Planck-Star Tunnelling-Time: an Astrophysically Relevant Observable from Background-Free Quantum Gravity*

Marios Christodoulou[a], Carlo Rovelli[a], Simone Speziale[a], Ilya Vilensky[b]

†

‡

(Dated: May 29, 2020)

A gravitationally collapsed object can bounce-out from its horizon via a tunnelling process that violates the classical equations in a *finite* region. Since tunnelling is a non-perturbative phenomenon, it cannot be described in terms of quantum fluctuations around a classical solution and a background-free formulation of quantum gravity is needed to analyze it. Here we use Loop Quantum Gravity to compute the amplitude for this process, in a first approximation. The amplitude determines the tunnelling time as a function of the mass. This is the key information to evaluate the relevance of this process for the interpretation of Fast Radio Bursts or high-energy cosmic rays. The calculation offers a template and a concrete example of how a background-free quantum theory of gravity can be used to compute a realistical observable quantity.

I. INTRODUCTION

A striking realization of the last decades is that our universe is teeming with gravitationally collapsed objects –or 'black holes'– of various sizes. The recent gravitational-waves observation of the merger of two black holes of unexpected size [1] makes this conclusion even more compelling.

Classical general relativity (GR) predicts that gravitationally collapsed objects are stable: once a dynamical [2] or trapping horizon forms (light surfaces shrink), it lasts forever (it is an 'event' horizon). But this prediction disregards quantum effects. Some of these are accounted for by the theory of quantum fields interacting with classical geometry, which predicts Hawking radiation. However, macroscopic black holes are still effectively stable on accessible time scales —a stellar-mass black hole takes $\sim 10^{50}$ Hubble times to evaporate via Hawking radiation. But this theory, or any perturbative formulation of quantum gravity, are *still* approximations, because they disregard non-perturbative quantum-gravitational phenomena. Among these is the possibility of black hole decay via gravitational quantum tunnelling[1].

The idea has a long history and has been considered by numerous authors [4–24]. Kieffer and Hajichek have found evidence that the quantum state of a spherically symmetric in-falling null shell tunnels into an outgoing one in the context of a minisuperspace model [25]. Quantum effects could indeed make collapsing objects bounce when they reach the "Planck star" stage [26], namely planckian density.

A key step was taken in [27], where it is shown that a violation of the Einstein equations within a *finite* space-time region is *sufficient* to allow a black hole tunnel into a white hole (an 'anti-trapped' region, where all light fronts expand). From the outside, the process looks like a quantum bounce of the in-falling matter, and it is akin in nature to the 'big bounce' of quantum cosmology [28].

This is a standard tunnelling phenomenon: evolution that violates the classical equations of motion in a finite spatial region and during a limited time. It is therefore a very plausible phenomenon. Its astrophysical relevance, on the other hand, depends on the time it takes. Dimensional arguments suggest that accumulation of small quantum effects could trigger the tunnelling already after a time $\tau \sim m^2$ in Planck units, where m is the mass of the collapsed object [27]. This is sufficiently long to be compatible with the black holes we observe in the sky, but much shorter than the huge Hawking evaporation time $\tau_{\rm H} \sim m^3$. Hawking radiation could be a sub-dominant phenomenon, with respect to the bounce. Writing $\hbar$ explicitly gives $\tau \sim m^2/\sqrt{\hbar}$, which indicates that this is not a perturbative phenomenon.

A lifetime $\tau \sim m^2$ implies that primordial black holes of lunar-size mass could be exploding today and yield observable signals [29]. A component of the expected resulting signal is tantalisingly similar to the recently observed Fast Radio Bursts [30]. Fast Radio Bursts [31–34] could thus be the first genuinely quantum gravitational phenomenon ever observed [35, 36]. A second, high energy, component of the signal could be the source of some very high-energy cosmic rays. In both cases the expected signal has a signature distance-frequency relation that characterises it [37, 38]. Maybe black holes could 'reveal their inner secrets' [39] after all, thanks to quantum theory.

The first objective of this paper is to compute the black-hole lifetime from a full quantum theory of gravity, to assess the credibility of the dimensional estimate of [27] and therefore ground the astrophysical relevance of black hole tunnelling.

Since the quantum bounce of a Planck star is a non-perturbative phenomenon, it is not captured by the small quantum fluctuations around a classical solution of the

*

†

‡

[1] Not "in a different universe" as in [3], but simply exploding in its actual location.