshift assignment can be done statistically, based on the sources for which the distance is known [**?**].

The main requirements to improve the sensitivity of time of flight studies that use astrophysical neutrinos are the following:

- precise estimate of the redshift of the sources
- improved energy reconstruction techniques for track events
- improved techniques for reconstructing the direction of cascade events
- increase the rate of observed neutrino events, so to allow for neutrino-neutrino time of flight studies

relation between how much one wants to open the time window, to go to higher energies, and how much one needs to shrink the angular window

very long term: stereoscopic neutrino detection

3.2.3. Birefringence Vacuum birefringence is a standard phenomenon known from QED, which can have interesting phenomenological consequences in the presence of specific QG phenomena for all photon wavelengths [120, 121, 122, 123]. Lorentz-violating effects could introduce modifications to the phase and group velocities of the circularly polarised modes, including flips, effectively altering the observed polarisation. To observe this effect, knowledge of the emission properties of the photon source is required. Moreover, since the degree of polarisation directly depends on propagation details, the properties of the medium ought to be known. For instance, uncertainties in the magnetic field could influence the polarisation through Faraday rotation. Furthermore, since the flipping probability depends on the density of the background field such as the EBL, these distributions have to be known precisely.

At high energies ($E \gtrsim 1$ GeV) polarisation is extremely hard to be measured and virtually impossible in detectors like Fermi and IACTs. Given the importance of gamma-ray polarimetry, there have been some suggestions on how to overcome these technical limitations [124, 125], in particular for the hard X-ray and soft gamma-ray bands [126, 127].

In the absence of such as instruments, this phenomenon can be searched through energy-dependent time delays for the different modes, which do not require direct polarisation information [?]. In this case, astrophysical time delays due to source or propagation effects constitute the main source of uncertainty.

3.2.4. LIV effects in point-source or diffuse fluxes of astroparticles (interaction anomalies) The interactions that astroparticles (cosmic rays, photons and neutrinos) can undergo in their sources, as well as in the propagation to the extragalactic space, can be modelled with modern simulation codes taking into account the distributions of photons and/or matter causing the interactions. As a general request for the study of the effects of new physics, their modelling should be implemented and libraries of simulations should be created, in order to be used in parametric studies in comparison to measurements.

Some examples of analyses are reported in the following, for some specific effects and/or messengers, examining the sensitivity requirements to detect LIV effects in point-source or diffuse fluxes. We note that we will restrict the discussion to the LIV scenario but one should not forget the possible alternative DSR scenario with an energy scale much lower than the Planck scale. In this alternative scenario one would have a modification of the fluxes of different high-energy astrophysical messengers when their energy approaches the energy scale of the deformation. The requirements to be able to identify this alternative scenario would be those allowing to exclude the correlation of effects in time delays and fluxes characterizing the LIV case. Moreover, the energy dependence of the modification of the fluxes in the DSR scenario will be different from the modification in the LIV case in the energy range close to the energy scale of DSR [10]. Therefore, any improvement in the determination of the spectral flux of the different messengers would translate in an improvement in the sensitivity to effects of QG in a DSR scenario.

LIV effects in diffuse UHECR fluxes The UHECR flux at the escape from their sources can be constrained with studies involving the energy spectrum and composition at the highest energies measured by the largest UHECR observatories, including the effects of the propagation in the extragalactic space [74, 83, 84, 128]. The predictions show that the spectral shape at the sources is harder than what predicted by the Fermi mechanism, and the maximum energy is comparable to the threshold energy of the processes governing the energy losses at the highest energies, such as the photo-pion production and the photo-disintegration (the latter in the case of UHECR nuclei). This finding, together with the evidence that the UHECR mass composition becomes heavier while the energy increase, worsen the capability of constraining parameters of new physics, which should manifest itself for extremely energetic particles. This is also shown in [75]. In order to improve the constraining power of new physics, the sensitivity to the proton fraction is one of the most relevant issues. The aim of the upgrade of the Pierre Auger Observatory (whose main additional detection technique is to use scintillators on top of the water Cherenkov detectors in order to increase the ability to distinguish the electromagnetic part of the shower from the muonic content), is to improve the discrimination power on the mass composition at the highest energies. In addition, new analysis techniques such as the ones involving DNN [129] can be considered for the same aims. The requirement to observatories would be to determine the proton fraction in the region of the cutoff of the UHECR spectrum, in order to support or discard the current interpretation of the UHECR spectrum and mass data, and test the sensitivity to parameters of new physics. In parallel to the improvements of the UHECR observatories, improvements in the modelling of hadronic interactions are expected to bring benefit to the interpretation of the UHECR mass composition.

LIV effects in point-source or diffuse photon fluxes High-energy photons can be produced directly at the sources, resulting from leptonic processes, such as the self-synchroton Compton mechanism, or from hadronic processes, as products of the neutral pion decay, or as subproducts of the interaction of UHECRs with the extragalactic backgrounds. These production processes, as well as the photon propagation during their path to Earth and in the atmosphere in the detection process, can be affected by LIV physics. Although not many works have deepened in the consequences of LIV in the production of photons at the sources (but see Ref. [130] for related effects), mainly because of the complexity and uncertainties of source mechanisms, there have been some studies on LIV limits from the development of atmospheric showers [131] and many others dwell on consequences from propagation effects [132, 133, 12, 134].

Specifically, a modification of the dispersion relation leads to a superluminal or subluminal velocity. Photon splitting and spontaneous emission put very strong constraints on a superluminal scenario from the detection of the highest energy gamma rays [135, 136, 137]. They can be based on the lack of indication of a sharp spectrum cutoff when using data from identified luminous sources [135, 137], or based on the detection of extremely high-energy single events [136, 137], like the one with energy 1.4 PeV detected by the LHAASO collaboration [138] thanks to their very good rejection capability (the probability of this event to be a non-rejected cosmic ray is estimated to be 0.028% [138]). To improve the sensitivity to LIV effects, experiments will need to feature, besides excellent rejection properties, a good energy resolution (which is fairly decent for LHAASO, 13% at 100 TeV for showers with zenith angle less than 20° [139]), and the ability to get a good estimate of the distance travelled by the gamma rays, which translates into a very good angular resolution (around 0.8° at 10 TeV and 0.3° at 100 TeV for LHAASO [139], which is however not good enough to firmly localize and identify the sources of the detected ultrahigh-energy gamma rays [138]).

The LIV effects are milder in a subluminal scenario, where there is a modulation of the energy spectra of gamma-ray sources, decreasing the absorption of gamma rays from their interaction with background photons. Constraints are usually derived in this case by comparing detected spectra with the propagation of a model for the intrinsic emission at the source in the LI and LIV cases. The essential ingredients are therefore the selection of the spectra to be used in the analysis, the model of the intrinsic spectrum, and the choice of the model of background photons affecting the gamma-ray propagation [133]. The best sensitivity to LIV effects requires spectra characterized by a large distance to the source and the highest possible maximum measured energy, ingenious methods of obtaining the intrinsic spectra (beyond the standard approach of using the LI attenuation at the distance of each source, which is probably too naive for LIV studies, as remarked in [133]), and improved models for the EBL background, which still suffer from large uncertainties [140, 70].

As for the source fluxes, the expected flux of cosmogenic photons in the subluminal scenario is affected by the EBL modelling. In addition, cosmogenic photons depend strongly on the characteristics of the UHECRs as emitted from their sources. Being produced by the decay of neutral mesons, the amount of cosmogenic photons is connected to the UHECR characteristics that maximise the photo-meson production, therefore a contribution of protons at the highest energies at the escape from UHECR sources would improve the ability to constrain LIV effects in this sector, as shown in [75]. An additional proton fraction at the sources, which is not yet constrainable with the current UHECR observatories, would increase the expected integral flux by 3 to 4 orders of magnitude at 10^{18} eV, therefore reaching the current sensitivity to photons.

The current sensitivity to measure photons through the atmospheric cascade of particles they produce is obtained by taking into account the standard development of showers, as for instance in [141]. If LIV effects are considered, as suggested in [142], photons might escape observation passing through the atmosphere without producing air showers. The current limits should be therefore revised taking into account these possible effects.

LIV effects in diffuse neutrino fluxes The expected neutrino flux is also sensitive to parameters of new physics, which could modify the propagation of neutrinos in the extragalactic space due to electron-positron pair creation and neutrino splitting [143, 17]. These processes could affect the expected neutrinos produced directly in the sources, as well as the cosmogenic ones, namely those produced by the cosmic rays interacting with background photons while they travel in the intergalactic space. In particular, changes in the position of the cutoff of the neutrino flux as well as in its shape at Earth are expected, due to the fact the decay probability strongly increases as the energy of the neutrino increases. The astrophysical neutrinos are sensitive to the scale of new physics responsible for changes of the flux in the energy region around 1 PeV [143], therefore we expect improvements from the increase of statistics of events in that energy region from IceCube or the next-generation neutrino experiments. The cosmogenic neutrino flux is expected to be originated in the interactions of cosmic-ray particles with the cosmic microwave background (contributing to the highest-energy peak of the flux) and with the EBL (contributing to the lowest-energy peak). It is shown that increasing values of the parameters of new physics manifest themselves in re-shaping the EBL or the CMB peak [work in progress, Reyes et al.]. Being the expected EBL peak strongly dependent on the spectral index of the parent CR flux at the escape from the sources [144, 83, 84], the enhancement of the exposure of the experiments in the energy region of $10^{15} \div 10^{17}$

eV is of great relevance in order to improve the sensitivity to new-physics parameters; in fact, the expected number of neutrinos is doubled with respect to the special relativity case, in the range $\Lambda/M_P < 10$ (considering a fixed scenario for the UHECR spectral parameters and for the source evolution [work in progress, Reyes et al.].

- In case high energy photon-like showers are detected, one could aim to identify the potential sources. This would be possible with detectors with an angular resolution around or better than 1 deg over all the energy range of interest. It is also important to have a huge area ground based detector based on a very robust technique which allows to have a duty cycle of about 100 in case of transient sources.
- For both cosmic rays and photons, it would be very important to have a detector capable of accessing the parameters that allow the primary mass to be distinguished. At the state of the art, these parameters are mainly the position of the shower maximum and the muon content at ground level. However, it is necessary to improve mass discrimination through the development of new detectors. Using the experience gained with Auger and AugerPrime as a starting point, using codes such as GEANT4 would make it possible to simulate the detectors' response in detail in order to estimate the experimental sensitivity to small violations and to define possible detector setups that increase the potential for discovery.
- Currently, shower simulation codes such as CORSIKA or Conex do not allow the simulation of events that violate Lorentz invariance. It is therefore necessary to first model and then introduce modifications to these simulation codes to compute the development of showers in the atmosphere in case of Lorentz symmetry breaking.

LIV effects in the development of atmospheric showers. Astroparticles at the highest energies are investigated thanks to the measurements of the cascade of particles generated after the first interaction in the atmosphere. Both the electromagnetic part of the shower and the muonic part can be affected by LIV effects, as investigated in [145, 146]. The change in the energy threshold of particle decays deplete the electromagnetic part of the shower faster than in the LI case, and the net effect is to move the shower maximum to higher altitudes, and in addition also the calorimetric reconstruction of the energy can be affected. In the muonic part of the shower, the relative fluctuations of the number of muons strongly decrease for protons as a function of the energy, if LIV is included. Current bounds shown in [146] will benefit from the improved determination of the UHECR mass composition as expected with the upgrade of the Pierre Auger Observatory. Other effects regarding the photon sector include the vacuum Cherenkov radiation in the atmosphere [147] as well as the modified pair production explored in [142], which could have an impact in the determination of the sensitivity for the observation of photons.

3.2.5. Effects in neutrino oscillations

- Ability to associate the neutrino signal to the different flavor components in order to reconstruct with great accuracy the experimental oscillation signal and search for small energy dependent deviations from the traditional oscillation pattern. This is quite an easy task for experiments (like the neutrino telescopes or, in future, HyperKamiokande) based on Cherenkov detectors. In case of multipurpose experiments with different detectors (like, for instance, the liquid scintillator of JUNO) an additional effort should be devoted to the development of specific experimental procedures, based for instance on the different time shape of the signals, in order to discriminate the events generated by muonic neutrinos from the electron neutrino signals.
- Optimal energy reconstruction and resolution. The search for energy dependent LIV effects require a good energy resolution, that would make possible also a better binning separation of the data. Present and future multipurpose experiments (like the already cited JUNO) can take advantage of their unprecedented values of the energy resolution. For the higher energy events it will be important to perform calorimetric measurements and to develop strategies of analysis to reconstruct the energies also of through going events. Particular attention should be paid also to avoid pile up problems.
- A correct reconstruction of the distance travelled by neutrinos will also be important.
- In order to search for this kind of LIV induced corrections with neutrinos of ultrahigh energies, like the highest energy atmospheric neutrinos and the cosmic ones, it will be important to identify some reasonable experimental observables in which the possibility of detecting the effect of these corrections is not cancelled by the uncertainties on the distance travelled by neutrinos and on their energies or diluted by the integration over these variables.

4. Proposals for new measurement strategies for QG research

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4.1. Gamma-ray experiments

The main target of gamma-ray astronomy from the quantum-gravity perspective concerns the possibility of in-vacuo dispersion. Therefore, one desires observing high-energy photons from very distant sources and sources which can be described as a short-duration burst (or have intelligible fine time structure that can be used for the time-of-emission considerations). Gamma-ray telescopes with polarization-measurement capabilities would have the added bonus of being able to investigate models in which the in-vacuo dispersion has a polarization dependence.

Clearly the plans being made and implemented about the CTA (Cherenkov Telescope Array) are very exciting from the quantum-gravity perspective, since they will provide many opportunities for observations of high-energy photons. One limitation of the CTA is that it should probably only see relatively nearby sources, which not only decreases the expected magnitude of the effects (that could be compensated by the high energies observed) but also prevents one from investigating the form of the redshift dependence of possible in-vacuo dispersion. Complementing the CTA with telescopes capable of also observing high-energy photons but sensitive to phenomena occurring at high redshift would be very important for quantum-gravity research. The ideal option would be some upgraded version of the Fermi telescope: even gaining just a factor 2 in effective area and sensitivity to high-energy photons (with respect to the Fermi-LAT) might lead to a significant step forward for quantum-gravity phenomenology. Looking further in the future, a very desirable prospect would be the one of network of a few of such "super-Fermi" telescopes displaced at solar-system-scale distances.

High-altitude air-shower observatories are also a top priority for quantum-gravity phenomenology, as shown by the interest generated by results already reported by the Large High Altitude Air Shower Observatory (LHAASO).

While all these strategies are extremely valuable, if one wants to imagine the ideal opportunity for quantum-gravity phenomenology it would seem that this would be provided by the observation of the prompt phase of GRBs in the energy range between 10 and 100 GeV, particularly the prompt phase of short GRBs. This can be challenging for the CTA (small field of view, limited chances of seeing the prompt phase of a GRB) and for high-altitude air-shower observatories (good sensitivity only above 1 TeV), but indeed could be achieved by planning a "super-Fermi" space telescope, with larger effective area. If the spectral break-off of gamma-rays caused by internal absorption is larger than 100 GeV, a viable alternative to "super-Fermi" space telescopes could be provided by the "HADAR project", planning a ground-based observatory with wide field of view and sensitivity to photons of energies 100 GeV and higher [148].

Traditional single-satellite telescopes can cover the whole sky in a few hours, but their effective areas are not very large. There might be benefits for the "discovery reach" of quantum-gravity phenomenology if there were space telescopes with much wider field of view (and therefore providing higher statistics), even if that came at the cost of a narrower and lower range of energies observed. From this perspective quantum-gravity phenomenologists are following with strong interest the advent of "distributed astronomy", using several nano-satellites that could serve as an all-sky monitor, with a keV-MeV energy band, providing high statistics at a small temporal scale, besides allowing a more accurate determination of the location of astrophysical events, like GRBs. Examples of this strategy is the GrailQuest mission [149] (which would launch a fleet of hundred/thousands of nano-satellites by the 2050s), which is under development through the HERMES project [150] (which plans to launch 6 telescopes in the near future).

Looking further ahead in the future, and assuming optimistically some rather large progress in our space-mission capabilities, one could hope for controlled experiments studying in-vacuo dispersion. For example, if it will become possible to do laser-light experiments with lasers exchanging a signal between the Earth and the Moon, one could test in-vacuo dispersion using the frequency-doubler strategy of Ref.[151]

4.2. Neutrino experiments

Neutrino observatories are also very relevant for in-vacuo dispersion studies [152, 153, 154, 155]. In addition, it has been conjectured (though none of the quantum-spacetime toy models that appeared in the literature supports this conjecture) that in-vacuo dispersion might affect differently particles of different families, so that in particular the in-vacuo-dispersion effects would be different among the 3 known types of neutrinos (e, μ, τ, neutrino flavour), producing a characteristic effect for neutrino oscillations [156] and astrophysical neutrinos play a significant role as they reach higher energies ($\sim$ PeV) and have longer propagation distances ($\sim$ Gpc).

The advent of a new generation of neutrino observatories, including KM3NeT [157] and IceCube-Gen2 [158], will surely be of great interest for quantum gravity. In planning these new observatories the quantum-gravity perspective would favour a high premium for the accuracy of energy determination (much more significant for the quantum-gravity interest in neutrinos rather than for the astrophysics interest for neutrinos) and increasing the statistics.

4.3. Cosmic-ray experiments

For cosmic-ray observations the main possible role of quantum gravity is not linked to in-vacuo dispersion but rather to how some modifications to the on-shell relation could affect certain interaction thresholds [159, 85, 160]. This can affect the so-called "GZK cutoff" and therefore change the maximum distance from which UHECRs can be observed; moreover, it can also affect the subsequent interactions of cosmogenic neutrinos and photons produced via UHECR interactions [161, 83]. The on-shell relation may also affect the lifetime of particles, which could impact the muon content of the air showers [146, 162]. Presently our most powerful cosmic-ray telescope is the Pierre Auger Observatory, and its results have provided the basis for several quantum-gravity-phenomenology analyses (see, *e.g.* Ref. [75]). The unresolved "muon puzzle", which consists in a mismatch between the theoretically expected and the experimentally measured number of muons [163], could also be a signature of some QG phenomenon [164]. However, in general converting cosmic-ray data into constraints on quantum gravity faces several challenges, including the lack of knowledge regarding UHECR sources, as well as the intervening magnetic fields [88] and background photon distributions [165], and some relevant photonuclear cross sections [165], but one can be optimistic about progress in these directions in the coming years [107].

Concerning the planning of the next generation of cosmic-ray observatories the top priorities for quantum gravity are "particle identification" (especially distinguishing between cosmic-ray protons and cosmic-ray heavy ions) and of course accuracy of energy determination. From this perspective we are excited about ongoing work, adding components of the observatory, aimed at increasing the sensitivity of the Pierre Auger observatory to the type of particle. We are similarly excited about ongoing work of upgrade of the Telescope Array, bringing its area from the present $700\,\mathrm{km}^2$ to about $2800\,\mathrm{km}^2$. For the next decade we endorse enthusiastically the planning of the Global Cosmic Ray Observatory (GCOS) [166], that anticipates a set of arrays with total area of the order of $40000\,\mathrm{km}^2$.

4.4. Gravitational-wave experiments

Our current and foreseeable capabilities of observation of gravitational waves do not look promising for tests of quantum-gravity-induced in-vacuo dispersion since these gravity waves are of very long wavelength. The interest of the quantum-gravity community in gravity-wave interferometry resides mainly in scenarios based on the idea of "spacetime foam", such that quantum-gravity effects might manifest themselves as an additional sources of noise [167, 168, 169] for gravity-wave interferometers. While modelling of this conjectured quantum-gravity noise is still at a very preliminary stage, it appears [167, 168] that the effects might be more noticeable at lower frequencies, which adds reasons of quantum-gravity interest in observatories like LISA [170], the DECi-hertz Gravitational-wave Observatory (DECIGO) [171], the Big Bang Observer (BBO) [171, 172] and the Einstein Telescope [173]. These planned (or "planable") gravity-wave observatories might have added valence for quantum-gravity research through their ability to test some models of the stochastic background of gravitational waves [174, 175, 176, 177].

5. Data availability and collaboration between telescopes

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The community working on quantum-gravity phenomenology within multimessenger astrophysics is strongly "interdisciplinary", combining theorists working on quantum gravity, theorists working on astrophysics and experimentalists involved in different telescopes, observing different types of messengers. This perhaps also renders this community particularly sensitive to an incomplete transition in the policies that concern public availability of data: some telescopes and observatories still work, even after many years of operation, with limited (and in some cases no) public availability of data, while others have adopted a strong commitment to release, archive, and serve the broader scientific community, also providing the information and tools necessary to understand and use the data. These differences probably reflect corresponding differences in policies adopted by funding agencies, some of which still pay no attention to public availability of data while others are placing an increasing emphasis on this important point.

We urge all funding agencies to take action in this direction. It is important that funding of telescopes and observatories includes the resources for a strong effort of public availability of data. We do not propose a specific recipe, since the optimal solution strongly depends on the specifics of the proposed observations, and we well realize that it is also important to find a good balance between the idealistic interests of pure Science and the practical interests of those devoting many years of their lives to preparing an observatory, who then use the embargo system for collecting deserved benefits for their efforts. Still, something needs fixing when our policies produce severe obstructions to our main mission which of course is to achieve in the shortest possible time the full potential for growth of mankind's scientific knowledge.

Among currently-operating experiments two examples that deserve mentioning are the Fermi-telescope data policy and the LIGO/Virgo data policy. Both of them moved from an initial phase of full embargo of their data, to then making an admirably strong commitment to release, archive, and serve the broader scientific community, also providing the information and tools necessary to understand and use the data. This combination of an initial phase of embargo with a following phase of full disclosure might deserve to be adopted more broadly, and the benefits for Science will be of course maximized if the embargo period is relatively short (the Fermi telescope had only one year of embargo, which could be an ideal choice, when other circumstances allow it).

While we are hoping that embargo phases will be short, when it happens that more than one telescope is within an embargo phase (presently many telescopes are in full embargo) one way to temper the impact on the progress of science is to allow at least collaborations among scientists working at different telescopes, making special provisions for such collaborations to have full access to the data of the telescopes involved. A good example of this possible practice is the initiative [112] that has involved researchers from HESS, MAGIC and VERITAS that describes a method to use combined data from these telescopes.

Another positive initiative is the Astrophysical Multimessenger Observatory Network (AMON), which uses subthreshold data (that are not suitable for astrophysical research) and public data from different observatories, like HAWC, ANTARES and

IceCube to search for coincident multimessenger events [178, 179]. These multimessenger initiatives can be boosted by platforms that emit alerts on astrophysical events involving several messengers, like Astro-COLIBRI [180], Gamma-ray Coordinates Network (GCN) [181], Astronomer's Telegram (ATEL) [182], IceCube alert system [183].

CTA	Cherenkov Telescope Array
CMB	cosmic microwave background
DSR	doubly special relativity
EBL	extragalactic background light
GRB	gamma-ray burst
GZK	Greisen–Zatsepin–Kuzmin
IACT	imaging air Cherenkov telescope
MDR	modified dispersion relation
SR	special relativity
LIV	Lorentz invariance violation
UHECR	ultra-high-energy cosmic ray
QG	quantum gravity

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