



Modulated Hawking radiation and a nonviolent channel for information release



Steven B. Giddings

Department of Physics, University of California, Santa Barbara, CA 93106, United States

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ABSTRACT

Unitarization of black hole evaporation requires that quantum information escapes a black hole; an important question is to identify the mechanism or channel by which it does so. Accurate counting of black hole states via the Bekenstein–Hawking entropy would indicate this information should be encoded in radiation with average energy flux matching Hawking's. Information can be encoded with no change in net flux via fine-grained modulation of the Hawking radiation. In an approximate effective field theory description, couplings to the stress tensor of the black hole atmosphere that depend on the internal state of the black hole are a promising alternative for inducing such modulation. These can be picturesquely thought of as due to state-dependent metric fluctuations in the vicinity of the horizon. Such couplings offer the prospect of emitting information without extra energy flux, and can be shown to do so at linear order in the couplings, with motivation given for possible extension of this result to higher orders. The potential advantages of such couplings to the stress tensor thus extend beyond their universality, which is helpful in addressing constraints from black hole mining.

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1. Introduction

If quantum mechanics governs nature, formation and decay of a black hole (BH) must be a unitary process. Local quantum field theory (LQFT) evolution on the semiclassical BH background [1] in contrast predicts dramatic loss of information. Unitarization of this evolution apparently requires significant new physics beyond such an LQFT description.

Key questions are where and how such modifications of this LQFT evolution become relevant. In particular, we expect that LQFT in semiclassical spacetime geometry furnishes a good approximate description of physics far from a BH. On the other hand, LQFT is expected to be strongly corrected in the deep interior, or core, of BH. This by itself appears insufficient to transfer information out of the BH and unitarize evolution. But, if there are also small corrections to LQFT in an intermediate region – the immediate vicinity or atmosphere of the BH – extending outside the horizon (see Fig. 1), these offer the prospect of unitarizing evolution.

An illuminating way to describe information transfer is via transfer of entanglement [2–4]. A BH builds up entanglement with its environment either by absorbing matter entangled with the surroundings, or through production of Hawking particles en-

tangled with interior excitations. Unitarity requires that all this entanglement ultimately transfers out, so that the fine-grained von Neumann entropy S_{VN} of pre- and post-BH states are equal. A simplest example of such transfer is just transfer of degrees of freedom [3]. A critical question, then, is what mechanism or dynamics is responsible for this transfer; such a mechanism appears beyond usual LQFT dynamics. In information-theoretic terms, we can frame the issue by focussing on the question: *what channel is responsible for escape of the information from the BH interior to infinity?* This approach contrasts with, e.g. [5–8], where LQFT is instead altered by modifying the property of *localization* of information.

There are many constraints on possible channels. In particular, if LQFT is exactly valid outside the horizon, such information transfer produces singular behavior at the horizon [9–12]. For this reason, it appears important that corrections to LQFT reach beyond the horizon, and the proposal that such corrections yield “nonviolent” transfer of information, preserving usual spacetime near the horizon to a good approximation, has been made and investigated in [13–17].

Even with such exterior corrections to LQFT, the general intuition that information transfer requires energy transfer appears borne out, and generic models for information escape produce extra energy flux beyond Hawking's [13–18]. This would indicate [19] that the internal states of a BH are not accurately

E-mail address: giddings@physics.ucsb.edu.

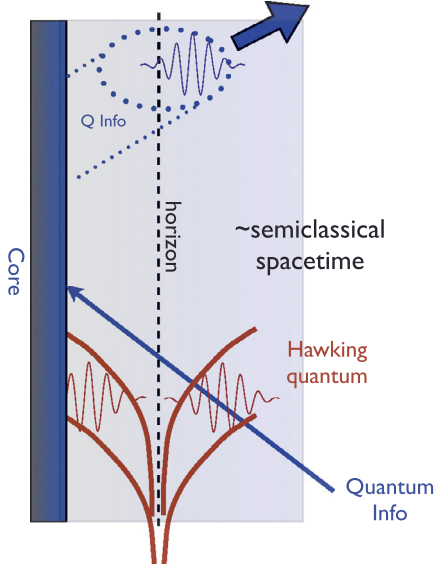


Fig. 1. Proposed schematic picture of unitary black hole evolution. Entanglement is built up between the BH and exterior through infall of quantum information or the Hawking process. Semiclassical evolution fails at the “core” of the BH. New effects extending through a region (shaded) including the BH atmosphere transfer information into outgoing modes that then escape, while preserving, to a good approximation, the semiclassical BH geometry.

parameterized by the Bekenstein–Hawking entropy S_{BH} . While this may be consistent [19], a more conservative and appealing alternative would be no extra flux.

In an asymptotic LQFT description, we certainly expect that there are quantum states with coarse-grained thermal properties of the Hawking radiation, but with vanishing S_{vN} . This motivates the proposal that the radiation carries the information in fine-grained modulations, with average energy flux matching Hawking’s. An important question is whether this flux arises from perturbations of the Hawking radiation. A possible loose analogy is that of modulation of a radio signal: an underlying carrier flux can be modulated to transmit information.

Specifically, one can investigate whether such modulation of the Hawking radiation can be induced, while avoiding destruction of the horizon [9–12]. An important question is what channel or mechanism imprints the information on the outgoing radiation yet preserves near-horizon spacetime. This paper will propose and investigate a candidate mechanism/channel for information to flow from the BH interior to asymptotic observer, which offers the possibility of avoiding extra net flux.

In particular, if such dynamics can be approximately parameterized as a small correction to LQFT, it might be described by couplings to near-horizon fields that depend on the state of the BH [15,16]. It is desirable for such couplings to be universal, in particular to address mining constraints [12,15], and this suggests coupling the internal state to external fields through their stress tensor [15]. Interestingly, we will find that these couplings avoid producing leading-order corrections to energy flux. Such couplings through the stress tensor can be picturesquely thought of as due to near-horizon metric fluctuations correlated with the internal state of the BH. While the *fundamental* picture is not expected to be via such nonlocal corrections to LQFT, this may be for present purposes a good *approximate* description of a more fundamental dynamics [14]. This paper will explore such a description. A more complete description is possibly based on a fundamental tensor-factor structure [20,14].

2. States and evolution: scrambling and transfer

Assume that a BH coupled to its environment is represented in terms of states in a product space, with factors corresponding to BH and environment subsystems; this is a coarsest decomposition of the overall Hilbert space, and more refined versions may be considered [14,19]. Let $|\hat{I}\rangle$ denote a basis of internal states $\mathcal{H}_M$ for a BH of mass $\leq M$, and suppose there are $\exp\{S_{\text{bh}}(M)\}$ such states. The entanglement entropy S_{vN} of BH with environment is bounded above by $S_{\text{bh}}(M)$. According to LQFT, the entanglement S_{vN} increases continually in the Hawking process [1]. But, once S_{vN} reaches S_{bh} , decrease of S_{bh} with M means that transfer of entanglement from BH interior to exterior must take place to preserve unitary evolution. Thus, one postulates [21–23,13–15] couplings that transfer information from the BH interior to environment. Within LQFT these would be forbidden by prohibition of superluminal signaling with respect to the semiclassical geometry.

The presence of such effects may provide a critical clue to the underlying nature of quantum gravity. For now we give a general approximate parameterization [15–17] of them in terms of couplings between the BH states and the states $\mathcal{H}_{\text{near}}$ in the near-BH atmosphere. The latter states are expected to be approximately described within LQFT. Consider a Hamiltonian description. LQFT evolution in the Schrödinger picture produces pairs of Hawking excitations in $\mathcal{H}_M \otimes \mathcal{H}_{\text{near}}$, transfers excitations from $\mathcal{H}_{\text{near}}$ to $\mathcal{H}_M$ (infall), and describes interactions between $\mathcal{H}_{\text{near}}$ and far states in $\mathcal{H}_{\text{far}}$.

The non-LQFT completion of this evolution necessary to restore unitarity may involve two other processes [14]. The first is *scrambling*, which can be described in terms of unitary evolution mixing internal states,

$$|\hat{I}\rangle \rightarrow U_{ij}(t)|\hat{J}\rangle. \quad (2.1)$$

U_{ij} is expected to depend on gauge [15]; for example, in LQFT evolution, in a gauge corresponding to a nice slicing [24,14], evolution of internal states freezes [25], implying $U = 1$ in this approximation.¹ In fact, while the internal Hilbert space and evolution U are sometimes modeled as generic [26], we expect that they have special properties, since the evolution of internal states should describe observations of infalling observers in what to them initially appears to be weakly-curved space, so should approximately match such an LQFT description for those observers.

The second new process is *transfer* of information from $\mathcal{H}_M$ to $\mathcal{H}_{\text{near}}$. It can be written in terms of couplings in the action or Hamiltonian (the latter being the generator of unitary evolution, in some slicing or gauge) between operators $\mathcal{A}_a$ acting on $\mathcal{H}_M$ and operators acting on fields in the atmosphere. General couplings were considered in [15,16], and linear couplings in [16,17]. Here we explore a model with couplings to the stress tensor $T_{\mu\nu}(x)$,

$$S_{\text{trans}} = \sum_a \int dV \mathcal{A}_a G_a^{\mu\nu}(x) T_{\mu\nu}(x) + \text{h.c.} \quad (2.2)$$

where dV is the near-horizon volume element, and the G_a ’s are x -dependent coefficients. The interaction in general transfers information from the degrees of freedom of $\mathcal{H}_M$ to those of $\mathcal{H}_{\text{near}}$.

Consider, for example, working in an interaction picture where the interaction Hamiltonian comes from (2.2) and the remaining evolution is absorbed into that of operators. Then, without (2.2), the state would be of schematic form $|\psi_0\rangle \approx |0\rangle_U \otimes |\psi\rangle$, where $|0\rangle_U$ describes the Unruh vacuum, and $|\psi\rangle$ the state of matter that

¹ In a more natural slicing [23], LQFT may describe some scrambling, but ultimately breaks down.

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