Decoherence in Quantum Gravity: Issues and Critiques

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Abstract

An increasing number of papers have appeared in recent years on decoherence in quantum gravity at the Planck energy. We discuss the meaning of decoherence in quantum gravity starting from the common notion that quantum gravity is a theory for the microscopic structures of spacetime, and invoking some generic features of quantum decoherence from the open systems viewpoint. We dwell on a range of issues bearing on this process including the relation between statistical and quantum, noise from effective field theory, the meaning of stochasticity, the origin of non-unitarity and the nature of nonlocality in this and related contexts. To expound these issues we critique on two representative theories: One [1, 2] claims that decoherence in quantum gravity scale leads to the violation of CPT symmetry at sub-Planckian energy which is used to explain today’s particle phenomenology. The other [3, 4] uses this process in place with the Brownian motion model to prove that spacetime foam behaves like a thermal bath. A companion paper [5] will deal with intrinsic and fundamental decoherence which also bear on issues in classical and quantum gravity.

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1 Introduction

1.1 Synopsis of BLH’s talk at this conference

The title of the invited talk delivered by one of us (BLH) in this meeting which this article stems from, was, "What is Quantum Gravity?" (QG). It presents the view that if one agrees that the common goal of QG is to search for a microscopic structure of spacetime, then perhaps one should place more emphasis on the macroscopic (M) to microscopic (m) issues than the classical (C) to quantum (Q) issues. The classical to quantum route (C → Q), such as finding a good set of variables in general relativity and quantizing them, is the way traditional quantum gravity effort has been placed, epitomizing in the current loop QG program. (See [6] for a collection of reviews on the various approaches to quantum gravity.) We advocate the importance, or even precedence, of the M → m route over the C → Q route: We need to find out the appropriate microscopic constituents before quantizing them. Or, in this viewpoint, one is doubtful that quantizing the macroscopic variables in a theory valid perhaps only at low energies, *vis*, the theory of general relativity (GR) can lead to a theory of microscopic structure of spacetime.

This view is shared with string theory; the difference is that, being less ambitious or brave (the ‘half full’ view is being more prudent and cautious), we take a ‘bottom-up’ rather than a ‘top-down’ approach. We build our intuitions on and seek our way from reliable physics at low energies, with the well established theories of semiclassical gravity and the newer stochastic gravity [7] (an extension of quantum field theory in a curved classical background [8] to include the expectation values of the stress energy tensor of quantum matter fields and their fluctuations as sources). In this approach one looks from the given macroscopic spacetime interacting with matter for the high energy relics (from experiments or observations) or suggestive hints (from theoretical constructs or conceptual reasons) of such microscopic structures. Admittedly this is a very difficult if not impossible task, but this is no different from most experimental and theoretical explorations in the history of physics.

Going from the micro to the macro and from the few to the many, we rely more on the tools and concepts of nonequilibrium statistical mechanics including critical phenomena, hydrodynamics and kinetic theory, aided by analog models and ideas from condensed matter physics. The two keys the speaker thinks are of most use (for us low energy creatures) to decipher the mysteries of the microscopic structures at higher energy scales are noise and topology, because colored noise (correlation-fluctuations) ingrains the nature of the environment and its influence on the low energy system of interest, and topological structures can better survive the re-constituting (including physical changes such as phase transition and descriptive adjustments such as the adoption of better collective variables) and unavoidably corruptive processes (in the sense of degradation of information by coarse-graining as one traverses different layers of structure and levels of interactions) in the time evolution (or energy scaling) of the system over history.
One earlier proposal of the speaker is to view GR as hydrodynamics of QG\textsuperscript{9} (regarded as a theory for the microscopic structures of spacetime). So, given a hydrodynamic theory our task would be to deduce the molecular dynamics and from it decipher the properties of the molecules. It is easier to go from the micro to the macro but there are ways to get some hints in the reverse direction, such as examining the hydrodynamic fluctuations and nonperturbative structures, and for these, critical phenomena, kinetic theory and stochastic processes can be of help. We want to know how and where different layers of structure and their interactions can emerge in the interceding processes. In this quest two conceptual pathways have been explored, the kinetic theory approach\textsuperscript{10} and spacetime as a condensate\textsuperscript{11}. One can find a summary of these ideas in a recent essay of the speaker\textsuperscript{12} which also uses this view to address the so-called ‘origin’ of the universe issue\textsuperscript{1}.

1.2 Aim of this work

Instead of repeating what was said and written before on this topic we would like to pick one representative issue in quantum gravity which bears on several aspects touched on in the talk, specifically, here, on decoherence in quantum gravity. This is an issue which has drawn increasing recent attention from researchers interested in the foundation of both quantum mechanics (such as intrinsic decoherence) – see e.g., Adler’s book\textsuperscript{21} and its bibliography, and general relativity (such as gravitational decoherence – see e.g.,\textsuperscript{22}), and those who are interested in exotic yet poorly understood (or even ill-defined) constructs such as spacetime or quantum foams, or by conjectured universal mechanisms, such as decoherence in quantum gravity. Usually one needs to draw on some features out of the familiar, like nonunitarity and nonlocality, to make new proposals work. One aim of this paper is to emphasize that one needs to check proposals against some known facts from detailed model studies of specific issues (e.g., quantum decoherence\textsuperscript{23}) or well-established mathematical (e.g., probability theory) or physical theorems. By clarifying the underlying ideas in such proposals, we hope to get a clearer view to define our goal and to get a better aim at the targets. We need to go through this step in order to establish a common language, agree on the common goals, to explore different methodologies and build up the systematics for a more fruitful expedition in this wild, exciting yet equally perilous terrain.

In this process the reader will see how this new (hydrodynamics) viewpoint

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\textsuperscript{1}It also contains a short bibliography of some latest papers in related approaches to QG. Amongst the different approaches to quantum gravity the issues expounded by Sorkin\textsuperscript{13}, the ideas proposed by Wen\textsuperscript{14} based on quantum order, the analog to condensed matter systems as expounded by Volovik\textsuperscript{15}, and the programs pursued by Ambjorn and Loll on Lorenzian dynamics of triangulated spacetime\textsuperscript{16}, that of Dreyer, Friedel, Levine, Markopoulo, Oriti, Rovelli and Smolin\textsuperscript{17, 18} on the structure and evolution of spin network are of particular interest, because one can use these explicit constructions to examine the issues raised here, e.g., seeing the hydrodynamic limit, or even the dynamically preferred dimension-four spacetimes.

Read the articles by these authors collected in Oriti’s book\textsuperscript{6}. See also work by Herzog, Son et al on the hydrodynamic limit of string theory and its features\textsuperscript{19, 20}. 

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and (bottom-up) approach to quantum gravity would bear on this issue. In fact, after analyzing the primary issues involved, we confess we failed to see why or how this issue of decoherence (in the sense of loss of quantum coherence) in quantum gravity could be of such importance towards the emergence of low energy spacetime physics. Decoherence is a central issue in the quantum to classical transition. The emergence of spacetime with a manifold structure is, in this new view, more an issue of micro to macro transformation. With dark energy hovering overhead we may one day even see a paradigm shift that today’s large scale spacetime structure is fundamentally quantum.

Finally, we want to emphasize that this article is more in the nature of comments than expositions, with the purpose of discussing points rather than covering an area, much less presenting or dwelling on a volume of systematic work. Companion papers are in progress addressing related issues such as intrinsic decoherence [5], gravitational decoherence in astrophysics [24] and in black holes [25].

1.3 Organization of this paper

We begin in Section 2 with a discussion of the meaning of decoherence in QG, and lay out a set of basic issues which one needs to address for the consideration of this problem. We caution that many common conceptions may not be valid or relevant here, and that as a result the discussion of issues in low energy physics being affected by Planckian physics is not straightforward. In analyzing the aspects possible new features of low energy physics stemming from quantum gravity novelties, we distinguish between two types of issues. First, there are issues originating from general mathematical or physical reasoning and their underlying assumptions. The other type of issues is specific to the particular quantum gravity approaches taken. To address them one needs to place them in the larger framework which these approaches adopt. In Sec. 3, we comment on these issues in relation to the long standing research program of Mavromatos et al [1] and in Sec. 4 we focus on Garay’s proposal on thermal spacetime foam [3]. Through these examples, we illustrate the cris-cross of issues involved, in quantum field theory and statistical mechanics, such as the assumptions behind the structure of spacetime foams, low energy effective theory, origin and nature of noise, the Brownian motion analog and the validity of the Markov approximation, etc. In Sec. 5 we continue our discussions into two more finer issues. We then summarize the points made in this paper into three key concepts, i.e., nonunitarity, nonlocality and stochasticity and give a discussion of them in a broader scope.

\[\text{This is just a warning that debates on these issues may not be so fruitful without considering the viability of their underlying framework. For lack of space we will not probe into the theoretical schemes at the base, but only bring out some issues common to them all.}\]
2 Decoherence in Quantum Gravity: Meanings and Issues

Before addressing the issues involved, let us begin by giving some careful deliberation on the meaning of decoherence in quantum gravity.

2.1 Three different Meanings

If we agree that quantum gravity is a theory for the microscopic structure of spacetime then the microscopic features are what we need to deal with, more so than the quantum features. Using ordinary physical objects as example, given a solid the first quest is to uncover its atomic constituents, the second quest is to find out the quantum nature of solids which would lead us to phonons and other collective excitations rather than atoms. Of course there are interesting quantum features associated with the atom, but this is a quest different from the first two. The mixing up of these two concepts is unfortunate but perhaps understandable because we usually view any microscopic world as described by quantum physics. If the quest is of the first kind then there is virtually no issue of decoherence in quantum gravity. For a long time studies in quantum gravity is of the nature of the second kind, i.e., finding ways to quantize the variables involved. The theoretical preconception of how GR emerges as a theory, defines the strategy one will follow for its quantization. The quantum theory thus obtained is assumed to be a theory for the microscopic structures of spacetime. It seems to us that this requires making some additional strong assumptions. If one assumes that the key feature of gravity is geometry at all energy and scale ranges, then the canonical quantization procedure does make sense, even though it is not the only possible strategy. A common assumption is the postulate of the existence of a minimal quantum area, for example, is similar to specifying that a solid of the size of an atom will give us the microscopic structure. But this postulate serves to demarcate the domain of validity of a solid’s quantized modes of vibration, but says very little about the atom from this theory of phonons, let alone its internal structure or its quantum features.

\[\text{\textsuperscript{4}}\text{Maybe so, until recently: Macroscopic objects can also show quantum features as witnessed by experiments defining the new emergent field of macroscopic quantum phenomena (MQP) \textsuperscript{20}. However, it is usually believed that macroscopic objects decohere more readily than microscopic objects and they can be described effectively through their collective variables as a classical object. \textsuperscript{27}.}\]

\[\text{\textsuperscript{4}}\text{Quantization assumes a function inverse to that of coarse-graining. A wrong coarse-graining hypothesis may lead one completely astray. For example, if the coarse-graining is hydrodynamic, a Hamiltonian quantization would be as meaningless as quantizing the Navier-Stokes (or the Euler) equations and arguing that the quanta of the mass density are the atoms.}\]

\[\text{\textsuperscript{5}}\text{For the same reason we don’t believe that the quasi-normal modes of a black hole which describe its classical vibrations can be simply extrapolated to reveal the microscopic structure}\]
2.1.1 Quantum-Classical transition versus micro-Macro manifestation

To give the best reading of what practitioners could have meant by decoherence in quantum gravity, and to make it more interesting and meaningful we should perhaps take on the third quest: i.e., that it is about the decoherence of the quantum features of the microscopic constituents of spacetime, like the quantum features of the atom after we make the discovery that solids are made of atoms. Note that our best reading also catapults us to a futuristic world where we already know what the atoms of spacetimes are and we want to know how the classical spacetime described by general relativity theory comes into being. Some optimists would consider that future is now, the atoms of spacetime are strings or loops or spin-nets. Fine. Let’s examine what issues we need to deal with in such a picture, and then examine how the practitioners really think about them and what they actually do.

To give a hint that this may not be the right question or the most interesting question to ask, let us return to the atoms in a solid for a moment. This question pertains to how the classical features of a solid could arise from the quantum nature of atoms. We know there are more interesting questions in condensed matter physics than this one: How the solid appears as we put the atoms together depends on atomic bonds and that in turn depends on quantum dynamics between atoms. One can also ask how the symmetries of crystals emerge (be mindful that the art of crystallography predated quantum physics). Or, how the thermodynamic laws in the macroscopic world emerge. Many classical features of solids can indeed be traced to the quantum interaction amongst atoms, but they are not about decoherence or recoherence. How does the classical nature of a solid arise from the decoherence of quantum atoms is not really a burning issue in solid state or atomic physics.

In gravitational physics, assuming strings play the role of the atom of spacetime, we see that the more urgent issues are to get the low energy spectrum (note that the particles made from strings are quantum objects), and how spacetime emerges\footnote{It may not be too unfair to say that at this stage, even getting classical GR or low energy particle spectrum out of strings or loops is a big issue. In the landscapes scenario it seems to us that these real physical issues are relegated to metaphysics – \textit{how} do metastable states come about, and \textit{why} we are in this particular one?}. The focus is not so much on how the classical nature of spacetime emerges from the decoherence of strings. This would be a ‘letdown’ of sorts to those who believe they already have the microscopic constituents at hand, because decoherence is about degradation of information, and usually in an indiscriminate way, by the action of an environment. The heavily laden statistical procedures which underlie this process known as coarse-graining almost does violence to the more important tasks we face, that of constructing the macroscopic world from the precise information about the constituents\footnote{One analogy is to take pride in discovering the Maxwell-Boltzmann distribution at the high temperature limit of a quantum gas, while ignoring the many interesting physics associated with a bose or fermi gas.}. In this sense, of a quantum black hole or the ‘atoms’ of spacetime, as some earlier claims seem to suggest.
the discussion of gravity induced decoherence at low energies is an indirect way to make contact with possibly observable effects in the low energy world.

2.1.2 Quantum vs Statistical

Let us now focus on what the practitioners addressing this issue really are referring to. Maybe they want to uncover the structure and nature of spacetime at a scale smaller than the Planck scale (e.g., Garay’s thermal spacetime foam [3]), or use a presumed structure to deduce some hidden and yet important relations in physics (such as the relation between clocks, computers and black holes as in Ng’s picture [28]). Maybe they want to understand the origin of fundamental relations in quantum mechanics, such as the uncertainty principle (e.g., [29]), thinking that gravity may play a hidden yet significant role [30], even at today’s low energy. Maybe they think that certain symmetries cherished at today’s low energy can be broken by some quantum gravity process [1]. An examination of the targets of these investigations is useful perhaps not so much for the purpose of finding out what decoherence can bring forth as how the issues can play out in the quantum gravity context.

Before we address these issues and try to extract their underlying meaning, for concreteness, we need some entity or notion of an entity to focus our thoughts. In the realm of quantum gravity the word spacetime foam or quantum foam are used often to connotate that phase of spacetime at a higher energy than the Planck energy. Spacetime foam as conjured by Wheeler refers to the primordial state of spacetime made up of foamy structures of multiply-connected topologies. There is in principle nothing quantum about it even though in the pre-Planckian epoch most people would allow for quantum fluctuations of spacetime to contribute to these foamy structures. We make the distinction here between these two entities, calling the former spacetime foam and the latter quantum foam. The reason is that there are subtle and physical differences between statistical and quantum entities.

Consider first the statistical mechanics of classical foam-like structures [31]. In the statistical foam we have a single ‘spacetime’ manifold (or spatial three-surface) which at the Planck scale is manifests a ‘foam-like’ multiply-connected topology. The statistical aspect rests on how this topology averages at the sub-Planckian scale and what are the effective variables that describe this average. In the quantum foam, we have many different ‘virtual’ spacetimes, each with a different Planck-scale structure and the issue is to determine the effective dynamics arising from the contributions of all histories (in a path integral representation). (For an interesting recent work on observables in effective gravity, not necessarily related to spacetime foams, see [32]).

What would decoherence in quantum gravity as embodied in Planck-scale foam entail? For quantum foams this would pertain to the dominance of the classical configuration. Some might argue that one can transform a statistical problem to a quantum problem by invoking the equivalence between a generating functional and the partition function. But this invokes an Euclidean path integral formulation or presumes a canonical ensemble, which in turn assumes
an equilibrium condition, as in thermal field theory. Also the Wick rotation is not unique without a background notion of time—even in special relativity one needs the full Poincaré group to make it unique. The quantum fluctuation formulation usually presumes the existence of a background spacetime, which has the smooth manifold structure. So one cannot quite talk about the geometry of trans-Planckian spacetime without a low energy background.

One useful way to connect to low energy physics is by way of effective field theory, from which another range of problems enters. We will have something to say in the next subsection.

Just these simple descriptions above which are familiar to most readers bring forth a number of issues: 1) can one replace statistical by quantum formulation or vice versa in these considerations? If so argued, what are the conditions which validate it? 2) How does coarse-graining of micro structures determine the salient features of a large scale structure? 3) What gives rise to stable low energy configurations? 4) Does decoherence at high energy alter the symmetry at low energies?

2.2 Issues

2.2.1 Decoherence in quantum gravity: an open system perspective

How does one inject decoherence into this picture of quantum gravity? The simplest way is to apply the popular environment-induced decoherence scheme to spacetime foams. The first question one needs to ask is, “What could constitute the system? What the environment?” Usually because of the ‘inertia’ of the gravity sector (due to the discrepancy between the Planck energy and our ordinary energy—see below) one would be tempted to say that the gravity sector is the system and the matter sector its environment. If one wants to use this scheme, it should be done without asking for the aid of a manifold structured spacetime, because otherwise one is not addressing decoherence in quantum gravity (in the third sense above) but decoherence due to classical gravity below the Planck energy.

But what could the environment be in an earlier epoch, at the level of the substructure? What are the criteria which separate a subsystem from the others which can evolve into the macroscopic spacetime we are familiar with? Decoherence due to Planck scale (top–down) effects that cannot be identified from the theory at low energy involves by necessity assumptions about Planck scale physics. To our knowledge these questions have not been yet been fully or properly addressed.\[^{[8]}\]

\[^{[8]}\]There are proposals of decoherence due to Planck scale effects based on specific limits of ‘measurability’ posed by gravity. Many arguments start with Wigner’s analysis of the spacetime uncertainty relation, (e.g. \[^{[28]}\] \[^{[35]}\] ). However, fundamental uncertainties definitely do not imply decoherence by themselves: they involve additional assumptions in order to do so. For example, Milburn \[^{[29]}\] models these uncertainties by a stochastic process. In effect, these works treat the spacetime foam as something that has properties similar to a classical source of noise. Quantum coherence of the foam is ignored, as well as non-Markovian effects. We will address the insufficiency of Markovian assumptions in the last section and discuss
2.2.2 Spacetime structure at high energy from a low energy view

The usual assumption is that somehow spacetime structure and quantum fields emerge as an approximation at energies lower than the Planck energy. The first question is in what sense these properties emerge, or, what class of coarse-graining will likely give rise to these properties, and what are their attributes?

At least three possibilities have been discussed in the literature:

A. Born-Oppenheimer (BO) Approximation (sometimes called "Hamiltonian coarse-graining") is what we have referred to above: If one looks at the ‘phase space’ of the full theory at a coarser resolution, those degrees of freedom with a bigger ‘inertia’ (in the sense of Gell-Mann and Hartle [33]), would appear to behave classically—see also [34]. The gravitational sector being weighted by the Planck energy over the matter sector is what justifies the introduction of a WKB time in quantum cosmology and how it produces the limit of quantum field theory in curved spacetime [36]. This is a kinematical rather than a dynamical explanation for the transition from quantum to classical. According to this perspective there can be no phenomena at low energy due to gravity but by that described by the theory of general relativity, because classical gravity dominates (is weighted favorably in the GH sense, under the BO approximation) below the Planck scale.

B. Correlation hierarchy – When there is a distinct discrepancy (in time, length, mass) between two sectors one can use the open system paradigm to describe the dynamics of the subsystems of interest. A more difficult situation is when no such discrepancy exists as in the case of a molecular gas, where each gas molecule is autonomous. Nonetheless, Boltzmann taught us how to order the information in the system, in terms of one particle distribution function, two particle correlation function, etc, which form the correlation (BBGKY) hierarchy. He also taught us how to introduce a coarse-graining in accordance to the precision we can access the information in the system, where the Boltzmann entropy acts as a measure of the degree of ignorance of such. This might be a more suitable way to view the pre-Planckian dynamics of the sub-constituents, analogous to molecular dynamics before hydrodynamics takes shape. There again, quantum decoherence is not as important or urgent an issue as studying how the hydrodynamic limit comes about, or from that state deduce the molecular properties.

C. Effective theory and scaling of coupling constants This familiar concept is well adopted in particle theory to address the hierarchy problem. The idea of scaling which works very well for the study of critical phenomena also added much richness to this paradigm. It allows one to talk about low energy phenomenology, without paying too much attention to the underlying more fundamental theory. The important parameters or scales are the thresholds where the low energy effective theories break down, in ranges where new particles and interactions become important.

A natural question to ask is “What could have survived from the high energy...
ergy sectors?” Calzetta and Hu \cite{37} answered this question in terms of noises coming from the coarse-grained higher energy sectors (which could be colored and multiplicative depending on the interactions prevailing), but they fall off exponentially fast below threshold. One could try to decipher the degraded information from the nature of noise, but overall this result affirms the philosophy of effective field theory, that it is not easy for high energy processes to cause appreciable effects at low energies. This issues about noise from effective theory will arise in Sec. 4.

2.2.3 Breaking of symmetry at low energy due to decoherence at high energy

One hope some practitioners place on decoherence is that open system dynamics are non-unitary: if such dynamics can be obtained from quantum gravity, the resultant low energy dynamics would also be nonunitary, thus providing a convenient way to break important low energy symmetries, like CPT. This argument involves the physics in two separate scales, a familiar low energy one endowed with a symmetry and a causal spacetime structure, and another unknown one at higher than Planck energy. This cannot be easily justified, irrespective of the definition of decoherence one employs. For example, in the usual environment-induced decoherence framework, the open system may arises from the effects the ordinary gravity sector at today’s energy. However, in schemes such as the above, the dynamics becomes non-unitary because of the influence of an ‘environment’ that involves trans-Planckian constituents engaging in (unknown to us) quantum gravitational processes. There is an obvious mismatch here, which we believe to be unphysical for the following reasons:

Looking at the problem in the high energy realm, any entity of quantum gravity vein such as spacetime foam is at the Planck scale—supposedly before spacetime with a Lorentz structure emerges. One needs a strong case to show that these high energy effects can escape the coarse-graining and scaling which subsumed their effect to that of the average, as the large scale manifold structure of spacetime emerges. In our opinion, the most reasonable assumption is that their average behavior is contained in the theories that survive to the low energy limit, in particular GR—it appears very counterintuitive to assume otherwise. If this is the case, the non-unitary corrections cannot be of order $G$—effects to this order are contained in the usual gravitational dynamics—but much much smaller.

Looking at the problem from the low energy realm, the coupling of matter to gravity is through the stress-energy tensor $T_{mn}$. If the Lagrangian of matter is invariant under a symmetry, this would be reflected in the $T_{mn}$. There is no way to get a symmetry violation, unless it is already there at the low energy theory. Moreover, if there is non-unitarity due directly to Planckian effects, it would not affect specifically one type of symmetry, but all of them: hence one should expect besides CPT violation, a violation of the spin-statistics relation, of the causality properties of quantum fields, and perhaps of less universal symmetries like baryon and lepton number. For these reasons, we believe that the study of gravitational decoherence at low energies should primarily focus on the physics
of GR: Penrose-type reduction, collapse models, gravitons as environment etc. Otherwise, one would have to answer the very difficult question “Through what mechanism would Planck scale effects dominate over ordinary gravity effects at this low energy?” A postulate of exotic open system dynamics can only be justified if it is tied to a concrete theory of quantum gravity.

3 Quantum Gravity Decoherence and CPT violation

Continuing on the last point, we comment in this section on a related proposal [1], which evokes spacetime foams, in order to provide rationales for results in high-energy physics phenomenology (‘high energy’ here does not refer to Planck scale). The suggestion is that the presumed non-unitarity from Planck-scale processes may appear in particle physics experiments, e.g. neutrino or neutral meson oscillations.

Two classes of models have mainly been employed in this regard. The first is a Markovian master equation for the distinguished degrees of freedom, flavor for neutrinos—for three generations the Lindblad operators may correspond to generators of the $SU(3)$ group [2]. The second approach involves the study of neutrino oscillations in a stochastic medium (Mikheev-Smirnov-Wolfenstein effect [3]), which they identify with fluctuations from the spacetime foam.

While the results of this analysis can fit the experimental data, we would like to make some points concerning the relation any such presumed decoherence effects to gravity. First, even if it turns out that there is a decoherence effect in neutrinos, it would be premature at this stage to attribute it solely or even dominantly to gravity. Any kind of environment due to higher energy processes that may be involved in the weak interactions could play the role of a decohering agent. Second, gravity (as described in general relativity) couples universally to all types of matter and to all degrees of freedom that contribute to the stress-energy tensor: hence, the isolation of specific degrees of freedom cannot be justified from first principles. In the case of neutrinos, the universality of gravity would suggest a significant coupling between the flavor and the translational degrees of freedom. If there are specific processes that distinguish the flavor degrees of freedom, present knowledge suggests that their origin lies in weak interaction physics, not in gravity. Finally, there is also the issue of the Markov assumption, or of the modeling of the stochastic background: as we will argue in Sec. 5 the possible behaviors of the Planck scale foam are not exhausted in the Markovian regime and there is no guarantee that they can be modeled adequately by a stochastic process.

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9The issue of dominating over low energy theories is important. For example, the conjectured ‘large’ extra dimensions could presumably be sources of symmetry breaking, but their contribution to gravitational dynamics responsible for decoherence are expected to be small compared to ordinary GR.
3.1 CPT violation

Another argument in [1] is that the non-unitarity effects arising from quantum gravity may lead to CPT violation in high energy physics experiments. The argument is based on the fact that the CPT theorem requires Lorentz covariance and unitarity. If the effective low energy dynamics is non-unitary or non-Lorentz covariant then one of the basic conditions for the CPT theorem is violated: CPT violation is then plausible.

We urge the exercise of caution on this point. The fact that the effective dynamics is non-unitary is not sufficient to guarantee CPT violation. To see this, one may consider a low energy theory (say QED), in which the soft photon modes have been traced out. The effective dynamics of the theory is non-unitary. However, there is no CPT violation in the effective description: photons have no anti-particles; left-handed and right-handed photons are treated symmetrically in QED. The channel of interaction of the system to the environment involves no CPT violation. The same would hold for any field coupled to the gravity, if one traces out the effect of gravitons: gravitons have the same CPT properties with photons, and the effective dynamics they generate when treated as an environment, fully respect CPT.

In other words, for the effective non-unitary dynamics of a low energy theory to violate CPT, it is necessary that the channels of interaction with the environment (which are represented by the Lindblad generators in the Markovian regime) are themselves not CPT invariant. This can happen only if the total Hamiltonian of system and environment involves CPT violating terms. Hence, the possibility that the effective dynamics at low energy is non-unitary does not suffice to establish CPT violation. One has to identify specific physical processes (i.e. terms in the total Hamiltonian) that do so. Moreover, even if there is CPT violation near the Planck scale, there is no guarantee that its effects will be felt at low energy. In our opinion, the most natural assumption is that such terms would take the form of small corrections to the combined predictions of general relativity and standard model. The (by far) dominant contribution to gravitational decoherence at low energies would then come from the non-CPT violating effects: the graviton environment or other suggested low-energy gravity mechanisms (e.g. Penrose-type).

4 Quantum Foam and Emergence of Classical Spacetime

We mentioned earlier that the emergence of spacetime and low energy physics is often viewed as a sequence of effective field theories each of them valid at a different scale. A necessary assumption in this approach is that somehow after the Planck scale a full-fledged spacetime structure with its basic properties has emerged – it is technically impossible to work in absence of this. The basic variables in an effective field theory are not required to be and often not the same as the fundamental variables of full quantum gravity. In condensed
matter or nuclear physics, the effective degrees of freedom may be collective or hydrodynamic. We have to work much harder to decipher how attributes of a Planck scale entity such as the spacetime foam could enter into the low energy physics we are familiar with. We mentioned before the two features which could carry these remnant information, such as nonlocal noise (through the correlations of the collective variables) and topological structures (likely convoluted by intervening processes).

In the present context, the question is whether the effective theory for physics after the emergence of spacetime may cause observable effects (in particular, decoherence) at low energies that differ from the ones obtained from our known low energy theories (i.e. standard model + GR). A priori, this is not very plausible. There are energy thresholds, and effects appearing only in energies above a specific threshold are strongly suppressed in energies below the threshold.

In Refs. [3, 4], Garay explores a different alternative, namely that the dynamics of the effective degrees of freedom after spacetime has emerged are non-local. This involves a rather non-trivial assumption, namely that local dynamics is a distinct property (and it arises at a different scale) from the spacetime structure that is necessary in order to phrase a quantum field theory meaningfully. While this separation is mathematically sound, its physical meaning is not straightforward: at least in GR it is difficult to separate between the local structure of spacetime and the locality of dynamics. The locality of the action in general relativity is a necessary feature that allows one to connect the mathematical objects “metric” and “spacetime point” with physical geometry; for example, locality is necessary in order for free-falling particles to move in geodesics. But even outside the context of general relativity, continuity of the effective variables is closely tied to locality of dynamics. This is the case in ordinary hydrodynamics: there is no way to separate the regime, in which the continuum approximation holds, from the regime of local dynamics; one assumption does not make sense without the other.

In Ref. [3] a separation of three scales is assumed: the Planck scale $l^*$, the scale of the gravitational fluctuations $r$ and the scale of low energy physics $l$. Let $\phi$ denote the variables of the effective theory, and $h_i(\phi)(t)$ denote a basis of local interactions at a spacetime point $(x, t)$. Then one introduces into the action a term of the form $I = \sum_N I_N$, where $I_N$ is an $N$-local interaction term

$$I_N = \frac{1}{N!} \int dt_1 \ldots dt_N c^{i_1 \ldots i_N} (t_1, \ldots, t_N) h_{i_1}(t_1) \ldots h_{i_N}(t_N).$$

The functions $c^{i_1 \ldots i_N} (t_1, \ldots, t_n)$ should not depend on the location of the gravitational fluctuations, hence they should be functions the relative location of the interactions. Moreover, they should vanish if the relative distance is substantially larger than the scale $r$. It is reasonable to assume that fluctuations involving a large number of spacetime points are suppressed; hence at first (weak-coupling) approximation one may keep only the bilocal terms.

Assuming that the dynamics is described by the Euclidean path integral, and keeping only the bilocal terms we obtain an expression $\int D\phi \exp[-I_0]$
\[ \int dt dt' e^{i\delta_j (t - t') h_i (t) h_j (t')} \], where \( I_0 \) is the action part that describes the self-dynamics of the effective degrees of freedom. Using a standard manipulation of the quadratic interaction term, together with a Wick rotation back to Lorentzian spacetime, one obtains the following expression for the path-integral

\[ \int D\alpha P(\alpha) \int D\phi e^{iS_0 + i \int dt a^i(t) h_i(t)}, \]  

(2)

where \( \alpha \) is an auxiliary variable and \( P(\alpha) \) is a Gaussian probability measure

\[ P(\alpha) = \exp\left\{ -\int dt \int dt' \gamma_{ij} (t - t') \alpha^i (t) \alpha^j (t') \right\}, \]  

(3)

where \( \gamma_{ij} \) is the operator inverse of the kernel \( c_{ij} \). Eq. (2) essentially describes unitary propagation under a stochastic external force \( \alpha^i (t) \), which fluctuates according to a classical stochastic measure \( P(\alpha) \).

Eq. (2) is analogous to similar expressions appearing in the study of quantum Brownian motion QBM (even though the exact interpretation of this object depends on the choice of boundary conditions for \( \phi \)). In fact, as Garay argues in [4], one expects that the most general possible bilocal dynamics can be expressed in terms of an influence functional

\[ W[\phi, \phi'; t] = \exp \left\{ -\frac{1}{2} \int_0^t ds \int_0^t ds' (h_i[\phi(s)] - h_i[\phi'(s)]) (v^{ij}(s - s') h_j[\phi(s')] - v^{ij}(s - s')^* h_j[\phi'(s')]) \right\}, \]  

(4)

in terms of a complex-valued kernel \( v^{ij} \).

Following (2) one may derive a master equation assuming an ensemble of unitarily evolving systems, each acted upon by an external force, whose ensemble average is provided by \( P(\alpha) \). At lowest order in \( r/l \), the result is

\[ \dot{\rho} = -i[H_0, \rho] - \int_0^\infty d\tau e^{ij} (r)[h_i, [h_j, \rho]]. \]  

(5)

Note that this master equation does not contain any dissipation term, which seems to be of a higher order in \( r/l \). This expression is then compared with one obtained from QBM in a thermal bath of harmonic oscillators with a \( h_i \)-coupling to the effective variables \( \phi \). The conclusion is that the leading behavior at the classical noise limit (when the commutators of the bath variables can be ignored) is the same as in (5), and hence that it is meaningful to talk about the spacetime foam as a thermal quantum bath.

We want to argue that while it is reasonable (in fact, natural) to compare the phenomenology of non-local effective theories to quantum Brownian motion, the conclusion that the assumed non-local fluctuations of spacetime foam behave similarly to a thermal bath involves specific modeling assumptions and cannot be considered as definitive.

Concerning the first point, we agree that the quantum Brownian motion provides the most natural framework for the discussion of non-localities in quantum
gravity. In fact, using the QBM language, it is not necessary to postulate fundamental non-localities at sub-Planckian scales, which may bring about issues of causality violation extending to low energy physics. The reason is the following.

The variables $\phi$ that appear in the effective field theory are probably collective degrees of freedom arising out of the Planck bath. The existence of non-localities in their dynamics is essentially the statement that the foam bath exhibits intrinsic correlations of characteristic scale $r$. We can compare it with the analogous situation in ferromagnetism: the basic local thermodynamic variable is the magnetization, however in some regime (e.g. near the phase transition) the correlations of the system become important and in some phenomena they contribute significantly. For this regime, one can write an effective non-local Hamiltonian for the magnetization, but one can equally well introduce new phenomenological fields. Alternatively, one may say that the true degrees of freedom are not the local fields, but some specific combination of them (one would consider for example an analogy with magnons).

In effect, the non-local interactions are equivalent to local ones that involve additional phenomenological fields $A^i$. They should correspond to a correlation length of order $r$, which is equivalent to them being characterized by a mass $M$ of order $r^{-1}$.

For the total system of phenomenological fields $A^i, \phi_i$, it is sufficient to postulate a local interaction term $\int dt A^i h_i$. The effective interaction between the $\phi$ fields will then be similar to $I_2$ considered in Garay’s model – the role of the kernel $c_{ij}$ will be played by the two-point function of $A^i$ – as long as the effective theory is viewed from scales larger that $r$. However, in scales of order $r$ the dynamics of the fields $A^i$ will be significant, and a non-local action like $I_2$ may not be adequate to describe physics at this scale. Still, as argued in [4], an expression like that of the influence functional (4) will be relevant.

Since the fields $\phi$ involve degrees of freedom that are accessible to low energies, and the dynamics of the $A^i$ fields are frozen at low energies it is meaningful to trace out the contribution of the latter. In effect, the problem reduces to that of QBM with the environment consisting of relatively heavy fields. Hence, QBM provides a more general paradigm for the treatment of non-localities than the postulate of a specific non-local effective interaction. The issue is then what is the physically relevant state of the bath. If the $A_i$ fields are similar to fields of low energy physics (e.g. scalar fields), and if we assume that they can be described by a thermal state of temperature $T$, for $T << r^{-1}$, an effective dynamics described by a version of $I_2$ is plausible, while for $T \sim r^{-1}$ the dynamics will be of the more general form (4).

However, we believe that the identification of spacetime foam with a thermal bath involves specific modeling assumptions for the environment, and it is not a necessary conclusion. The reason is the following. In standard QBM, different assumptions about the dynamical properties of the environment (in particular self-dynamics and initial state) lead to very different behavior of the reduced degrees of freedom. The analysis is often simplified by invoking the Born approximation, i.e. assuming that the back-action of the system to the bath is negligible. However, this approximation is not always adequate: for a
Planck scale bath, in particular, it involves very strong assumptions about the physics of spacetime foam. In general, the consideration of back-action leads to stronger correlations between the system and the bath, which are not fully contained in a master equation. For some environments, these correlations are preserved even in the semi-classical regime and they affect significantly the evolution of specific observables. In such cases, open system dynamics do not lead to decoherence.

In particular, a Markovian master equation that leads to decoherence for the reduced degrees of freedom [say, of type (5)] arises only under the assumption of very specific conditions for the bath. A weak coupling assumption is necessary (which typically does not hold in strongly correlated environments), but also an assumption that the quantum correlations in the bath are suitably suppressed. For example, in the special case of a thermal bath of harmonic oscillators, it is only in the high-temperature regime and with an Ohmic distribution of frequency modes that the resulting master equation is Markovian. All other regimes are non-Markovian and decoherence therein is generally less effective. For these reasons, we believe that in an open system analysis of the Planck fluctuations, the thermal behavior of the quantum foam arises only in specific regimes for its internal dynamics.

Finally, we note that at the low energy limit the coupling of matter to gravity is through the stress energy tensor. If we assume that the phenomenological fields $\phi$ reduce to the ones of low energy physics, one would expect that the coupling terms $h_i[\phi]$ should reduce at low energy to components of the stress-energy tensor for matter, irrespective of its specific form near the scale $r$. Here the roles of the metric fluctuations and the matter fields are reversed as compared to stochastic gravity [7], where the matter fields are regarded as the environment of the metric perturbations. In that case, the metric perturbations appear as the argument of the influence functional whereas the kernels involve two-point quantum correlation functions of the stress tensor operator of the matter fields.

5 Further issues and Key concepts

We now conclude with a discussion of two more issues which could be overlooked, or dealt with out of convenience than from principles. They are the universal coupling of gravity and the Markovian approximation. We end with a revisit of the key concepts discussed in this paper, that is, non-unitarity, non-locality and stochasticity, which we believe play a fundamental role in this class of problems.

5.1 Two More Issues

Two common assumptions about the structure of the gravitational degrees of freedom are made in many schemes of quantum gravity, because they simplify

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10 As shown in [39], the evolution law of the reduced density matrix does not in general capture the temporal correlations of the open system: a sufficient condition is that the reduced dynamics is time-homogeneous Markovian—see also [40].
the calculations enough to produce some results. But we have not seen too much physical justification for these assumptions.

The first assumption concerns the nature of open-system dynamics generated by gravitational degrees of freedom, namely that they are Markovian. The second type of assumption involves the \textit{a priori} isolation of specific degrees of freedom that are decohered by gravity and comes in conflict with the universality of the gravitational coupling.

5.1.1 Results under Markovian approximation are not generic

To begin with, open system dynamics contains memories of its past from the backreaction of its environment which has a different set of time scales. Thus it is generically non-Markovian. There are specific conditions related to the appearance of Markovian behavior, e.g., the response time of the bath must be much shorter than the dynamical time-scale of the system. In QBM, the response time is related to the effective cut-off of the excited frequencies for the vacuum, or to the inverse temperature of a thermal bath.

If we consider a graviton bath, there is no physical justification to assume that it lies in a thermal state, because gravitons thermalize very weakly, at least now. Since the coupling to gravity is very weak, the excited frequencies are small, and by all reasonable estimates the corresponding time-scale is very large in comparison to the ones characterizing the motion of the particle—at least as long as we do not consider planet-sized objects. Hence, the separation of time scales goes the opposite direction of that in ordinary Brownian motion.

If one tries to tie decoherence to spacetime foam, i.e. highly non-linear Planck processes, the issue of light-cone fluctuations comes into account. It is not clear how to interpret time there, much less assume that the dynamics have specific properties with respect to time. In fact, the notion of Markov behavior may not make any sense at all in the Planck scale.

5.1.2 Gravity coupling is different from how other fields are coupled

According to GR the gravitational coupling is universal: the channel through which matter interacts with gravitons is always the stress-energy tensor. There is no room for manoeuvre in that issue: for any model to connect to reality it must take this fact into account. One should therefore be sceptical about any ad-hoc assumptions involving isolation of specific degrees of freedom, specification of convenient open-system dynamics etc. As long as one trusts the equivalence principle, universality is a fundamental feature of gravity and this should be mirrored also in the treatment of decoherence. (Even if the equivalence principle is violated, the violations will only be small corrections to the dominant contribution that is encoded in the stress-energy tensor.)

The specific coupling of gravity to matter through the stress-energy tensor $T_{\mu\nu}$ is quite different from that of other fields. Even if the assumption of a Markov dynamics were acceptable, the choice of the Lindblad operators cannot be arbitrary. They must be obtained from the stress-energy tensor. Moreover,
for extended systems it is not necessary that the Lindblad operators commute with energy (as it is sometimes assumed). This may be the case for single isolated particles (for example, see [41]), but when one considers many-particle systems or fields (especially massless ones) there is no reason for this assumption to hold. (There is definitely some energy loss due to the quadrupole moment).

5.2 Key concepts: Nonunitarity, Nonlocality and Stochasticity

Non-unitarity in sub-Planckian vs trans-Planckian physics

1. Decoherence in Quantum Gravity and Non-unitarity in sub-Planckian physics

We commented in Sec. 2.2.3 and Sec. 3 about the issue of using nonunitarity in open systems (dissipative dynamics) as a source or explanation for the violation of symmetries in physics at the sub-Planckian scale. For completeness we add here an old consideration of non-unitarity in quantum gravity stemming from black hole physics.

2. Non-unitarity in Quantum Gravity from black hole evaporation arguments

A usual argument in support of decoherence at low energies is the hypothesis that the dynamics of quantum gravity is non-unitary, which is motivated by the consideration of the black hole evaporation process. We recall here the argument: matter in a pure state collapses and forms a black hole; the black hole slowly evaporates by emitting thermal Hawking radiation; after total evaporation there will be no horizon and the information of the initial state will have been lost: a pure state will have become mixed. Hence, the dynamics of quantum gravity must be non-unitary.

Setting aside the issue whether the non-unitarity of quantum gravity is the only solution to the black-hole evaporation ‘paradox’, we need to point out that the same process also involves violation of certain important conserved quantities of high-energy physics, like baryon number. If the only motivation for assuming non-unitary dynamics is the above, then one would have to expect that the non-unitary quantum gravity processes would be manifested together with baryon number violation. Otherwise, one would have to assume distinct underlying physical mechanisms that cause these phenomena in black hole evaporation. Hence, if decoherence effects at low energy are attributed to the same cause as the ones related to black hole evaporation, one should also expect a violation of baryon number of the same order of magnitude.

Moreover, at low energies there are different (non-Planck scale) processes that may be responsible for gravity-induced decoherence. The graviton vacuum acts as a universal bath for all systems and to some degree this may also be the cause for effective open system dynamics for matter. There is also the suggested Penrose mechanism [30], whose effects can be identified even at the level of Newtonian gravity. It seems to us that these mechanisms will be more efficient in causing decoherence (if they do that) than presumed Planck scale mechanisms, whose effect is more likely to be suppressed at low energy.
Nonlocality in open systems vs in quantum mechanics and general relativity

This is a complex and difficult issue. We can only make a few comments here on different types of nonlocality. Nonlocality in quantum mechanics of the EPR like is probably the best known. It is tied to measurements being of a local nature and measurement instruments of a classical nature. This is taken up in earnest in quantum information and communications. Then there is nonlocality in time in open systems, i.e., memories in the form of nonlocal dissipation and colored noises. Nonlocality in space shows up in a number of current theories about fundamental particles, strings and fields. (For a discussion of nonlocality in gravity and string theory, and black holes see, e.g., [42] and references therein.)

It is sometimes argued that the ‘non-locality’ may arise from the presence of horizons in the spacetime foam, which manifest a ‘non-local’ behavior. Indeed, here is a sense, in which even ordinary GR is ‘non-local’ because of general covariance. We should note, however, that this ‘non-locality’, like that of QM, fully respects causality. Effective theories like the ones suggested in most likely do not: they seem to involve ‘instantaneous’ transmission of information at a scale where the spacetime manifold has already emerged.

One may argue that any effective field theory is non-local. Non-localities at some length scale $r$ larger than Planck length may survive at low energies. However, the non-locality assumption is essentially equivalent to the introduction of an additional (universal) field of mass $r^{-1}$ that interacts locally with the remaining degrees of freedom. One then traces out the contribution of this field: we essentially have a QBM-type of situation with a specific environment. Attributing this effect to decoherence due to gravity is a matter of interpretation: Any (unobservable) field could play the same role. Viewing effective field theory from an open system viewpoint one can easily see that the lower hierarchy will have nonlocal dissipation on in its dynamics driven by colored noises due to its interaction with fields higher in the hierarchy acting as an environment to the low energy sector.

Stochasticity: different appearance at different levels of structure

Any discussion of spacetime foam relates inevitably to the notion of spacetime fluctuations. There are many arguments, ranging from simple dimensional analysis to more complex ones that involve specific approaches to the quantization of gravity, that the description in terms of the spacetime continuum breaks down at the Planck scale and that the concepts we employ in low energy physics

\[11\] “Non-local” is perhaps not the most accurate denotation – “sensitive to global structure” is more appropriate. To make a local measurement of the geometry, one needs to fix a reference frame. To do so, and interpret these results in terms of distant frames of reference it is necessary to know the geometry outside the location of the measurement: this is important especially when the asymptotic flatness approximation cannot be employed. This is very different from theories on a background spacetime, in which the set-up and interpretation of an experiment needs only involve local knowledge.
arise only as approximations. In that sense, the underlying quantum theory will be manifested in the form of strong fluctuations for the effective quantities.

This is how the notion of randomness or stochasticity is often invoked in quantum gravity, notwithstanding our ignorance of what this theory is. Wheeler's spacetime foam started this. Random geometry in the 80's related to conformal field theory has made great advances. If we stick to the definition that quantum gravity is about theories for the microscopic structure of spacetime, then it is plausible to think about a stochastic stage intervening between the micro and the macro, much as hydrodynamic fluctuations from molecular dynamics. In addition to its intrinsic features, one needs to factor in the level of structure one is focussing on and the scope and precision of observation into the system. Let us examine what stochasticity entails.

Fluctuations could carry different meanings in different contexts: deviations from a deterministic evolution, statistical fluctuations in a many-body system, the limits to the definability of specific phenomenological (or emergent) quantities. These notions refer largely to the intrinsic behavior of the system and each of them applies to a different physical circumstance. There is, however, a different use of the word "fluctuation" as it appears, for example, in the context of measurement theory: it refers to all possible external factors that can influence the outcome of an experiment or simply the statistical spread in different trials or samplings. This notion of fluctuation is *extrinsic* to the system under study, and is usually represented by an external noise or random statistical distribution. It is a usual practice in applied probability theory to simulate the effects of external noise with stochastic processes. One may employ general theorems or criteria to select a suitable process that will give good agreement with the observed statistics.

At the Planck scale, many or all of these factors could enter into one's consideration, intrinsic – pertaining to the interaction of the constituents, and extrinsic – pertaining to how the information is extracted by the observer, as in our present consideration, at very low energies or later times. For example, spacetime foam is intrinsically a geometric structure with non-trivial topology. One needs to take that into account *ab initio*. One could posit that at large scales this structure may appear to be smooth and the emergent aggregate has a trivial topology which joins with the manifold structure of classical gravity nicely. Here stochasticity of an extrinsic nature enters, in how a coarse-grained limit would appear to the low energy observer. This latter set of issues are more subtle and just as important as the intrinsic ones, because it enters in all considerations of micro-macro manifestations. (For a discussion of how different coarse-grainings bring forth different structures of varying stability and robustness, see [43].)

One may be tempted to apply these same statistical notion of fluctuations to spacetime foam. Spacetime foam has a structure of its own, independent of how we low energy creatures try to describe it. Its structure and dynamics depend on the physics at the Planck scale, period. We invent easier ways such as fluctuation theory to try to capture its essence, but without due consideration of its microscopic attributes, this could be a self-fulfilling prophecy because the results are either *trivial* (often invoking the central limit theorem) such
as a thermal bath for something stochastic, or circular, because the result is ingrained in the assumptions. When we introduce probability arguments such as assigning a certain type of noise to capture its gross feature, we are introducing extraneous information into its description which not only could be totally off the mark but defeats the purpose of our investigation (An example is using white noise to describe strongly correlated systems – it is doomed to fail from the beginning because it is contrary to its spirit.)

We have warned against randomly invoking statistical fluctuations. Now we add the quantum aspect. Intrinsic fluctuations at the Planck scale are believed to be quantum mechanical in origin. Thus the terminology ‘quantum foam’. However, quantum effects cannot in general be described in terms of stochastic processes. Coherence and nonlocality (e.g., Bell’s theorem) are inherent quantum properties which are lost in a stochastic description. Quantum theory involves ‘interference’ effects which do not allow the definition of a stochastic measure for different aspects of this see, for example [33, 34, 44, 45].

Many proposed schemes involving fluctuations of spacetime conceptually invoke a hybrid picture. That is, while insisting that it is a quantum entity (otherwise it is not about quantum gravity) one treats the foam-like structures as classical stochastic sources. This is in fact the hidden motif in many quantum gravity decoherence schemes [12].

Likewise, we cannot invoke the existence of a separate classical regime. The fluctuations are effectively part of the classical world which describes our low energy physics. A classicalized spacetime foam is very efficient as a decohering agent; a fully quantum one may be not. (This brings back our earlier discussion on the relation of statistical versus quantum.) We see a circular argument here: this classical world comes about from decoherence in quantum gravity but the source of decoherence comes from statistical fluctuations of classical geometries.

To summarize, there is no a priori argument why the spacetime fluctuations should be modeled by a stochastic process, even though in many situations stochasticity can be seen as a limiting sub-case of quantum behavior. In a fundamentally quantum system (like the spacetime foam) it cannot be assumed without a justification in terms of the physics of the system at the appropriate scale, not by the imposition of an external stochastic source.

To end, no discussion of quantum gravity can be complete without bringing forth the issue of time. We postpone it to the end not because it is not important. Time is implicitly assumed in any description of dynamics, deterministic or stochastic, spacetime or matter. It is because we don’t have anything intelligent to say beyond the familiar. We can only express our opinion: We would like to see time and the causal properties it brings forth as emergent from the

\footnote{There are admittedly special regimes in physical system where the distinctively quantum features such as coherence are safely suppressed: the high temperature ohmic bath regime of quantum Brownian motion is an example. In such cases, one may employ classical probability and model the fluctuations through classical stochastic processes. However, one needs to justify this on a case-by-case basis. It is by no means generic. For QBM in a supra-Ohmic bath at low temperatures, quantum coherence persists much longer, as does quantum entanglement between the system and the bath [46].}
interaction of microscopic constituents, together with spacetime endowed with a manifold structure, but not as an extrinsic element outside of the micro-system.

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An example is the time scale or even the arrow of time in dynamics of collective variables, such as hydrodynamics and thermodynamics. They are only indirectly related to the time (without the arrow) in molecular dynamics. It is enlightening to extract these macro features from the micro structures in the various proposals (footnote 1).
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