Black holes in the framework of semiclassical gravity: Information, entropy, and decoherence

Thiago T. Bergamaschi and Daniel A. T. Vanzella

Abstract— **We present some open questions concerning black hole physics that illustrate the interplay between gravitation, quantum field theory, thermodynamics, and quantum information theory. Namely, we discuss how black holes can lead to loss of quantum coherence due to a complete evaporation process, how the nature of black hole entropy can lead to insights on how and where they storage information, and how decoherence may occur even if a quantum state is merely in the vicinity of a black hole.**

Keywords— **Black hole information problem. Black hole entropy. Hadamard states. Decoherence.**

I. INTRODUCTION

Black holes are defined as regions of spacetime from which not even light can escape from, thus, they are causally disconnected regions. When considering both quantum field theory and general relativity, one is naturally led to the formalism of semiclassical gravity, in which black hole dynamics has led to many important questions. Most notably, concerning the *preservation of information* during their formation and complete evaporation [1], the nature of the degrees of freedom responsible for their *entropy* [2], [3], [4], and *decoherence of quantum states* due to long-range fields [5]. As simultaneity is a relative concept, in order to provide a covariant description of such dynamics, analysis over time in this framework is given by “slices” of spacetime, such that each “slice”, Σ, can be interpreted as an “instant of time”. Consequently, the protagonist is the *state of a quantum field* on each slice. In this paper, we present these problems to highlight how gravitation, quantum theory, and thermodynamics give rise to them, and stress that, even though they can be rigorously posed, it is evident that their solution will only be possible in light of an *adequate description of the fundamental interactions at the Planck scale*. Emphasis is put on the fact that none of these issues are necessarily “paradoxical”, but they remain interesting questions that can lead to the development of a more comprehensive theory.

II. BLACK HOLE INFORMATION PROBLEM

Suppose one starts with a pure state describing a time independent energy distribution that will eventually collapse to form a black hole. Following the conjecture that black holes always reach a stationary configuration, the *Hawking effect* implies an evaporation process. In expectation of a physically acceptable class of states, one imposes the *Hadamard condition*, such that the two-point function is given by

$$\langle \hat{\psi}(a)\hat{\psi}(a')\rangle = \frac{u(a,a')}{(2\pi)^2\sigma(a,a')} + v(a,a')\ln\sigma(a,a') + w(a,a'), \tag{1}$$

which implies that there will be *entanglement between causally complementary regions* in spacetime. If one assumes that black holes evaporate completely, there will be information loss due to a non-unitary dynamical evolution (see Figs. 1 and 2). Namely, information loss is a *physical* prediction of semiclassical gravity [1]. This result may be interpreted as a consequence of the singularity “opening” the system.

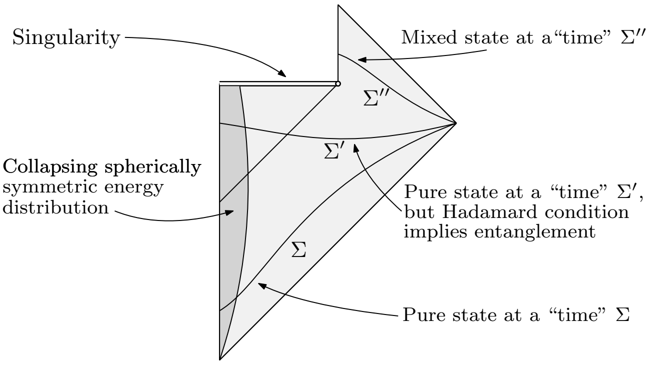

Fig. 1. Conformal diagram of a spherically symmetric black hole that has completely evaporated, as a consequence of the Hawking effect.

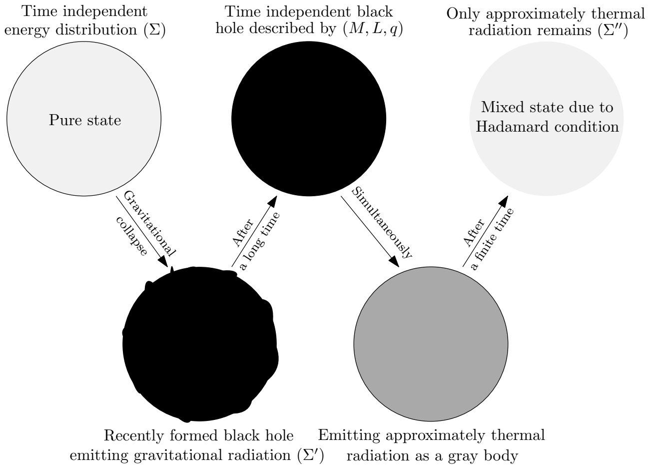

Fig. 2. Illustration of how black holes can lead to loss of quantum coherence in the process of complete evaporation.

Thiago T. Bergamaschi, Sao Carlos Institute of Physics, University of Sao Paulo, IFSC – USP, Sao Carlos, SP, e-mail: tbergamaschi@ifsc.usp.br; Daniel A. T. Vanzella, Sao Carlos Institute of Physics, University of Sao Paulo, IFSC – USP, Sao Carlos, SP, e-mail: vanzella@ifsc.usp.br.

III. BLACK HOLE ENTROPY PROBLEM

Classical properties of black holes are mathematically analogous to the laws of thermodynamics (see. Table I). A physical correspondence was proposed due to the Hawking effect, which predicts that black holes will effectively emit an approximately thermal spectrum of particles with temperature given by the *Hawking temperature*,

$$T = \frac{\hbar\kappa}{2\pi c k_B}, \tag{2}$$

where κ is the black hole surface gravity. Similarly, it was proposed that black hole entropy is given by *Bekenstein-Hawking entropy*,

TABLE I

CLASSICAL PROPERTIES OF STATIONARY BLACK HOLES.

	Black holes
Zeroth law	constancy of κ
First law	$c^2\delta M = \frac{\kappa c^2}{8\pi G}\delta A + \Omega\delta L + \Phi\delta q$
Second law	$\delta A \geq 0$
Third law	$A \to$ constant as $\kappa \to 0$

$$S_{BH} = \frac{c^3 k_B A}{4\hbar G}, \tag{3}$$

where A is the black hole area. However, if one "naturally" interprets this entropy to be the entanglement entropy of the quantum field degrees of freedom inside the black hole, one is led to a contradiction between the evolution of the entanglement entropy associated with the Hawking effect (blue line in Fig. 3) and the Bekenstein-Hawking entropy (black line in Fig. 3). It is precisely due to the fact that one does not know how to describe the degrees of freedom responsible for black hole entropy that one is led to this apparent contradiction. A notable proposal to remedy this is given by the "Page curve" [4], which states that at some "Page time" radiation predicted by the Hawking effect should strongly deviate from thermality. In this perspective, the expected evolution of the entanglement entropy would be given by the red line in Fig. 3, but it is challenging to conceive a mechanism responsible for such deviations at arbitrary energy scales.

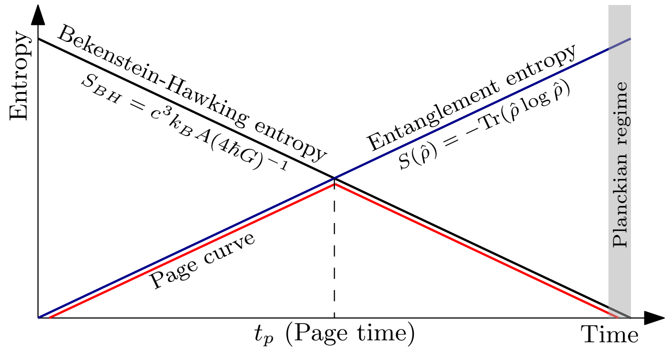

Fig. 3. Qualitative sketch of the Page curve, entanglement entropy, and Bekenstein-Hawking entropy over time.

IV. GRAVITATIONALLY INDUCED DECOHERENCE

It has been shown that the presence of a black hole will eventually decohere a quantum spatial superposition due to the long-range field associated with charges, more precisely, the Coulombian and Newtonian fields. This decoherence, $\mathscr{D}$, is mediated by the emission of soft particle, such that

$$\mathscr{D} = 1 - \exp\left(-\frac{1}{2}\langle N\rangle\right) \tag{4}$$

If the a initial spatial superposition is separated by d, while being at a distance D from a black hole with mass M, the expected number of entangling soft photons/gravitons for each case are given, respectively, by [5]

$$\langle N\rangle \sim \frac{G^3M^3q^2d^2}{\epsilon_0\hbar c^6 D^6}T \text{ (EM)}, \ \langle N\rangle \sim \frac{G^6M^5m^2d^4}{\hbar c^{10}D^{10}}T \text{ (GR)}, \tag{5}$$

where q and m are the associated electromagnetic and gravitational charges. In particular, a local description of this decoherence phenomena for the case of a black hole requires the Hawking effect, hence, it is expected that this type of gravitationally induced decoherence be fundamentally related to other two issues presented in this paper.

V. CONCLUSIONS

The open questions concerning the loss of quantum coherence due to black holes and the degrees of freedom responsible for its entropy indicate an intimate connection between quantum theory, thermodynamics, and gravitation. Indeed, they are perhaps some of the most interesting clues available to the development of a more general theory of fundamental interactions. Below we summarize the most pertinent questions.

- Does black hole complete evaporation imply information loss in a complete theory of gravity?
- How to describe time evolution of black hole entropy?
- What and where are the degrees of freedom are responsible for black hole entropy?
- How to evaluate the universal entanglement entropy associated with the Hawking effect?
- What is the role of decoherence to the development of quantum gravity?

ACKNOWLEDGEMENTS

This study was financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

REFERENCES

[1] T. T. Bergamaschi, *On the nature of the black hole information problem*, Master's Dissertation, University of Sao Paulo, 2024.

[2] R. M. Wald, "The Thermodynamics of Black Holes thermodynamics", *Living Rev. Relativity* v. 4, 6, Jul. 2001.

[3] E. Bianchi and M. Smerlak, "Entanglement entropy and negative energy in two dimensions", *Phys. Rev. D*, v. 90, pp. 41904, Aug. 2014.

[4] A. Almheiri et al., "The entropy of Hawking radiation", *Rev. Mod. Phys.* v. 93, pp. 35002, Jul. 2021.

[5] D. L. Danielson et al., "Local description of decoherence of quantum superpositions by black holes and other bodies", *Phys. Rev. D* v. 111, pp. 025014, Jan. 2025.