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Emergent/quantum gravity: macro/micro structures of spacetime

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Abstract. Emergent gravity views spacetime as an entity emergent from a more complete theory of interacting fundamental constituents valid at much finer resolution or higher energies, usually assumed to be above the Planck energy. In this view general relativity is an effective theory valid only at long wavelengths and low energies. We describe the tasks of emergent gravity from any ('top-down') candidate theory for the microscopic structure of spacetime (quantum gravity), namely, identifying the conditions and processes or mechanisms whereby the familiar macroscopic spacetime described by general relativity and matter content described by quantum field theory both emerge with high probability and reasonable robustness. We point out that this task may not be so easy as commonly conjectured (as implied in the 'theory of everything') because there are emergent phenomena which cannot simply be deduced from a given micro-theory. Going in the opposite direction ('bottom-up') is the task of quantum gravity, i.e., finding a theory for the microscopic structure of spacetime, which, in this new view, cannot come from quantizing the metric or connection forms because they are the collective variables which are meaningful only for the macroscopic theory (valid below the Planck energy). This task looks very difficult or almost impossible because it entails reconstructing lost information. We point out that the situation may not be so hopeless if we ask the right questions and have the proper tools for what we want to look for. We suggest pathways to move 'up' (in energy) from the given macroscopic conditions of classical gravity and quantum field theory to the domain closer to the micro-macro interface where spacetime emerged and places to look for clues or tell-tale signs at low energy where one could infer indirectly some salient features of the micro-structure of spacetime.

1. Emergent / Quantum Gravity
Beneath the diversity of theories and proposals [1] there is at least general agreement from all camps on the definition of quantum gravity: It is a theory for the microscopic structure of spacetime. The major disagreement lies in whether such a theory may be obtained by quantizing general relativity (GR), a highly successful theory for the macroscopic structure of spacetime, or we are familiar with. The alternative viewpoint is that GR is a low energy effective theory, and

1 This is a descriptive summary of the main themes presented in invited talks in the following meetings: Workshop “From Quantum to Emergent Gravity: Theory and Phenomenology”, Trieste, Italy, June 11-15, 2007; Peyresq Physics Meeting, June 16-22, 2007; Loops '07 Meeting, Morelia, Mexico, June 25-30, 2007; Workshop on “Condensed Matter meets Gravity”, Lorentz Center, University of Leiden, Holland, August 27-31, 2007; Symposium on Foundations of Physics, University of Maryland, April 24-27, 2008; Workshop on “Emergent Gravity”, MIT, August 25-29, 2008; 4th International Conference DICE2008, Castiglioncello, Italy, September 22-26, 2008.
the metric and connection forms are the collective or hydrodynamic variables of some unknown microscopic theory. These variables will lose their meaning at shorter wavelengths and higher energies. Classical gravity in this view is emergent from quantum gravity (definition above) but not the classical limit or correspondence of a theory obtained by quantizing GR. Taking this view the effort in the past half a century in seeking suitable ways of quantizing this classical theory is considered largely misdirected, in that doing so will not lead to a microscopic theory of spacetime. In the analogy of a crystal made of atoms quantizing the vibrational modes yields phonons, not atoms. Finding the atomic structure of matter does not come from simply quantizing its collective degrees of freedom, but takes a very different path. We will discuss these two routes, namely, finding features in the microscopic structure of spacetime (quantum gravity) from the given macroscopic spacetime described by GR (we shall refer to this as the ‘bottom up’ approach – up here refers to energy scale), and recovering the emergent properties of the familiar macroscopic theory of spacetime from candidate theories of quantum gravity (‘top-down’) by studying the mechanisms and processes of emergence. Thus the title of this essay.

The emphasis and approaches, the goals and methodology of these two routes are very different. To motivate why this new view makes better sense I have given examples before from atomic - condensed matter physics, molecular and hydro-dynamics, quantum fluids and critical phenomena (see below). Instead of finding better ways to quantize GR the new challenge is to infer the microscopic structure from the known macroscopic phenomena, not an easy task as it entails reconstructing lost information. However, this is not a new demand, it has been the task for physicists for centuries. For this purpose, concepts and methods from nonequilibrium statistical mechanics and examples from strongly correlated many-body systems will probably play an essential role hitherto largely ignored in quantum gravity.

In the top-down direction one may think that deducing the macro theory from a known micro theory is easy. This is the attitude behind a ‘theory of everything’. One can invoke familiar procedures such as taking the hydrodynamic or thermodynamics limits in classical physics or using the correspondence principle or applying effective field theory in quantum physics. But as we shall see, this may not be so straightforward as imagined because there are different types of emergence. If we don’t know the underlying constituents we can learn from the characteristics of many emergent theories in the description of nature to understand and formulate the basic rules of emergence. We could then apply the insights gained to describe the conditions and processes or mechanisms for the emergence of spacetime. These are the new tasks for emergent gravity in the ‘top-down’ direction.

1.1. Emergence

The view that gravity is emergent can be reached in a number of ways. My own path of search and discovery is illustrated by the following observations: a) Cosmology as ‘condensed matter’ physics (1988) [2], pointing to the importance of recognizing that processes like cosmological phase transition, structure formation or even ‘birth of the universe’ scenarios are not only governed by the underlying general relativity and quantum field theories, but also follow the rules more often found in condensed matter physics. b) Semiclassical (mean field) and stochastic (fluctuations) gravity as mesoscopic physics (1994) [3], highlighting the key role played by noise and fluctuations in many important processes in cosmology and black hole physics. c) Decoherence and the emergence of classical spacetime from wavefunctions of the universe. We point out that the outcome of decoherence (see, e.g., [4]) and the existence of relatively stable quasi-classical domains resembling our universe depends critically on how coarse-grainings in the environment or histories are chosen and implemented, including considerations of the balance between variability and robustness in the advent of these structures [5]. And, in an open system [6] conceptual framework it is always important to make judicious choices of collective
variables for the best description of macroscopic phenomena at every level of structure and their interactions (see also [7]). d) General relativity as hydrodynamics (1996) [8]; conservation laws aids in the decoherence of long wavelength modes [9, 10] and the appearance of quasiclassical domains, and e) From stochastic gravity to quantum gravity (1999) [11, 12]: How to retrieve quantum coherence information in the gravity sector from metric fluctuations induced by (higher order) correlations in the quantum field f) Kinetic theory approach to quantum gravity (2002) [13], via a new Einstein-Boltzmann hierarchy of equations relating the correlations in the matter to that in the gravity sector, with the Einstein equation as the lowest rung of this hierarchy. g) Spacetime as condensate (2005) [14]: Why it is not total nonsense to view the ultracold spacetime today as a quantum entity? What benefits can one derive from taking this view? What can we learn about quantum gravity from Bose-Einstein condensate (BEC)? The overarching goal is to find the microscopic constituents and their interactions from the collective dynamics of the macroscopic variables. (The last three themes will be summarily described in Sec. 4 below.)

1.1.1. Emergent Theories Emerging  In the last three years this viewpoint is increasingly embraced by researchers from the string theory [15, 16], particle and nuclear physics [17, 18, 19, 20] communities in the light of string-gravity-gauge dualities [21, 22, 23, 16], and pursued by an increasing number of young researchers in the quantum gravity community as witnessed in the talks at the present meeting. Two major proponents of this view before it became popular are Volovik [24] and Wen [25].

Emergence is not a strange new concept. Originated in biology and sociology but also prevalent in condensed matter physics, emergence phenomena are more commonly encountered in nature than constructs deduced from the reductionist paradigm based on linear logical inductions. An extreme version of the latter is the theory of everything (TOE) which says that if we knew all the elementary constituents and their interactions we could deduce the structure and dynamics of everything in the physical world. In reality, there are new emergent rules or laws governing the organization and dynamics of the basic constituents and new modes of interaction at every level of structure. This counterpoint is cannonized in Anderson’s 1971 outcry (at a time when elementary particle physics and its philosophy seemed to overshadow other subfields): “More is different”. Nonetheless it is well-known that progress in particle physics required the injection of ideas from condensed matter physics, symmetry breaking being a well-acknowledged example.

In truth these two aspects are always present in our quest to comprehend the physical world: Something assumed to be ‘elementary’ at a lower energy or with a coarser resolution at one time will later be found to be a composite at a higher energy or under a finer resolution. Though their emphasis and approaches are very different these two paradigms are equally important and functional in the development of our conception and understanding of nature. The degree of difficulty may vary. Constructing the macroscopic structure and dynamics from known microscopic constituents is often easier, such as getting hydrodynamics from molecular dynamics. Going the other way, i.e., deducing molecular features from hydrodynamics, is more difficult. For spacetime structures, the former is the task of emergent gravity, the latter is the goal of quantum gravity. Note, however, that even if we have the precise knowledge of the fundamental theory, seeing the emergent behavior at lower energies is not as straightforward as often presumed.

1.1.2. Deducible and non-deducible Emergence  To understand the characteristics of emergent theories, and the rules of emergence one should distinguish in the start those which can be logically or methodically deduced from a microscopic theory and those which cannot, at least not without the benefit of knowing certain attributes of the macroscopic theory. Hydrodynamics from molecular dynamics or nuclear physics from QCD are examples of the former and quantum
Hall effect is often quoted as an example of the latter: One can construct useful theories only after such an effect was observed, but not (or highly unlikely) before. One can appreciate how nontrivial this task is by looking at the challenges of string theory or loop quantum gravity in reproducing the physical world of low energy phenomena.

1.2. Emergent Gravity: Macro from Micro
If spacetime is an emergent entity then its large scale structures should be deductible from the underlying constituents and their interactions, like a crystal structure or a condensate constructed from atoms. Collective (macro) features such as elasticity (in gravity, metric elasticity [26]) associated with such a (micro) structure can lend themselves to a nice geometric depiction but these features will cease to make sense at scales close to or smaller than an atom. In these cases, the task of emergent gravity is similar to the derivation of hydrodynamic equations of motion and thermodynamic laws from molecular dynamics.

1.2.1. Top-down: Micro to Macro  Spacetime is the resultant large scale structure formed by the interaction of sub-level constituent particles. Even when the micro constituents are believed to be known - strings [27], loops [28], spin-foams [29], simplicials [30] - one still needs to show the macro limit exists and how it is attained from their interactions. It is a necessary criterion any candidate theory of quantum gravity needs to meet. For deductive emergent behavior, path could be tortuous but in principle attainable.

As is known from many examples of condensed matter physics, it is often a nontrivial task to deduce mesoscopic behavior from micro-dynamics: one usually encounters nonlinear or even nonlocal interactions in strongly correlated systems, and needs some ingenuity to identify collective variables at successive levels of structure to make the analysis simpler. Using the molecular to hydro dynamics example, this intermediate scale corresponds to finding the appropriate kinetic variables and the associated dynamics (e.g., use of maximal entropy laws at successive stages of complexity).

In addition to nonlinearity, nonlocal properties can emerge from every level of structure and dynamics. This makes the transition to macroscopic limit much more involved. It requires not just a linear progression of deductions from one single level, but the injection of new ideas at many levels of construction.

The above assumed that we are dealing with deductive-predictive theories. But we should be mindful that this macro manifestation could be via a nondeductive emergent behavior from the micro structures, in which case even micro- to macro-, sub- to super- structures would not be easy, some cases could even be impossible.

1.2.2. Emergence from existing theories of quantum gravity  We can use some major candidate theories of quantum gravity (micro structure of spacetime) to examine the key issues listed above. I see the causal dynamical triangulation program pursued by Ambjorn and Loll et al (see [30] and earlier references therein) as the more intuitive and operationally accessible option. Regge’s original conception (of Regge Calculus and Regge-Ponsano calculus) is to reduce the essential ingredients of spacetime to its rudimentary constructs, i.e., the simplices, such as having the curvature of spacetime residing on the vertices. One can see how piecing together these simplices give rise to different spacetime structures, many of them have fractal dimensions and few grow to the size of our universe. This scheme is useful to see how the macroscopic structure emerges, a welcoming recent result is the 4-dimensionality of our spacetime. However, since the simplices are chosen to contain the key features of the macroscopic spacetime (e.g., curvature), they are
good building blocks \(^2\) yet may not contain readily decipherable information about the true degrees of freedom in the microscopic substructure (like strings or loops, if they are proven so). Spin-foam theory \([29]\) is aesthetically appealing and rich in mathematical structure. But I still cannot see how a macro variable such as the connection form when quantized would turn into a micro-variable (such as the basic differences between a phonon and an atom). As for string theory, the AdS/CFT correspondence \([21, 22]\) is often cited as an example of emergent gravity. This to me is not a real answer. One needs to show that both gauge theory and gravity emerge from the same more basic theory, presumably the M theory, but that is a hope short of a proof \([31]\). For recent developments of these theories see \([32]\). For other proposals, especially the causal set theory, see \([33]\) and \([1]\). To claim emergence each of the candidate theories of microscopic structure of spacetime needs to identify at least the principal mechanisms responsible for generating the macroscopic spacetime with distinct identifiable properties. Gauge-gravity duality relation \([16]\) has been applied to many branches of physics from gauge fluid viscosity in RHIC \([18, 34]\) to quantum phase transition in condensed matter (in terms of dyonic black holes ) \([35]\) and superconductivity \([36]\) with surprising results. I will have a short comment on the implications of these recent developments in the last section.

1.3. Quest for Quantum Gravity: A theory for the microscopic structures of spacetime

Compared to working out the macroscopic limits of a known microscopic theory, going the reverse way is always more difficult because of the missing information. One has only the macroscopic features at hand which are often grossly coarse-grained from the microscopic. From the degraded information one hopes to catch a glimpse of the micro structure. The task is daunting. But this is how physics has progressed through the centuries.

1.3.1. Bottom-up: Macro to Micro To proceed from bottom up we think that focusing on two key elements may help:

1) **Topological structures**, because they are more resilient to evolutionary or environmental changes. For examples see the works of Volovik \([24]\) (He\(^3\) analog, Fermi surface) and Wen \([25]\) (string-nets, emergent light and fermions; see also \([37]\)).

2) **Noise-fluctuations.** Fluctuations could reveal some sub-structural contents and behavior, such as deducing molecular interaction from hydrodynamical fluctuations, or finding the universality classes of systems from the critical exponents in a phase transition.

1.3.2. **Common features of collective states built from different constituents** In the depiction of the structure and properties of matter there are two almost orthogonal perspectives: One is by way of its constituents and interactions, the other according to its collective behavior. If we regard this chain of QED - QCD - GUT - QG as a vertical progression depicting the hierarchy of basic constituents, there is also a horizontal progression in terms of the stochastic - statistical - kinetic - thermodynamic/hydrodynamic depiction of the collective states. There exist similarities between matters in the same collective state (e.g., hydrodynamics) but made from different constituents. Macroscopic behavior of electron plasmas are similar in many respects to the quark-gluon plasma. Indeed, one talks about magneto-hydrodynamics from Maxwell’s theory as well as magneto-chromo-hydrodynamics from QCD. In this long wavelength, collision-dominated regime, their behavior can both be adequately depicted by the laws of hydrodynamics. The underlying micro-theories are different, but the hydrodynamic behavior of these constituents are similar. The macroscopic, hydrodynamic equations and their conservation laws are all based

\(^2\) It is like the fine powders ground from a diamond, even though much smaller in scale, each speckle still possesses the crystal structure of the macroscopic object. Without a drastic increase in resolution it cannot reveal the underlying atomic structure.
on the dynamical and conservation laws of microphysics (e.g., Newtonian mechanics) but now in terms of a new set of collective (hydrodynamic) variables, this new theory of the macroscopic behavior emerges with a simple yet distinct life of its own.

2. Nonlocality and Stochasticity in quantum and statistical mechanics
With increased attention to quantum information in recent years one hears more about ‘nonlocality’ in quantum mechanics, referring to the issues raised in EPR [38] and Bell’s inequalities. Even though predictable correlation exists between spatially-separated quantum states and quantum entanglement can exist between objects outside each other’s light-cones [39], quantum mechanics is unambiguously local [40], as is quantum field theory. Nonlocality in statistical mechanical is an older subject, perhaps less conspicuous than that which is mis-conjured in quantum mechanics. We will start with a simple observation which illustrates two main themes of this exposition: The first theme is that locality or nonlocality depends sensitively on the level of structure and dynamics it pertains to or the degree of precision in one’s measurements. Micro-locality in general has nothing to do with macro-locality. The second theme is that nonlocality (correlations) and stochasticity (fluctuations) often appear together, and one could use noise and fluctuations to probe into the nonlocality of structures and dynamics.

2.1. Collective Variables constructed from constituent variables
At the risk of appearing naïve and pedantic, I’ll give two household examples to illustrate this point. Perhaps the first collective behavior we learned in physics is wave phenomena. There, many individual particles each undergoing a simple harmonic motion in a well-coordinated manner give rise to waves propagating in the medium of these particles. Already here we see the relation between the micro dynamics and the macro behavior. The rules of wave mechanics is different from that of the constituent particles. The waves obey a wave equation while the molecules obey Newton’s second law. Surely one can deduce the macro behavior from the micro dynamics but the reverse relation is many to one: transverse mechanical and electromagnetic waves or longitudinal sound waves share the same waves mechanics description. One feature to observe relevant to our theme is the relation of locality to nonlocality. Waves can propagate from one point in space to another (snapshot graph) which is correlated with the evolution in time at any one point in space (history graph). However each individual particle only undergoes a simple harmonic motion around its point of origin and there is nothing nonlocal (used here in a non-technical sense) about it. Another feature to observe is that quantizing the wave degrees of freedom (sound modes becomes phonon) neither yields the dynamics of the constituent particles nor reveal any microscopic information about the molecules. The conception of wave phenomena simply ceases to exist and the theoretical constructs of wave mechanics irrelevant at the microscopic level. For the description of atomic motion we need to use the quantum wave functions for the atom but that is a far cry from the mechanical waves.

As another commonly encountered example, consider two depictions of gas or fluid dynamics, one at the level of molecular dynamics, the other of hydrodynamics. A molecule will collide with many others at very high speed for a long time before diffusing a short distance. That molecule’s locality in a collective entity as a gas or fluid element is very different from that induced by following its own history at the micro scale where multiple collisions take place along the trajectory. Other molecules arriving at the same time in this gas or fluid element bear no locality relation with this particular molecule before or after the instant of collision (assuming a short-ranged or contact potential). The smoothness and continuity of the fluid elements’

3 We thus advise against the use of the word ‘nonlocal’ in this context because it leads to unnecessary confusion.
movement described by the Euler equation as reported by a macroscopic observer belie the stochastic nature of molecular dynamics \(^4\).

2.2. Locality is specific to the choice of observables
These two elementary examples show that the notion of locality is very specific to the observables chosen for the description of a particular physical phenomenon of interest (e.g., molecular dynamics or wave propagation). Nonlocality often appears when one tries to translate physics expressed in one set of collective variables suitable for one level of structure to another set.

2.3. Nonlocality and Stochasticity in statistical mechanics
I shall comment here only on temporal nonlocality, i.e., processes with memory (non-Markov). This is common in open system dynamics (see, e.g., [42] and references therein). Nonlocality in space or spacetime is more involved. An example of how this issue is addressed can be found in the causal sets approach of Sorkin [43]. For two interacting subsystems the two ordinary differential equations governing each subsystem can be written as an integro-differential equation governing one such subsystem, thus rendering its dynamics non-Markovian, with the memory of the other subsystem’s dynamics carried by the non-local kernels. All this is happening in a closed system except now one has shifted the attention to one of its subsystems. Should the other subsystem possess a much greater number of degrees of freedom (called environment) and are coarse-grained in some specified way, the nonlocal kernels are then responsible for the appearance of dissipation and noise. It is the act of coarse-graining which renders open this particular subsystem of interest. (For a general discussion, see, e.g., [44, 45].)

Nonlocality is linked to stochasticity in nonequilibrium dynamics. Nonlocal dissipation and nonlocal fluctuations (colored noise) arise naturally in the open-system dynamics of Langevin and the effectively-open system dynamics of Boltzmann, or the dynamics of correlation hierarchy. These features originate from the choice of coarse-graining measures and backreaction processes. NonMarkovian dynamics is an example of nonlocality in time, meaning that prior history or past memories enter in the determination of future time development.

Another angle towards nonlocality and stochasticity is correlation. Correlation functions measure nonlocality and can be related to fluctuations. (e.g., one form of fluctuation-dissipation theorem can be phrased in terms of correlations). Strongly interacting and correlated systems offer an excellent arena to see how these two aspects are played out: locality at one level versus nonlocality at a different level, and how coarse-graining leads to stochasticity. Many condensed matter physics models offer these insights [46].

3. Nonlocality and Stochasticity in Quantum Gravity
There is probably more confusion in our understanding and use of the notion of nonlocality in quantum gravity. An example in loop quantum gravity is how to relate a weave state to spacetime. This was addressed in a classic paper by Ashtekar, Rovelli and Smolin [47]: A weave state is a kinematical state designed to match a given slowly varying classical spatial metric. The concept of quantum threads (say, from a spin-network) weaved into a fabric (manifold) of classical spacetime already tacitly assumes (wrongly, as is now known) a particular kind of micro to macro transition, where there is a simple correspondence or even equivalence between locality at the micro and the macro levels. An improvement over the original suggestion was the so-called nonlocal weave states which leave marks on the fabrics of spacetime [48]. Bombelli, Corichi and Winkler [49] use combinatorial methods to turn random weave (micro) states into (macro) states of spacetime manifold. But this remains an oversimplification, as the low-brow example of emergence from molecular to hydro- dynamics has illustrated. Markopoulou and

\(^4\) Quantum correlations and entanglement have added layers of complexity [41].
Smolin [50] recently pointed out that most weave states, including Bombelli et al’s, assume that these weave states all satisfy an unstated condition of locality (edges connect two nodes of Planck length metric distance), and that there are plenty of weave states which do not satisfy this condition. The question is: How does one weave from these nonlocal micro states a fabric (manifold) with the familiar macroscopic locality? From our view, (non) locality at one level may have little to do with (non) locality at other levels.

To unravel these two aspects in quantum gravity one can first try to understand how these issues play out in known physical models, then apply to spacetime, incorporating its special features such as diffeomorphism invariance (which, in the emergent gravity view, is associated only with the emergence of spacetime manifold and is thus no longer an issue at the deeper level of its sub-structures). Many symmetries we are familiar with associated with the macroscopic spacetime will become meaningless at the microscopic level (quantum gravity). One should also use the various candidate theories of quantum gravity, such as strings, loops, spin-nets, spin foams and causal sets, to examine the sense of locality at different levels of structure, and see how they could be related to locality in our macroscopic spacetime.

3.1. Metric Fluctuations and Stochastic Gravity

Keeping gravity classical but allowing for the averaged value of quantum matter field as source constitutes the theory of semiclassical gravity. Including the consideration of the fluctuations of quantum matter fields as source constitutes the theory of stochastic semiclassical gravity (see [12] for a review). Metric fluctuations, both intrinsic (in the gravitational field) and induced (by quantum matter fields) are the central figures in this relatively new theory. With a wider acceptance of the view that gravity is emergent and that quantizing general relativity does not yield a theory of the microscopic structure of spacetime, stochastic gravity’s theoretical significance and practical applications are better recognized and utilized. For instance, the influence of induced metric fluctuations on cosmological structure formation is not easily considered in the traditional methods [51]. The Einstein-Langevin (E-L) equation has also been applied recently to the analysis of backreaction of Hawking radiation and metric fluctuations near the event horizon of an evaporating black hole [52].

Stochastic gravity can be derived in the quantum open system conceptual framework [12]. As with all open systems nonlocality and stochasticity in their dynamics are innate features. They appear in the nonlocal dissipation and colored noise kernels which give rise to history-dependent and stochastic trajectories. It is anticipated that these features are prevalent as one traverses any two adjacent levels of structure in any of the macro, meso and micro domains.

3.2. Stochastic in relation to Semiclassical and Quantum Gravity

Intuitively, the difference between quantum and semiclassical gravity is that the latter loses all the coherence in the quantum gravity sector. Stochastic gravity improves on semiclassical gravity in that partial information related to the coherence in the gravity sector is preserved. This is reflected in the backreaction from the quantum fields and manifests as induced metric fluctuations. The noise terms carry quantum information absent in semiclassical gravity. The coherence in gravity is related to the coherence in the matter field, as a complete quantum description should be given by a coherent wave function of the combined matter and gravity sectors. Since the degree of coherence can be measured in terms of correlations the strategy of this approach is to examine the higher correlations of the matter field, starting with the two point function of the energy momentum tensor in order to probe into the partial quantum coherence remaining in the gravity sector. Note that in retrieving this quantum coherence of the gravity sector, we do not pretend to be constructing a microscopic theory of spacetime. As long as one uses metric or connection as a dynamical variable, the theory remains macroscopic. For our purpose here metric fluctuations can provide precious information about how spacetime behaves.
at the interface (phase transition or cross-over) between the micro and macro domains, not unlike fluctuations (in, e.g., heat capacity at constant volume) near a critical point contains valuable information about the universality class of the system undergoing such a phase transition.

If we view classical gravity as an effective theory, i.e., the metric or connection functions as collective variables of some fundamental constituents which make up spacetime in the large and general relativity as the hydrodynamic limit, we can also ask if there is a mid-way weighing station like kinetic theory from molecular dynamics, from quantum micro-dynamics to classical hydrodynamics. This transition involves both the micro to macro transition and the quantum to classical transition, characteristics of the mesoscopic regime. Stochastic gravity is of the nature of a mesoscopic theory: the noise in the Einstein-Langevin (E-L) equation contains the 4th order correlation of the quantum field (or gravitons when considered as matter source). One can work out higher correlation functions of the quantum matter field and obtain from a generalized E-L equation the higher order induced metric fluctuations.

In our research program several routes have been proposed to move from the bottom up, that is, starting from the well-established foundation of semiclassical gravity, adding the considerations of fluctuations and trying to inch our way towards the macro-micro interface from below, with the hope of unraveling some microscopic features of spacetime. We describe a few below: a) a kinetic theory approach to quantum gravity, b) universal 'metric conductance' fluctuations; and c) spacetime as condensate⁵.

4. Routes from bottom up

4.1. Spacetime Correlations and Fluctuations: Einstein-Boltzmann hierarchy of equations

To better appreciate the relation of this mesoscopic regime between the macro and the micro, we need to explain the representation of kinetic theory in terms of correlation dynamics. In [53] Calzetta and I introduced the master effective action for an interacting quantum field where one can obtain the hierarchy of Schwinger-Dyson equations. From this one can derive the kinetic equations [54] and an expression for the correlation noise arising from the slaving of the higher correlation functions. The resulting equation is known as the stochastic Boltzmann equation. This kinetic theory structure emerging from an interacting quantum field illustrates how the macro (hydro) dynamics is linked to the micro (molecular) dynamics. The minor difference is that there are two distinct sectors, classical gravity and quantum matter field. This enables one to adopt an open system approach in treating the relation between them, such as the Einstein-Langevin equation, while using the Boltzmann-BGKY hierarchy to systemize the quantum matter field sector. The linkage between these two sectors exists at every level of structure and dynamics, the lowest being the semiclassical Einstein equation which involves only the expectation value of the stress energy tensor. The next level up is stochastic gravity which involves the two point function of the stress-energy tensor. The hierarchy of equations governing the higher order induced metric fluctuations from the higher correlations of the stress-energy tensor of the quantum field is what I called the Einstein-Boltzmann hierarchy of equations which provides a staircase towards the micro-structure in this kinetic theory approach to quantum gravity⁶.

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⁵ The following section summarizes the ideas described in Sec 1.1. Readers familiar with them can skip over to the next section.

⁶ This is not the Einstein-Boltzmann equation in classical general relativity and kinetic theory – it frames the classical matter in the Boltzmann style as source of the Einstein equation. Our Boltzmann-Einstein hierarchy of equation refers to the layers of structure in the gravity sector. 'Boltzmann' is to show the kinetic theory nature, and 'Einstein' to show its spacetime structure, albeit these two giants provide their respective theories only for the lowest correlation order and its dynamics: in distribution function of spacetime and in geometro-hydrodynamics respectively.
4.2. Strongly correlated systems: Spacetime Conductance Fluctuations

In earlier expositions of this subject matter, I proposed to view semiclassical and stochastic gravity as mesoscopic physics [3]. Viewing the issues of correlations and quantum coherence in the light of mesoscopic physics, the stress-energy two point function on the right hand side of the Einstein-Langevin equation is analogous to conductance which is given by the current-current two point function. What this means is that we are actually calculating the transport function of (the matter particles as depicted by) the quantum fields. Following Einstein’s keen observation that spacetime dynamics is determined by (while also dictates) the matter (energy density), we expect that the transport function represented by the current correlation in the matter (fluctuations of the energy density) may also have some physical significance or even (perhaps less refined) a geometric representation at a higher energy scale (akin to the pseudo-Riemannian spacetime of GR at the low energy limit).

This is consistent with viewing general relativity as hydrodynamics: Conductivity, viscosity and other transport functions are hydrodynamic quantities. For many practical purposes we don’t need to know the details of the fundamental constituents or their interactions to establish an adequate depiction of the low or medium energy physics, but can model them with semi-phenomenological concepts (like mean free path and collisional cross sections) 7. When the interaction among the constituents gets stronger, effects associated with the higher correlation functions of the system begin to show up. Studies in strongly correlated systems are revealing in these regards [55, 56, 57]. For example, fluctuations in the conductance – from the 4 point function of the current – carry important information such as the sample specific signature and universality. Although we are not quite in a position, technically speaking, to calculate the energy momentum 4 point function, thinking about the problem in this way may open up many interesting conceptual possibilities, e.g., what does universal conductance fluctuations mean for spacetime and its underlying constituents? (In the same vein, I think studies of nonperturbative solutions of gravitational wave scattering [58] will also reveal interesting information about the underlying structure of spacetime beyond the hydrodynamic regime.) Thus, viewed in the light of mesoscopic physics, with stochastic gravity we may probe into the higher correlations of quantum matter and the associated excitations of the collective modes in geometro-hydrodynamics and the kinetic theory of spacetime micro-dynamics.

4.3. Spacetime Condensate: the Universe as the Ultimate Macroscopic Quantum Phenomenon

Working within this novel conceptual framework of geometro-hydrodynamics, we suggest a new way to look at the nature of spacetime inspired by Bose-Einstein condensate (BEC) physics. We ask the question whether spacetime could be considered a condensate, a low temperature quantum entity, and if so, its immediate implications. This is an utterly unconventional thought because the universe below the Planck energy is still at a very high temperature, and even more radically, it implies macroscopic quantum phenomena observed in today’s universe. The challenge here is to see if such a view could make outstanding issues like the dark energy easier to understand. Note also that unlike BEC in atomic physics we want to describe its salient features even without the knowledge of what the ‘atom of spacetime’ is. Please refer to [14] for background discussions such as the meaning of a condensate in different context, how far this idea can sustain, its advantages and pitfalls, and its implications on the basic tenets of physics and existing programs of quantum gravity. See also [59]

4.3.1. Unconventional view 1: All sub-Planckian physics are low temperature physics We believe that the physical laws governing today’s universe are valid all the way back to the GUT

7 In the mesoscopic domain the simplest kinetic model of transport using these concepts are no longer accurate. One needs to work with system-environment models and keep the phase information of the collective electron wave functions, in so doing extending the Buttiker-Landauer formula.
(grand unification theory) and the Planck epochs, even at the Planck temperature $T_{PI} = 10^{32} K$. Since the spacetime structure is supposed to hold for all sub-Planckian eras, if we consider spacetime as a condensate today, it should have remained so from the Planck era onwards.

In fact, one should push this concept to its limit and come to the conclusion that all known physics today, as long as a smooth manifold structure remains valid for spacetime, the arena where all physical processes take place, are low-temperature physics. Spacetime condensate began to take shape at below the Planckian temperature $T_{PI}$, according to our current understanding of the physical laws. In this sense spacetime physics as we know it is low temperature hydrodynamics, and, in particular, today we are dealing with ultra-low temperature physics, similar to superfluids and BECs.

The metric or connection forms are hydrodynamic variables, and most macroscopic gravitational phenomena can be explained as collective modes and their excitations (of the underlying micro-theory): from gravitational waves in the weak regime as perturbations, to black holes in the strong regime as solitons (nonperturbative solutions). There may even be analogs of turbulence effects in geometro-hydrodynamics, possibly predictable and detectable when our numerical techniques and observational skills are improved.

4.3.2. Unconventional view 2: Spacetime is, after all, a quantum entity An even more severe difficulty in viewing spacetime as a condensate is to recognize and identify the quantum features in spacetime as it exists today, not at the Planck time. The conventional view holds that spacetime is classical below the Planck energy, but quantum above. That was the rationale for seeking a quantum version of general relativity, beginning with quantizing the metric function and the connection forms. Our view is that the universe is fundamentally a quantum phenomena, but at the mean field level the many body wave functions (of the micro-constituents, or the ‘atoms’ of spacetime) which we use to describe its large scale behavior (order parameter field) obey a classical-like equation, similar to the Gross-Pitaevskiy equation in BEC, which has proven to be surprisingly successful in capturing the large scale collective dynamics of BEC [60], until quantum fluctuations and strong correlation effects enter into the picture [61].

Could it be that the Einstein equation depicting the collective behavior of the spacetime quantum fluid has the same footing as a Gross-Pitaevskiy equation for BEC? The deeper layer of structure is ostensibly quantum, it is only at the mean field level that the many-body wave function is amenable to a classical description $^9$.

4.3.3. The Universe as a Macroscopic Quantum Phenomenon The obvious challenge is, if the universe is intrinsically quantum and coherent, where can one expect to see the quantum coherence phenomena of spacetime? Here again we look to analogs in BEC dynamics for inspiration, and there are a few useful ones, such as particle production in the collapse of a BEC (called bosenova in the experiment of Donley et al [62]). One obvious phenomenon staring at our face is the vacuum energy of the spacetime condensate, because if spacetime is a quantum entity, vacuum energy density exists unabated for our present day late universe, whereas its origin is somewhat mysterious for a classical spacetime in the conventional view. It is highly desirable to explore the implications of this view on the cosmological constant and coincidence problems.

One encouraging fact is that in most condensed matter systems the collective excitations have energies of the same order of magnitude as the ground state, rarely with a severe discrepancy as in particle physics scales (the gauge hierarchy problem). The observed fact that the dark energy is 0.7 of the total budget and not $10^{-120}$ came as a big surprise. But not so much so

$^9$ In truth, for any quantum system which has bilinear coupling with its environment or is itself Gaussian exact (or if one is satisfied with a Gaussian approximation description) the equations of motion for the expectation values of the quantum observables have the same form as its classical counterpart. The Ehrenfest theorem interwoven between the quantum and the classical is one common example under these conditions.
from the viewpoint of spacetime as a condensate. The vacuum energy of the condensate and its excitations are similar in magnitude. One can investigate this issue from this perspective, using well-studied models of superconductivity and superfluidity to explore the implications of viewing spacetime as a condensate [63].

5. Quantum + Gravity: Look harder at low energy physics

Rather than forcing the union of quantum mechanics (QM) and general relativity (GR), such as is attempted to quantize GR, to try to get the microscopic structures of spacetime, it pays to explore more thoroughly the intersection of these two theories at today’s low energy in order to find out the true nature of their conflicts and their implied meanings. Perhaps both theories lose their meaning and applicability at a higher energy. In the emergent gravity view, GR is an effective theory which is no longer valid at the Planck energy. There are also speculations that quantum mechanics is also an emergent theory which fails at a deeper level where nonlocality and stochasticity appear [64, 65, 66, 67, 68]. Our improved understanding of basic issues like quantum measurement brings forth new issues in this arena such as the effect of gravity in quantum decoherence [69] and collective effects in macroscopic quantum systems [70]. Penrose has made challenging theoretical claims [71] and proposed interesting experimental tests [72] in this realm. We share the same view in the underlying assumption of Penrose’s proposal, namely, low energy physics could be useful in our search for a new theory which encompasses both GR and QM as limiting cases of it. We mention two aspects worthy of further probing and deliberations.

5.1. Quantum and gravitational low energy phenomena

To explore the interplay of quantum mechanics or field theory and gravitational phenomena at today’s energy, one could start with the simplest set up of the interaction between a particle (with charge and mass) or atom (entity with internal degrees of freedom) with a gravitational field under the influence of a quantum field, including finer considerations of quantum correlation, entanglement and decoherence. This is necessary for designing laboratory experiments for high precision tests of quantum effects in gravitation and cosmology. It can also address basic issues of quantum measurement. These preparatory probes are useful for finding anomalies or ‘cracks’ in the existing theoretical structure which is the starting point of the ‘bottom-up’ approach to QG.

In a quantum field a classical particle will not move along a geodesic [73] because of the influence of quantum fluctuations. We know how these effects show up as stochastic forces acting on its mean trajectory, i.e., via the Langevin equation [74, 75]. Particle motion is affected both by the intrinsic and induced (called active and passive by Ford [76]) fluctuations of the quantum field. Studying the effects of an atom in a gravitational field (see, e.g., [77]) and the effects of a gravitational field on atom-optical or quantum fluid devices (e.g., SQUID) can also provide some channel to explore subtle effects hitherto unknown arising from the interplay between quantum systems and a classical gravitational field. One could tap into the capabilities of today’s atomic-optical and superconductor / superfluid experiments which have reached a high precision level for these purposes (many experimental schemes have been proposed, see, e.g. [78, 79]).

From a theoretical viewpoint many of the systems of relevance to our goals are at the mesoscopic scale. In order to check against the results from prospective precision experiments our current understanding of the interaction of mesoscopic quantum systems with gravity need be improved [80]. The interaction of strongly correlated quantum systems with coherent classical gravitational fields using, e.g., the Schwinger-Keldysh effective action method for quantum transport [81]), real time description of macroscopic and dissipative quantum tunneling [82]
(which can be applied to ‘Birth’ of the Universe scenarios), and analysis of the properties of the stochastic Schrödinger equation in the presence of gravity are just a few sample problems.

Coherence (even for classical fields) from a much extended space and time range can affect the local observations. Thus all nonlocal and memory effects should be properly accounted for. (One sees this in gravitational radiation reaction). The best way to ensure these effects are not lost is to do a quantum field calculation from the beginning and only at the end take the non-relativistic quantum limits to compare the results with experiments. The physics we are probing is very delicate, thus prompting this caution.

These land-based or space experiments in Earth’s vicinity are designed to test the interaction of quantum probes (atom-optical or superconductivity devices) with weak gravity, but to really get to the heart of the problem, one needs to probe quantum effects in strong gravitational fields, such as near a black hole or in the early universe. Obviously it is not easy to do experiments near a real black hole but analog models may offer some valuable insights [84]. By contrast, observations in cosmology can provide bounds on quantum processes in the early universe, at the GUT or even the Planck scales. Investigations like this could provide some hints on how macro features may emerge from the underlying constituents. Again we do not want to imply that such studies whose backdrop assumes a manifold structure whose dynamics is described by GR will give us directly the microscopic structure, but they may reveal some traits of it at the interface. A more direct link is provided by the duality between strong gravity (black holes) and quantum gauge fields [16] in a holographic view, which we mention below with a comment.

5.2. Implications of results from gauge-gravity duality

In recent years the gauge-gravity duality relation has been expounded in application to a variety of sub-fields of physics with astounding results. Examples are viscosity of strongly interacting gauge fluids obtained from gravitational perturbations from black holes in an AdS space [17, 18], gluon-gluon scattering and deconfinement transition in QCD [85, 86] related to Hawking-Page transition [87] in hot Schwarzschild-AdS space, quantum phase transition [35] and superconductivity [36].

What do these unexpected connections suggest, and what essential elements enter into the duality? AdS-CFT is built on the holography principle [23], i.e., physics in a classical AdS space in the bulk is related to conformal field theory (CFT) on the boundary. Thus one could get information on strongly interacting quantum gauge fields (such as viscosity in a strongly interacting fluid or deconfinement transition in QCD) by examining the corresponding gravity effects in AdS space (such as quasi-normal modes of black holes and the Hawking-Page transition, respectively).

A very attractive aspect of this approach as I see it is that both parties entering in this duality relation, quantum gauge field and classical gravitational field, are familiar objects in ordinary low energy physics. Although this duality was first discovered in the context of string theory one does not need to invoke any progenitor theory at the Planck scale. This is an example of what we mean by looking more closely at the relations between quantum (here the strongly interacting gauge fields) and gravity (here the black holes, which are non-perturbative solutions in GR) at today’s low energy.

Another observation I can make related to the main theme discussed here is that in all the applications of this duality principle we have seen so far only classical gravity enters, not quantum gravity. The only entity in gravity which is quantized is the linear gravitational perturbations (gravitons, or spin-2 particles, acting in the same role as phonons in solids). There is no need or place for quantum geometry in this relation which governs macroscopic phenomena between quantum gauge fields and classical gravity.
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