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Remnant for all black objects due to gravity's rainbow

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Abstract

We argue that a remnant is formed for all black objects in gravity's rainbow. This will be based on the observation that a remnant depends critically on the structure of the rainbow functions, and this dependence is a model independent phenomena. We thus propose general relations for the modified temperature and entropy of all black objects in gravity's rainbow. We explicitly check this to be the case for Kerr, Kerr–Newman-dS, charged-AdS, and higher dimensional Kerr–AdS black holes. We also try to argue that a remnant should form for black saturn in gravity's rainbow. This work extends our previous results on remnants of Schwarzschild black holes [1] and black rings [2].

1. Introduction

Lorentz symmetry is one of the most important symmetries in nature, and this symmetry fixes the form of the standard energy–momentum dispersion relation, $E^2 - p^2 = m^2$. However, most approaches to quantum gravity suggest that the Lorentz symmetry might only be an effective symmetry in nature, and so, in the ultraviolet limit the Lorentz symmetry might break modifying

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the standard energy–momentum dispersion relation. For example, it is known that even though gravity is not renormalizable, it can be made renormalizable by adding higher order curvature terms. These higher order curvature terms produce negative norm ghost states in the theory. It is possible to add terms with higher order spatial derivatives to the theory, without adding any terms with higher order temporal, which reduces to the general relativity in the infrared limit. This theory is called Horava–Lifshitz gravity, and in it the standard energy–momentum dispersion relation gets modified in the ultraviolet limit [3,4].

Furthermore, one of the most famous approaches to quantum gravity is the string theory. Even in string theory, it is expected that the standard energy–momentum dispersion relation will get modified. This is because it is not possible to probe spacetime below the string length scale, and the existence of this minimum length scale will induce a maximum energy scale in the theory [5,6]. This maximum energy scale will in turn deform the standard energy–momentum dispersion relation [7,8]. In fact, the modification of the standard energy–momentum dispersion relation seems to be an almost universal feature of all models of quantum gravity, such as spacetime discreteness [9], spontaneous symmetry breaking of Lorentz invariance in string field theory [10], spacetime foam models [11] and spin-network in loop quantum gravity (LQG) [12], and non-commutative geometry [13].

The standard energy–momentum dispersion relation gets modified because of the existence of a maximum energy scale E_P in nature. Hence, just as the velocity of light is the maximum attainable velocity in special relativity, the Planck energy is the maximum attainable energy in these theories with modified dispersion relations (MDR). In fact, it is possible to construct a generalization of special relativity with two universal invariants, i.e. the velocity of light and Planck energy [14]. This generalization of special relativity is called doubly special relativity (DSR) [15]. In fact, it has been possible to generalize DSR to curved spacetime, and arrive at a doubly general relativity, or gravity's rainbow [16]. The name gravity's rainbow is motivated by the fact that in this approach the geometry of spacetime depends on the energy of the particle used to probe it, and so, this geometry is represented by a one parameter family of energy dependent metrics forming a rainbow of metrics.

Since gravity rainbow is based on generalizing DSR to curved spacetime, it is important to define the modified dispersion relations in DSR. These modified dispersion relations have to be constrained to reproduce the standard dispersion relation in the infrared limit. Thus, we can write,

$$E^2 f^2(E/E_P) - p^2 g^2(E/E_P) = m^2 \tag{1.1}$$

where E_P is the Planck energy, and the functions $f(E/E_P)$ and $g(E/E_P)$ are called rainbow functions. They modify the energy–momentum dispersion relation in the ultraviolet limit, and they reproduce the standard dispersion relation in the infrared limit, if the following limits holds,

$$\lim_{E/E_P \to 0} f(E/E_P) = 1, \qquad \lim_{E/E_P \to 0} g(E/E_P) = 1. \tag{1.2}$$

Now the modified metric in gravity's rainbow can be constructed using [16]

$$g(E) = \eta^{ab} e_a(E) \otimes e_b(E), \tag{1.3}$$

and the energy dependence of the frame fields is given by

$$e_0(E) = \frac{1}{f(E/E_P)} \tilde{e}_0, \qquad e_i(E) = \frac{1}{g(E/E_P)} \tilde{e}_i, \tag{1.4}$$