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No fire-walls in quantum gravity

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In an approach to quantum gravity where space-time arises from coarse graining of fundamentally discrete structures, black hole formation and subsequent evaporation can be described by a unitary evolution without the problems encountered by the standard remnant scenario or the schemes where information is assumed to come out with the radiation while evaporation (firewalls and complementarity). The final state is purified by correlations with the fundamental pre-geometric structures (in the sense of Wheeler) which are available in such approaches, and, like defects in the underlying space-time weave, can carry zero energy.

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The second law of thermodynamics is not a fundamental principle in physics but rather a statement about the (illusory) asymmetry of time evolution when sufficiently complicated systems are put in special initial conditions and later described statistically in terms of coarse physical variables that are unable to discern all the details of the fundamental system. The idea is easily illustrated in classical mechanics. On the one hand, Liouville's theorem implies that the support of the phase space distribution of the system spans a volume that is time independent; on the other hand, the shape of the support is not restricted by the theorem. An initially simple distribution supported in a ball in Γ will (in suitably complicated systems) evolve into a more and more intricate shape whose apparent phase space volume, when measured with a devise of resolution lower than that of the details of the actual distribution, will grow with time. In a practical sense, the second law implies that information is degraded (yet not lost) in time when encoded in coarse variables. The words in a newspaper are gone when the newspaper is burned, the data in a hard drive deteriorate due to fluctuations in the magnetic medium, the writings on a marble headstone wash out under the obstinate action of rain drops. In some cases information can be long lived if encoded in variables protected from the statistical fluctuations of the ambient medium by an energy threshold (e.g. binding energy of DNA molecules at room temperature) or, in a more quantum mechanical setting, by the existence of decoherence free subspaces (e.g. in quantum computing systems). However, as in the opening examples of this paragraph, this information will be degraded as soon as the ambient conditions are suitably changed so that new degrees of freedom become available to the system. In all these examples there is a physical account of the phenomena where information is preserved in the sense that the system is unitary. Information goes into the correlations among more basic degrees of freedom which are inaccessible to the (coarse) observer that defined the notion of information in the first place: after burning the newspaper the story remains written in the correlations of the gas molecules diffusing in the atmosphere.

In this note we argue that, as in the previous more familiar situations, information is degraded but not lost in black holes. The underlying quantum discreteness of geometry, expected from non perturbative quantum gravity approaches, provides a simple mechanism for maintaining unitary evolution without running into the contradictions recently raised in [1], and without radically changing the semiclassical understanding of black hole dynamics. However, as in the more familiar systems mentioned above, and despite unitarity of evolution, the underlying quantum geometry degrees of freedom imply the degradation of low energy quantum field theoretical information when black holes form and subsequently evaporate due to the standard phenomenon of decoherence. This implies the scattering or S-matrix approach based on a background geometry in asymptotic regions cannot be viable for the description of the fundamental unitary evolution. According to the view advocated here, such formulations are bound to miss relevant correlations with degrees of freedom that are not describable as field excitations on a smooth background geometry and will thus run into problems with unitarity. The fundamental system is unitary but cannot be described in terms of fields living on a background geometry. One recovers in this sense the original Hawking conclusion [2] as far as low-energy QFT degrees of freedom living on a classical geometry is concerned. A more detailed version of this work can be found in [3].

Our argument is based on the assumption that a theory of quantum gravity will necessarily imply a radical change in the way space-time is conceived. We are assuming that at the fundamental scale space-time is replaced by a more basic notion made of fundamentally discrete constituents

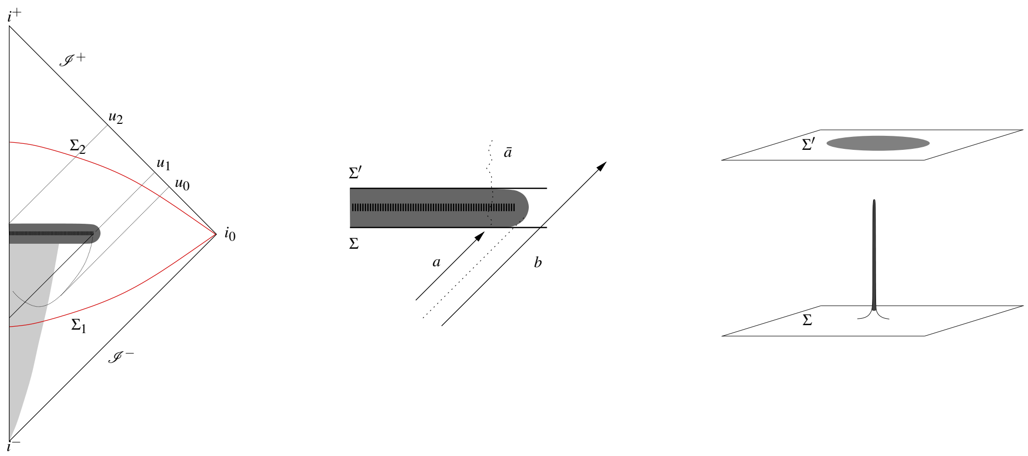

Figure 1: The global space-time causal structure according to the AB-paradigm. The black hole evaporation takes place according to semiclassical expectations until the horizon approaches Planck's area. The classical *would-be-singularity* is represented by the shaded region where quantum geometry fluctuations are large and no space-time picture is available. The space-time becomes classical to the future of this region: it emerges into a classical (essentially) flat background as required by energy-momentum conservation.

governed by quantum mechanical laws. For concreteness we will set the discussion in the context of LQG; however, we believe that the picture presented here is general enough to resonate with other approaches proposed in the literature.

Assume that we start from a pure quantum state of matter fields and geometry on $\mathscr{I}^-$ (see left panel on Fig. 1). The state is assumed to be a semiclassical state. For that reason the 'fast' dynamical process leading to the formation of the BH is well approximated by the classical field equations. The system undergoes gravitational collapse, matter and gravity waves fall into the singularity while matter and gravitational radiation is sent out to $\mathscr{I}^+$. The 'fast' era ends with a stationary BH with Bondi mass M at u_0 (we assume the both angular momentum and charge vanish for simplicity). Such classical picture is incomplete in to aspects: the classical singularity inside the horizon indicates the need of a full quantum gravity treatment there, and non-trivial local correlations in the initial state across the horizon lead to the evaporation of the initial Bondi mass as Hawking radiation (a slow quantum gravity effect driving the asymptotic global structure of the space-time in Fig. 1).

Let us first concentrate on the strong quantum effects close to the singularity. Here we follow [4]. Close to the singularity the curvature scale approaches Planck's scale and dynamics has to be described by a quantum gravity theory. The shaded region in Fig 1 surounding the *would-be-singularity* is a region where the usual notion of space-time is inapplicable due to large quantum fluctuations of geometric observables: the fundamental granular structure of the space-time foam precludes the use of any notion of background geometry there. Nevertheless, a unitary evolution of fields and geometric degrees of freedom across this region is expected to be well defined. Moreover, one assumes that as a consequence of this evolution the space-time becomes classical again at some later 'time' Σ_2 to the future of the *would-be-singularity*. As mentioned above this assumption is realised in quantum-cosmology as well as in spherical collapse models and further explored in 2d models.

If there is no singularity can we talk about a BH horizon in the scenario of Fig. 1? At first sight the answer is no. Notice that the conformal diagram suggests that every space-time point is, according to the discussion above, causally connected with $\mathscr{I}^+$. Therefore, there is no BH region in the usual sense. Nevertheless, one can still define the BH region as the complement of all space-time points that can be joined to $\mathscr{I}^+$ by causal curves that do not enter into the *would-be-singularity* region. Basically, here one is using the usual definition with a qualification in the notion of the past of $\mathscr{I}^+$. We could call this the *classical past* of $\mathscr{I}^+$. Notice that this is equivalent to using the standard definition in a space-time where the shaded region around the *would-be-singularity* is removed from the manifold. Hence, under the usual assumptions of asymptotic predictability and energy conditions the usual (classical) BH theorems would apply (and be physically relevant in the past where quantum effects are still unimportant). The apparent horizon—a *generalized dynamical horizon* represented here by the dotted line—has interesting physical properties that we will not discuss here [5].

Now we are ready to describe the slow quantum effect of Hawking evaporation from the viewpoint of external observers. Physically, outside of the BH region and after a sufficiently long time u_0 (measured in terms of retarded time u at $\mathscr{I}^+$ see Fig. 1) the BH becomes stationary and its state is labelled by an 'initial' Bondi mass M. A very slow process of Hawking radiation (well described at first by semiclassical equations) becomes the main dynamical process outside of the BH horizon. The Bondi mass $M_B(u)$ decreases slowly with a rate proportional to $\ell_p^2/M_B^2(u)$ during the semiclassical era. When the Bondi mass of the BH approaches the Planck mass a full quantum gravity treatment is necessary. The *would-be-singularity* becomes naked at u_1. From u_1 to u_2 the *would-be-singularity* is visible from $\mathscr{I}^+$. By the time u_2 the Bondi mass has become basically zero, the space-time is classical again and hence isomorphic to a portion of Minkowski space-time.

The causal structure in Fig. 1, which in a loose sense is globally hyperbolic (yet recall that no space-time interpretation is possible in the grey region around the *would-be-singularity*), and the assumption of unitarity of the underlying quantum theory implies that the information contained in an initial state defined at instant Σ_1 should be recovered in the state at instant Σ_2. If the system is to be unitary, the causal structure tells one that the purification of the radiation from the BH evaporation must take place with degrees of freedom excited after time u_1. This by itself eliminates the *fire wall* problem but it raises the question on how the information can leave after u_1. The BH *inside-outside* correlations at Σ_1 should become correlations between the whole of the early radiation due to the collapse process plus the Hawking radiation—both emitted before u_1—and *something* encoded at $\mathscr{I}^+$ after u_1. Most importantly, as for remnant scenarios, the purifying excitations after u_1 must carry basically zero energy.

What is the nature of the purifying degrees of freedom? In order to answer this question let us first consider the heuristic picture of pair creation at the BH horizon as depicted in the central panel of Fig. 1 which is a zoom of the *would-be-singularity* region of Fig. 1. A pair *a*-*b* is 'created' and particle b escapes to infinity to be part of Hawking radiation. The positive energy flux of particles like b at $\mathscr{I}^+$ and the semiclassical field equations imply the decrease of the Bondi mass mentioned above. While particle b carries positive energy to $\mathscr{I}^+$ particle a carries 'negative energy' to the singularity. Now particle a falls into the region where the semiclassical description is no longer applicable. The conservation of energy arguments at null infinity given above require a to be striped off its energy and to emerge on the future of the singularity transformed into a new degree of freedom $\bar{a}$; as argued below, a pre-geometry defect in the space-time weave (more details in [3]).

The transmutation of a QFT degree of freedom a into a pre-geometric one $\bar{a}$ seems possible even from very general classical and quantum arguments. For instance, according to the Belinskii-Khalatnikov-Lifshitz conjecture as we approach the space-like singularity individual points decouple and geometry evolves in a chaotic manner which is well understood in certain cosmological scenarios. Such ultra-local dynamics can formally be recovered in the strong coupling regime by simple dimensional analysis. These analysis have been used to argue for the existence of a dimensional reduction from 4d to 2d as one approaches the UV regime in quantum gravity. In such context the nature of the field degrees of freedom a in the Planckian environment of the *would-be-singularity* should be expected to be very different from its original Fock-like excitation at low energies.

Unitarity implies that the correlations between the degrees of freedom of $\bar{a}$ and b remain intact. Therefore, $\bar{a}$ must carry no energy but yet correspond to true degrees of freedom. These cannot be propagating degrees of freedom on the flat background after evaporation because as such they would have to carry energy. Then one would be back to a scenario similar to that of a long lived remnant and with its standard difficulties. However, there is an infinite pool of Planckian degrees of freedom in background independent formulations of quantum gravity. Moreover, there seem not to be any selection rule protecting these defects from developing. With the view that anything that is allowed to happen will happen to preserve the unitarity of the underlying fundamental description—and in the context of the space-time Fig 1—$\bar{a}$ must be one of these pre-geometry defects in the underlying space-time weave hidden to low energy observers but yet carrying non trivial information.

On the right label of Fig. 1 the geometry of Σ and Σ' slices right before and after the *would-be-singularity* quantum region is illustrated. We can estimate the scaling of the volume of the shaded region in the flat hypersurface Σ' by requiring it to contain at least as many volume 'bits' as necessary to purify the radiation emitted during the Hawking evaporation process. This number is of the order of the initial BH entropy $A(M)/(4\ell_p^2)$, where $A(M)$ is the area of the BH at retarded time u_0 (see Fig. 1). From this one gets

$$V(\Sigma') \propto \ell_p M^2. \tag{1}$$

From which a characteristic size $L = 10^{-11}(M/M_\odot)^{2/3} m$ of the naked *would-be-singularity* follows. For a BH with $M = 10^{15} g$ (e.g. primordial BHs completing evaporation at present) this gives a size of about $10^{-2}\ell_{LHC}$ where ℓ_{LHC} is the shortest scale to which the *Large Hadron Collider* is sensitive today.

The basic idea of this article is that, in a theory of quantum gravity where the fundamental degrees of freedom are discrete and combinatorial at the Planck scale, the effective low energy description in terms of quantum fields living on a smooth background geometry cannot be unitary when singularities in the geometry develop. The lack of unitarity is a consequence of such effective description: close to the *would-be-singularity* the smooth background geometry notion breaks down and correlations with Wheeler's pre-geometric structures become important. Unitarity of the fundamental theory implies that correlations subsist in the future when the state admits again background space-time geometry interpretation. However pre-geometric structures are now only detectable to low energy QFT observers though the loss of quantum coherence of their effective field variables.

In the usual situations where no singularities develop consistency requires that decoherence with the Planckian substructures, evoked in our argument, to be negligible in order to recover the usual unitarity of standard quantum field theory. This is a non trivial constraint that must be fulfilled by the low energy limit of theories like LQG which in our view is related to the non trivial requirement of Lorentz invariance. Lorentz invariance implies that the space-time granularity of quantum geometry cannot be interpreted literally as associated to a special rest frame [6]. Space-time granularity compatible with Lorentz invariance becomes important only in regimes of high curvature [7]. It is in these situations where decoherence between QFT degrees of freedom and defects in the space-time weave becomes important.

The picture presented is very much compatible with the second law. Close to the *would-be-singularity* space-time granularity becomes relevant and so new degrees of freedom become available. Information is not lost at the fundamental level where unitarity holds; however, the unitary dynamics entangles the low energy degrees of freedom (field excitations on a background geometry) with those quantum geometric degrees of freedom that do not admit such low energy characterisation. Correlations with these hidden variables become important and information in QFT type of variables is degraded by decoherence. The quantum 'defects' created in the 'fire' of the high curvature region close to the singularity remain hidden to external observers for a long time of order M^3/ℓ_p^2 but regain causal contact with them when the BH completely evaporates its energy content in Hawking radiation. These 'defects' are like the ashes of the naked singularity 'fire' that purify the final state of the whole system.

Finally, our scenario does not require any correlations between the early and late Hawking radiation for $u \in [u_0, u_1]$ in Fig. 1. This means that the quantum state of fields during the semiclassical era are allowed to be maximally correlated across the horizon as there is no need to evacuate information to preserve unitarity during the evaporation process. More precisely, to the past of a sufficiently early Cauchy surface before the *would-be-singularity*—where a formulation in terms of standard QFT on curved space-time is a good approximation—the quantum state of fields on the space-time representing gravitational collapse must be a Hadarmard state with its characteristic short length correlations, in particular across the horizon. For such states, the expectation value of the energy-momentum tensor will be regular at the horizon eliminating the problem of firewalls.

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