

Article

Long-Range Quantum Gravity

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Abstract: It is a tantalising possibility that quantum gravity (QG) states remaining coherent at astrophysical, galactic and cosmological scales could exist and that they could play a crucial role in understanding macroscopic gravitational effects. We explore, using only general principles of General Relativity, quantum and statistical mechanics, the possibility of using long-range QG states to describe black holes. In particular, we discuss in a critical way the interplay between various aspects of long-range quantum gravity, such as the holographic bound, classical and quantum criticality and the recently proposed quantum thermal generalisation of Einstein's equivalence principle. We also show how black hole thermodynamics can be easily explained in this framework.

Keywords: quantum gravity; black hole thermodynamics; equivalence principle

1. Introduction

Conventional wisdom asserts that quantum gravity effects may be relevant only at scales of the order of the Planck length $l_p = \sqrt{\hbar G/c^3} \sim 10^{-33}$ cm. This simple result comes upon equating the Compton length associated with a self-gravitating object with its gravitational size, its Schwarzschild radius, R_s . On one hand, this would imply that only Planck-size black holes have an intrinsic quantum gravity nature. Conversely, astrophysical black holes, originated from the collapse of stars which, in turn, have proved their existence through gravitational waves detection [1–7] and from the first photo of their light ring [8], can be described by means of classical gravity only. On the other hand, starting from the pioneering works of Hawking and Bekenstein [9–11], we know that black holes are thermal objects, whose thermodynamic behavior cannot be explained by classical gravity alone. From a microscopic point of view, black holes entropy and temperature are a manifestation of the existence of some (yet unknown) internal degrees of freedom (DOF), i.e., quanta, whose dynamics should be responsible for both the quantum and the thermodynamical properties of these objects [12–16].

It is logically possible that the macroscopic behaviour of black holes is the result of a microscopic-Planck scale-QG theory, in the same way as black body emission and specific heat of solids are manifestation of microscopic quantum mechanics. However, there are strong indications that this may not be the case. The area-law, which encodes the so-called holographic principle, the information paradox [17,18] and the fact that black holes have no hairs [19], altogether they imply that the quantum characterization of a black hole must be done at the horizon scale, R_s . Indeed, the holographic principle tells us that the would-be DOF making up black hole entropy are localized on the horizon, the information paradox concerns only near-horizon physics and black hole hairs can be fully expressed in terms of the size of the black hole.

The logically simplest solution to this puzzle is to assume that the black hole is made up of a large number of QG states, which remain coherent at the horizon scale. This quantum portrait, which describes black holes similarly to Bose–Einstein condensates (BEC), has been first proposed in Ref. [20] and has been extended to describe several macroscopic effects of gravity (the de Sitter (dS)

universe, inflation, emergence of a dark force in galactic dynamics) as long-range QG effects [21–36]. In this description, black holes are considered as critical systems, saturating a *maximal packing condition*.

However, this simple solution produces a certain tension with the equivalence principle of General Relativity (GR), which sees the black hole horizon as a place with nothing special. This tension can be solved by the formulation of the quantum generalized thermal equivalence principle (GTEP) [29], which generalizes the classical equivalence principle of GR by postulating a fundamental relation between the temperature and the acceleration (the surface gravity).

In this essay we explore, using only general principles of GR, quantum and statistical mechanics, the possibility of using long-range QG states to describe black holes. The purpose of our paper is not to investigate in a technical way the long-standing problem of finding a consistent quantum theory of gravity. Rather, we will look into the consequence these general principles have for black holes. In particular, we discuss in a critical way the interplay between various aspects of this issue, namely the holographic principle, criticality and the peculiarities of the classical limit. We will show how the GTEP allows us to fit them in a nice and consistent description. Using a simple toy model to describe some aspects of black holes physics, we also show that the GTEP is a fundamental and unifying principle in QG. Indeed, we show that black hole thermodynamics can be fully derived from the combination of GTEP with another principle chosen from (1) the holographic bound, (2) classical and (3) quantum criticality. What is really interesting is that, whereas the GTEP appears to be a fundamental principle, the others give three complementary description of a black hole, respectively as (1) a state of maximal information, (2) a classical critical star and (3) a quantum critical state. We will be mainly concerned with black holes, but most of our considerations can be extended also to the case of the dS universe.

The structure of the paper is as follows. In Section 2, we discuss the main features of our QG description, namely criticality, the holographic bound, the classical limit and the GTEP. In Section 3, we use a simple toy model for a black hole to see how they are intertwined among themselves and we show how the GTEP can be used as unifying principle to describe black holes. Finally, in Section 4, we present our conclusions.

2. Long-Range Properties of Quantum Gravity

Quantum mechanics can be responsible for the macroscopic behavior of several physical systems, like Bose–Einstein condensates, superfluids, superconductors and neutron stars. These are all quantum objects that can maintain quantum coherence even at macroscopic scales, so that both their macroscopic phenomenology and microscopic properties are a clear manifestation of quantum mechanics.

There is growing evidence that a similar description could hold true also for gravitational systems like black holes and the dS universe [21,23–25,27–30,37,38]. Thus, long-range QG effects could be relevant for explaining macroscopic gravitational effects, such as, for instance, a non-Newtonian component of the acceleration in galactic and cosmological dynamics [29,32–36]. The existence of long-range QG states allows one to circumvent the usual argument that QG effects are only relevant at scales of the order of the Planck length l_p . As in BECs, where the scale of quantum effects is the size of the condensate itself, in principle we can think that, for QG effects, it coincides with the Schwarzschild radius R_s and the cosmological horizon L for black holes and the dS universe, respectively [29,39]. Moreover, in this picture, a mesoscopic length-scales for QG may be generated at galactic level, if an interaction between dark energy and baryonic matter is assumed [34,39].

The existence of a long-range QG regime is thus related to the peculiar features of gravity and in particular to: (a) the peculiarity of the classical limit in QG; (b) the criticality of the quantum gravitational systems; (c) the holographic character of gravity. All these features are ruled by a single length scale, representing the size of the system. In the following subsection, we will elucidate the interplay and the deep connection between these features, also arguing that a consistent description of them requires a generalization of Einstein's equivalence principle.

The simplest QG model for a black hole of mass M is that of a coherent state of N quanta of energy ε , with:

$$\varepsilon = \frac{\hbar c}{R_s}, \quad Mc^2 = N\varepsilon. \quad (1)$$

In other words, a black hole is modeled as a cavity of length $\ell \sim R_s$, whose quantum degrees of freedom are quantum states in this cavity (see also [40,41] for a quantum description of black holes and gravity in terms of coherent states).

Similar expressions hold true also for the dS universe, with R_s replaced by L and M by the total (dark) energy inside the cosmological horizon. In this picture, gravity emerges to sustain the coherence of a quantum critical system at large scales (see also [42] for a discussion on this topic).

2.1. Criticality, the Holographic Bound and the Classical Limit

For a generic gravitational system with radius R and mass M , whose quantum description is given by (1), the classical bound

$$\frac{2GM}{Rc^2} \leq 1, \quad (2)$$

translates into a maximally packing condition [43–45]

$$N \leq \frac{c^4 m_p^2}{2\varepsilon^2}, \quad (3)$$

where m_p is the Planck mass. The bound (3) simply follows from the substitution of the expressions for the mass M and the radius R , given by Equation (1), in Equation (2). Black holes saturate Equation (3) and, in this sense, they are critical objects (see Section 3.2). In terms of the maximally packing condition, criticality means that once the bound is saturated, adding any further quanta will result in changing the black hole radius. The physical origin of the bound (3) is not completely clear. It does not seem to be a consequence of the Heisenberg uncertainty principle alone [20], which only determines the relation between the size of the region and the energy of the single quanta, $\varepsilon = \hbar c / R_s$ or, equivalently, $M_{BH} = m_p^2 c^2 / (2\varepsilon)$. It is likely that a complete understanding of the bound (3) would require to bring into play many body effects, i.e., effects related to the presence of a large number of quanta and some effective repulsive interaction, which, in turn, stabilizes the black hole.

The criticality bound (3) can be written, upon using Equation (1), as

$$N \leq \frac{R_s^2}{l_p^2}, \quad (4)$$

which is the well-known holographic bound [46], limiting the quantity of information we can store inside a sphere with area $4\pi R_s^2$. A simple qualitative explanation of the existence of an effective repulsive interaction stabilizing the black hole can be given both in terms of the maximally packing condition (3) and of the holographic bound (4). Indeed, once those bounds are saturated, any attempt to put any other quanta into the black hole will increase the black hole radius R_s . This phenomenon implies the existence of a sort of repulsive interaction between quanta.

Although the two bounds (3) and (4) are equivalent, they are conceptually independent and have a completely different origin and interpretation. Whereas the former has an informational nature—its origin being related to the Bekenstein–Hawking formula for black hole entropy—the latter has a dynamical nature. These two different interpretations are linked to two different approaches, which have been followed in the literature to deal with open problems in black hole physics. The “informational” approach originates from the holographic bound, firstly proposed by ‘t Hooft [47] and Susskind [46], later it triggered the formulation of the AdS/CFT correspondence [48] and various emergent gravity scenarios (see Ref. [39] and references therein). The “dynamical” approach focuses instead on the existence of quantum coherent states responsible for gravitational interaction which,

in turn, should build the black hole. This field of research has produced the so-called “corpuscular gravity” description of black holes [22,25].

Furthermore, Equation (4) is intrinsically holographic, whereas Equation (3) does not give any hint about the localization of the N quanta—they may be as well localized inside the sphere or on its boundary. The intrinsically holographic character of Equation (4) has been investigated and explained in detail in the huge amount of investigations triggered by the AdS/CFT correspondence proposal [49–57]. Indeed, several macroscopic features of the black hole, including the Bekenstein–Hawking entropy formula, have been explained in terms of the existence of microscopic degrees of freedom living on the boundary CFT. We will further discuss this point in Section 3.

Even if they can be described as quantum critical systems, black holes (and the dS universe, too) are solutions of Einstein’s GR and thus must have also a classical interpretation. However, the transition from the quantum to the classical description is highly non-trivial. It involves both the usual classical limit $\hbar \rightarrow 0$ and a classicalization process related to the number of quantum coherent states of the system, N , and it occurs when $N \rightarrow \infty$ [20,58,59], as in BECs. Macroscopic quantum phenomena are thus associated either to a system with a large number of states or to a quantum state occupied by a large number of particles. This is surely quite intuitive for a black hole, where quantum states have macroscopic size of the order of its Schwarzschild radius. From a technical point of view, this is a typical feature of systems where conformal invariance arises [60].

A key point is that, in a statistical mechanical description, any quantum system is characterized by thermal macroscopic quantities reflecting its microscopic structure, like its temperature and entropy. Thus, the bridge between the classical and quantum description is provided by black hole thermodynamics, which has been widely used to give a coarse grained thermal description of black holes.

2.2. Generalized Thermal Equivalence Principle (GTEP)

The thermodynamic behavior of the Schwarzschild black hole is fully characterized by its temperature T , mass M and entropy S :

$$T = \frac{\hbar c}{4\pi R_s}, \quad M = \frac{R_s c^2}{2G}, \quad S = \frac{\pi}{l_p^2} R_s^2, \quad (5)$$

from which the first principle of thermodynamics $dM = TdS$ follows immediately by considering a classical process that changes the black hole radius R_s . Thus, black hole thermodynamics is fully defined in terms of fundamental constants (\hbar, c, G) and one single macroscopic quantity: the black hole radius R_s . This is the thermodynamic manifestation of black holes’ criticality, or, equivalently, of the maximally packing condition. More generally, Equations (5) imply that black hole thermodynamics is a manifestation of quantum physics acting at horizon scale.

Furthermore, we see that \hbar does not enter in the mass/radius relation. This latter can be thought as the analogous to compactness relation for a star and, in principle, can have a classical explanation. On the other hand, the entropy/radius relation depends on both \hbar and G and can therefore have only a QG origin. In terms of the coherent states building the black hole, it represents the maximal amount of information which can be codified in a spherical region of radius R_s via the holographic bound (4). Finally, the relation between the temperature and R_s is rather mysterious when considered in the classical limit. In terms of quantum mechanics, it reflects the fact that the temperature measures the average energy of the quanta, i.e., $T \sim \varepsilon = \frac{\hbar c}{R_s}$. This is particularly evident when one rewrites it in terms of the surface gravity a ,

$$T = \frac{\hbar}{2\pi c} a, \quad (6)$$

where:

$$a = \frac{c^2}{2R_s}. \quad (7)$$

This temperature/acceleration relation is quite puzzling, particularly considering that it does not depend directly of the strength of the gravitational interaction G . Another puzzling point is the tension that exists between the equivalence principle of GR, which implies that the black hole horizon is not a special place in spacetime, and the long-range QG description aiming to explain the black hole in terms of quantum states with horizon size.

The simplest solution of these puzzles, which also allows to reconcile the classical and quantum perspectives in describing black hole physics, is to explain Equation (6) as a consequence of a Generalized Thermal Equivalence Principle (GTEP) [29]. It has been formulated as the generalization of Smolin's quantum version of the universality of free fall (the thermal equivalence principle (TEP)) [61], which is based on the Deser–Levin formula [62–64]. The GTEP asserts that whenever we have a thermal ensemble at temperature T of quantum gravity degrees of freedom, the macroscopic acceleration produced on a test mass is given by the Deser–Levin formula

$$a = \frac{2\pi c}{\hbar} \sqrt{T^2 - T_{dS}^2}, \quad (8)$$

where T_{dS} is the dS temperature. One can easily check that Equation (6) simply follows from Equation (8) when $T \gg T_{dS}$. The GTEP has been used to explain galactic dynamics and in particular the Tully–Fisher relation, without assuming the existence of dark matter [29]. The connection with the QG description of black holes can be obtained using Equation (1) into Equation (7) to find a nice relation between the energy of the quanta and the acceleration:

$$a = \frac{c}{2\hbar} \varepsilon. \quad (9)$$

The same result can be obtained in the corpuscular model of black holes of Refs. [22,25,32,34,59].

Conversely, Equations (1) and (9) can be used to derive Equation (7), i.e., to understand the peculiarity of the classical limit involved in describing black holes as classical objects. Indeed, we see that the surface gravity (7) has a quantum origin, but its do not scale away in the limit $\hbar \rightarrow 0$ as it should be the case in standard quantum mechanics. This is because \hbar appears in the numerator of ε (see Equation (1)) but in the denominator of Equation (9).

Notice that Equation (7) is the result of both the GTEP and criticality. To see this, let us consider a non-critical classical gravitational system, i.e., a system for which the bound (2) is not saturated. We consider a spherically symmetric configuration of energy $E = Mc^2$, inside a sphere of radius R , which may or not coincide with the physical radius of the system. We also assume that the gravitational system allows for a microscopic long-range QG description in terms of N degrees of freedom characterized by the temperature T (derived upon a suitable coarse grained operation). Notice that, in this situation, Equation (1) does not necessarily hold. Furthermore, we assume: (a) the validity of GTEP, given by Equation (8) with $T \gg T_{dS}$, i.e., $a = \frac{2\pi c}{\hbar} T$; (b) the saturation of the holographic bound (4), $N = R_s^2/l_p^2$; (c) an equipartition rule for the energy inside the sphere: $E = Mc^2 = \frac{1}{2}NT$. One can easily check that Newton's law $a_N = GM/R^2$ simply follows from putting together (a), (b) and (c). Only when the criticality condition (2) is saturated, a_N takes the form (7).

Interestingly, our discussion and hence the GTEP also applies to dS universe. Using a static parametrization of the dS spacetime, we can associate a total mass m_Λ to it, representing the total dark energy content inside the Hubble radius L . In this way, one easily finds $m_\Lambda \approx L/G$ [34] which, apart from proportionality factors, is analogous to the black hole mass-radius relation. Using a corpuscular description of the dS spacetime given by Equation (1), with $M = m_\Lambda$ and $R = L$, one finds that the number of quanta N building the dS spacetime is related to L by $N \approx L^2/l_p^2$, which is the counterpart of Equation (4) for the dS universe. In the dS case, Equation (9) gives the well-known relation between the dS temperature and the cosmological acceleration H [62,63]: $a = H = \frac{2\pi c}{\hbar} T_{dS} = \frac{c^2}{L}$. The dS universe can be thought as an ensemble of quanta with typical energy $\varepsilon = \hbar c/L$, so that we find $a = \frac{c}{\hbar} \varepsilon$, which is similar to Equation (9) up to a factor of 2.

3. A Black Hole Toy Model

In the previous Section, we have seen how quantum and classical properties of black holes, including their thermodynamics, can be fully explained using three main principles: criticality, the holographic bound and the GTEP. Two important, albeit related, questions arise: are these principles logically independent one from the other or can one of them be derived from the others? Is one of them more fundamental than the others?

In this section we will try to settle down these issues by building a simple toy model to describe black holes as quantum gravitational systems, with a large number of internal degrees of freedom, $N \gg 1$, with typical energy and mass given by Equation (1).

3.1. Black Hole as a Critical Star

Let us assume, beyond the validity of GTEP, that a black hole has a classical description in term of GR. We define the Schwarzschild radius as $R_s = 2GM/c^2$. This means that the classical criticality bound (2) is saturated, namely the black hole is considered as a sort of critical star (see also [65,66]). Putting together Equation (1) and the definition of the Schwarzschild radius, we find that the number of degrees of freedom in the black hole cavity scales as the area, i.e., it scales holographically in the sense previously described:

$$N \sim \frac{c^3}{G\hbar} R_s^2. \quad (10)$$

This allows us to find that also the entropy of the black hole scales holographically as its area:

$$S \sim N \sim \frac{R_s^2}{l_p^2}. \quad (11)$$

By using the GTEP, we can easily find the black hole temperature and, more in general, characterize its thermodynamics. Since in the case under study we expect that $T \gg T_{dS}$, putting together Equations (7) and (8), we find the expected result:

$$T = \frac{\hbar c}{4\pi R_s}. \quad (12)$$

Thus, it is possible to derive black holes thermodynamics by considering them as critical stars in GR and assuming the validity of the GTEP. In this case, holography appears as a consequence of these two rather than a first principle.

3.2. Black Hole as a Critical Quantum System

Let us now consider a black hole of mass M as a quantum critical system. In this case, we assume the validity of the GTEP and the saturation of the bound (3):

$$N = \frac{m_p^2 c^4}{2} \frac{1}{\varepsilon^2}. \quad (13)$$

The total mass of the system is:

$$M = \frac{m_p^2 c^2}{2} \frac{1}{\varepsilon}. \quad (14)$$

Equation (13) states that for a given mass M , the number of quantum degrees of freedom cannot vary freely, rather it depends on the energy ε . In a system of finite size, we can pack many states of small energy or few states of large energy. This implies that, at Planck scales, black holes have $N \sim 1$, whereas astrophysical black holes have $N \gg 1$. This means that they satisfy the maximally packing condition described in Section 2. Thus, in a given region of size R_s and corresponding quanta of energy $\varepsilon = \hbar c/R_s$, we can put $N \leq m_p^2 c^4/\varepsilon^2$ quanta. Once the bound $N = m_p^2 c^4/\varepsilon^2$ is saturated we cannot

put other quanta in that region without enlarging it. Thus, black holes are classically characterized by the condition $M = Rc^2/2G$, which is analogous to the condition $N\varepsilon^2 = m_p^2 c^4/2$ in the quantum portrait [20,22,58,59]. The saturation of the holographic bound (4) easily follows from Equation (13) upon using Equation (1) and the Bekenstein–Hawking formula for the entropy in (11). On the other hand, the black hole temperature (12) still follows from the GTEP, whereas the mass/radius relation is now obtained from (14).

In this derivation, black hole thermodynamics follows in a straightforward way from the GTEP and the quantum criticality condition (13).

3.3. Black Holes as States of Maximal Information

In the previous subsection we have seen that the holographic bound (4) is equivalent, upon the use of Equation (1), to the criticality bound (3). It follows that we can derive black hole thermodynamics from the GTEP and the requirement of the saturation of the holographic bound (4). The Bekenstein–Hawking entropy S follows directly from the latter, the Hawking temperature follows from the former, whereas the expression of the mass M follows from the second Equation (1).

We stress again that, despite the equivalence between the holographic bound (4) and the criticality bound (3), they have a completely different conceptual meaning. Whereas the latter has an informational nature, the former has a fully dynamical meaning.

It is interesting to see how, in the last two derivations of black hole thermodynamics, the black hole mass $M = R_s c^2/2G$ is obtained by summing up the energy of N quanta (see Equation (1)). The mass M is a classical observable and cannot vanish in the $\hbar \rightarrow 0$ limit. Indeed, \hbar cancels out by putting together Equations (1) and (14). This is completely analogous to the \hbar classical limit cancellation, which occurs for the surface gravity. We expect this \hbar cancellation to hold not only for the mass but also for all black hole hairs.

4. Conclusions

In this paper we have explored the possibility that quantum gravity states remaining coherent at astrophysical scales could be used to describe black holes. They can be seen as quantum macroscopic critical objects, which are characterized by a typical length scale (their radius) which determines all their features in terms of N coherent states, i.e., quanta with a typical energy and temperature determined by the black hole radius. In the critical phase, it is not possible to put any further quanta in the system without changing its size. This is related to the saturation of the informational (entropy) bound which, in the case of black holes, appears as a holographic bound. One interesting point is that the same features are shared by the de Sitter universe.

We have also discussed the interplay between the various aspects of the long-range quantum gravity description of black holes, namely the holographic principle, criticality and the peculiarities of the classical limit. We have seen that a quantum, thermal extension of Einstein’s equivalence principle, which we called GTEP, allows for a nice, consistent and unifying description of black holes. In particular, we have seen how it is possible to derive black hole thermodynamics starting from three main principles: classical or quantum criticality, holography and the GTEP. The GTEP seems to be more fundamental than the others. Indeed, the choice of one instead of the other remaining principles leads to different complementary description of a black hole, i.e., as a state of maximum information, as a classical or a quantum critical state, respectively. In order to corroborate this assertion further investigations are needed. In particular, we have found evidence of the validity of the GTEP for black holes, the dS universe and at galactic scales [29]. If the GTEP has the status of a general principle, it must be valid for all gravitational systems, at least when quantum gravity effects are believed to be relevant. This is an issue that deserves further investigation.

On the other hand, we know that, at least at solar systems scales, the classical Einstein equivalence principle holds. Is there a way to derive such a principle as the classical limit of the GTEP? Could possible deviations from Einstein’s equivalence principle at galactic scales lead to its

generalization in a GTEP-like form? Let us remember that in its preliminary version due to Smolin [61], the (simple and not generalised) TEP was linked to deviations from Einstein's equivalence principle at galactic scales. It would be of interest to see if this is the case also for the GTEP. We leave the answer to these questions to future investigations.

Let us conclude with the main caveats of our description of black holes in terms of long-range QG. The discussion we have presented in this paper has a rather speculative character. Although based on general features of General Relativity, quantum and statistical mechanics, it suffers from the fact that until now, we do not have a well-defined quantum theory of gravity. Only in that framework, notions like "QG long-range coherent states" we have used in this paper would have a well-defined meaning. On the other hand, it is quite clear that any formulation of a quantum theory of gravity requires ingredients bridging between GR and quantum mechanics. The basic principles on which we have built our discussion, namely the holographic principle, criticality and the GTEP, have to be considered as bridging principles in this direction. One of the main results of our discussion is that the GTEP seems to work at a more fundamental level than the others.

Another question we have in mind (probably strongly related to the previous one) is about the physical mechanism underlying the stability of black holes. Classicalization and criticality should prevent the formation of singularities allowing the formation of stable critical (quantum gravitational) macroscopic systems made by a large number of quantum coherent states with energies of the order of $1/\ell$, where ℓ is the typical size of the system. However, if black holes can be described by something similar to a BEC, why does the condensate remain stable? Gravity is an attractive force, and in principle, a condensate of gravitons should collapse to form a singularity if some repulsive potential does not arise to compensate the gravitational interaction and stabilize the system. Standard BECs are stabilized by repulsive forces typical of Coulombian interactions between atoms in the critical phase. This is not the case of gravitational systems, where no repulsive components of the force arise in the system and the only fundamental force governing them seems to be gravity.

A different way to formulate the previous question is to ask about the physical origin of the holographic and the criticality bounds, in Equations (3) and (4), respectively. Have they a purely informational origin or have they a fundamental dynamical nature? It is quite clear that the answer to these questions is one of the main challenges of any quantum theory of gravity.

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