Astronomical and Astrophysical Transactions (*AApTr*), 2025, Vol. 35, Issue 1, pp. 107–126,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Testing loop quantum gravity with Gaia BH1: predicted orbital anomaly, gravitational wave echoes, and thermodynamic shifts

Natarajan Shriethar*

Research & Development Department, MaGa Tech Gramam, Salem, Tamilnadu, India

Received 11 April, 2025; accepted 28 April, 2025

We present unique solutions based on Loop Quantum Gravity (LQG) to understand near-horizon quantum effects. By adopting the predictions of an effective quantum boundary $r_q = (7/6)r_s$ (and its Kerr generalization $r_q \approx (7/6)r_+$), we derive several quantum gravity-based solutions which are distinct from classical general relativity. For systems like Gaia BH1, these solutions show 16.7% orbital precession anomaly, gravitational wave echoes with delay $\Delta t = r_s/3c, a$ -14% quasi-normal mode frequency shift, a Hawking spectral shift factor of $-1/7$, and entanglement entropy $S_{\text{ent}} = (49/36)S_{BH}$ that are consistent with the avoidance of firewall. The distinct astrophysical signatures derived from these LQG-based solutions, such as the specific orbital precession anomaly and gravitational wave echo characteristics, provide possible observational signatures for testing near-horizon quantum gravity effects.

Keywords: Loop quantum gravity, information paradox, gravitational anomaly, testing quantum gravity, Gaia BH1, near-horizon effects

1 Introduction

Black holes are some of the most extreme and mysterious objects in the universe, and understanding their properties and behavior is a key goal of modern physics. In particular, the study of quantum gravitational effects around black holes is important because black holes are thought to be one of the places where the principles of quantum mechanics and general relativity come into play in a strong and potentially observable way [O'Neill (2014); Hughston & Sommers (1973); Zhang & Zhao (2005)]. The Loop Quantum Gravity (LQG) theory is a leading candidate for explaining quantum gravity, which is the theoretical framework that aims to reconcile the principles of quantum mechanics with those of general relativity [Nicolai et al. (2005); Rovelli (2008); Bojowald (2008, 2001)]. The loop quantum gravity has background-independent formalism and has the non-perturbative approach to the quantization of

*Email: natarajan@techgramam.com

gravity [Thiemann (2003)]. The loop quantum gravity applied to the cosmological principles as the loop quantum cosmology which replaces the big bang singularity as the big bounce [Ashtekar (2007)]. From a cosmological perspective, the loop quantum cosmological principles address the various singularity resolutions [Li & Singh (2023)]. Similar singularity resolution of the loop quantum gravity solutions even works for black hole singularity which helps to understand the interior of the black holes and its evolution [Ashtekar (2020)].

In addition to the singularity resolution, the loop quantum gravity can describe the near horizon geometry of the classical event horizon r_s. These near-horizon quantum effects can provide various detailed solutions about the testable quantum gravity effects around a black hole. Numerous LQG solutions predict that the classical event horizon can be replaced with quantum boundaries which would be extended just outside the classical event horizon [Perez (2017); Ashtekar (2020)]. In these approaches, Haggard and Rovelli [Haggard & Rovelli (2016)] proposed an effective quantum boundary for Schwarzschild black holes which is inspired by analyses of quantum tunneling probabilities and effective dynamics near trapped surfaces. In this paper, we adopt this particular solution from Haggard & Rovelli (2016) as our primary hypothesis. We calculate the consequences of this single, well-defined assumption across a range of quantum gravitational effects, without introducing any additional parameters beyond the standard LQG scenario. We generalize this relation to Kerr black holes by mapping $r_q(a) \approx (7/6)r_+$, with the quantum correction scales as well as the relevant classical horizon radius.

Black holes, especially those in binary systems or which could be detectable through gravitational waves (GWs), can act as unique laboratories for testing these derived theoretical predictions. The recently discovered Gaia BH1 system [Rastello et al. (2023); Li et al. (2024)] contains a stellar-mass black hole and a Sun-like star. This provides an excellent, concrete testbed for applying our solutions and predictions and those are measurable with current or next-generation instruments. The solutions discussed here attempt to connect to fundamental questions in black hole physics, such as black hole thermodynamics [Bekenstein (1980)] and the information paradox [Giddings (1995)].

While directly observing the quantum structure at the Planck scale near a black hole horizon remains experimentally inaccessible, theoretical solutions like Loop Quantum Gravity predict modifications to the classical spacetime description. These modifications, even if originating at microscopic scales, can eventually lead to observable astrophysical consequences.

This paper investigates specific and observable astrophysical phenomena predicted by adopting an effective quantum boundary radius, $r_q = (7/6)r_s$, which is derived by LQG for the Gaia BH1 system.

This paper is structured as follows. In Section 2, we introduce the quantum-corrected radius r_q as the core assumption of our solutions. Section 3 applies this assumption to calculate the radius for the Gaia BH1 system. Section 4 briefly reviews the black hole thermodynamics and Hawking temperature. Section 5 discusses LQG entropy, discusses the necessary large value for the spin network label j, and introduces the Kerr solution of $r_q(a)$. Section 6 confirms the consistency of $b = 1$ with the r_q which suits both Schwarzschild and Kerr cases. Section 7 calculates the information capacity related to the quantum transition layer. Section 8 presents the testable

predictions of these solutions. The paper ends with the conclusion of the discussed solutions. The main focus of this work is the study of quantum gravitational effects around black holes. Specifically, we use rotational Kerr black holes as a model for gauging and simulating these effects. Understanding the quantum gravitational effects near the horizon of a black hole is important because this region is where the principles of quantum mechanics and general relativity are expected to come into play in a strong and potentially observable way. By studying these effects, we can gain new insights into the fundamental nature of the universe and the fundamental laws of physics.

2 The quantum gravitational effects near the horizon

In order to study the quantum gravitational effects near the horizon of a black hole, application of the loop quantum gravity is an apt way. To study black holes in the context of LQG, we consider modified circular orbits around a rotating black hole. By studying the trajectories around black holes, we can gain insight into the quantum gravitational effects that are present in these extreme environments. Due to the quantum gravitational consequences of supermassive black holes, translational quantum gravitational effects will perturb it even beyond its respective Schwarzchild radius. Recently observable loop quantum gravitational effects on Sagittarius $A^{\star}$ are studied by Haggard & Rovelli (2016).

We can discuss the quantum gravitational correction to the horizon radius as

$$r = r_s \left(1 + \frac{b}{6}\right). \tag{1}$$

The finite radius r will exist beyond the Schwarzchild radius. In such a radius limit, quantum effects usually take precedence. From Haggard & Rovelli (2016) it has been suggested that b can be assumed as $b = 1$. Then Eq. 1 is rewritten as

$$r = \frac{7}{6} r_s \,. \tag{2}$$

The quantum effects will manifest themselves as a result of the distance expressed in Eq. 2.

This radius r is interpreted not as a directly observed entity, but as the distance where quantum gravitational effects are suggested to become dominant, and this can perturb the spacetime structure from the classical GR description. While this modification originates at a microscopic scale relative to the classical system, its influence on the effective gravitational potential and boundary conditions can lead to macroscopic consequences which can be detectable via the astronomical observations.

This specific value arises from solutions such as the Böhmer–Vandersloot model [Böhmer & Vandersloot (2007)] or considerations of trapped surfaces in the quantum regime [Bar (2007)]. This radius r_q is interpreted as the place where quantum gravitational effects become dominant. This replaces the classical horizon as the possible boundary. The radius suggests that the quantum gravitational effects may extend beyond the limits that are predicted to be extended already. For any supermassive black hole with a radius of r_{sh}, the safest distance for observing quantum gravitational effects $q(r)$ may be the safest distance. The numerical value of such a parameter is

the distance at which the quantum gravitational effects are dominated beyond the black hole Schwarzchild radius. In addition to the gravitational effects of black holes, we also consider the thermal contributions.

2.1 Gaia BH1

We may implement this calculation to the recently discovered near solar family black hole Gaia BH1 [El-Badry et al. (2022)]. The Gaia BH1 is a binary system that is located approximately 1,560 light-years away in the constellation Ophiuchus. The system consists of a Sun-like star and a stellar-mass black hole [Kotko et al. (2024)]. The corresponding black hole is estimated to have the mass as a mass of about $9.62M_{\odot}$. With the mass of Gaia BH1's black hole $(M) = 9.62 \times M_{\odot}$, the Schwarzschild radius can be computed as

$$R_s = \frac{2 \times 6.674 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}} \times 1.913 \times 10^{31}\,\mathrm{kg}}{(3 \times 10^8\,\mathrm{m/s})^2}\,, \tag{3}$$

$$R_s \approx 28.38\,\mathrm{km}\,. \tag{4}$$

Hence we can determine that the Schwarzschild radius of Gaia BH1's black hole is approximately 28.38 kilometers. The $q(r)$ is then calculated as

$$q(r) = \frac{7}{6} \times 28.38\,\mathrm{km} \approx 33.11\,\mathrm{km}\,. \tag{5}$$

Thus, $q(r)$ is approximately 33.11 kilometers.

3 Loop quantum gravity and thermal contributions

To study quantum gravitational effects around a black hole, we must consider the observational setup around the black hole and its placement relative to the horizon. In particular, it is important to consider the distance from the horizon at which the quantum gravitational effects are dominant, as this distance will also be subject to the thermal and tidal effects of the black hole. In order to obtain a clear understanding of these effects and their impact on the spacetime geometry, we are going to use the Kerr metric [O'Neill (2014); Psaltis et al. (2008); Gourgoulhon (2018)] and the quantum gravitational radial distance. The black hole thermodynamics laws explain such possible relationships [Bekenstein (1980); Carlip (2014); Page (2005)].

In addition to that, such a distance should be in a safe zone where the thermal effects and tidal effects are minimal. To obtain those distance calculations, the quantum gravitational radial distance from the black hole by Rovelli is introduced. Quantum gravitational effects from such a distance will cause variations in the thermal fluctuation around the black hole.

The proper time τ and the Schwarzchild time t are related [Engelhardt et al. (2015); Bodendorfer et al. (2019)] to each other as suggested from Haggard & Rovelli (2016):

$$\tau = \sqrt{1 - \frac{2MG}{c^2 r}}\; t\,. \tag{6}$$

The temperature influences the relationship between thermal time and proper time [Rovelli & Smerlak (2011)].

$$T = \frac{\hbar}{K_B}\frac{d\tau}{ds}\,. \tag{7}$$

Here, $d\tau$ is proper time, ds is thermal time, T is temperature, and K is the Boltzmann constant. At every point in the spacetime of the timelike curve, the temperature is the ratio of thermal time flow to proper time.

$$\xi^{\rho} = \frac{1}{KT}\frac{d}{ds}\,. \tag{8}$$

Here ρ are the statistical states. Hence,

$$\frac{d}{ds} = \frac{1}{K_B T}\frac{d}{d\tau}\,. \tag{9}$$

So, the following relationship is obtained as

$$\frac{d\tau}{ds} = \frac{1}{K_B T}\,. \tag{10}$$

By integrating both sides, thermal time is obtained as

$$\tau = \frac{1}{K_B T}s\,. \tag{11}$$

Thermal time, or thermal flow, refers to the flow of time as perceived by an observer experiencing a particular temperature. This flow of thermal time can have an effect on the geometry of spacetime. This can be understood in terms of the relationship between thermal time and proper time, which is defined as the time experienced by an observer following a particular timelike curve. The flow of thermal time can be described mathematically by considering the ratio of thermal time to proper time, and how this ratio changes as a function of temperature. This can then be related to the geometry of spacetime through the use of appropriate mathematical tools such as the equations of motion or the Einstein field equations. Hence it can be stated that the flow of thermal time has geometric effects on spacetime geometry

$$\xi = \frac{1}{K_B T}\frac{d}{dt}\,, \tag{12}$$

where t is mechanical time. The ratio of thermal time to mechanical time is calculated as KT. Hence

$$\frac{d\tau}{ds} = \sqrt{1 - \frac{2MG}{c^2 r}}\;\frac{1}{K_B T}\,. \tag{13}$$

This is the temperature of a supermassive black hole, which has quantum gravitational effects at a large radius.

Hawking Temperature at Infinity (T_∞) for the Gaia BH1 black hole is calculated as

$$T_\infty = \frac{\hbar c^3}{8\pi G M k_B}\,, \tag{14}$$

$$T_\infty = \frac{2.841 \times 10^{-9}}{0.4434} \approx 6.41 \times 10^{-9}\,\mathrm{K}\,. \tag{15}$$

This matches the expected Hawking temperature for a $9.62M_\odot$ black hole (approximately $6.17 \times 10^{-8}/9.62 \approx 6.41 \times 10^{-9}\,\mathrm{K}$).

Such a low temperature $T = 1.696 \times 10^{-8}$ K is physically meaningful for the cases of black hole thermodynamics. In fact, this temperature shows the expected Hawking radiation temperature that is adjusted for an observer at the quantum-corrected radius. However, it is not observable with current equipment and does not exhibit quantum gravitational effects for a stellar-mass black hole like Gaia BH1.

Black holes emit thermal radiation due to quantum effects near the event horizon. This is referred to as a phenomenon known as Hawking radiation [Page (2005); Hawking (1975)]. This thermal emission is explained by Hawking temperature. For a Schwarzschild black hole, Hawking temperature is written as

$$T_H = \frac{\hbar c^3}{8\pi G M k_B} = \frac{\hbar \kappa}{2\pi c k_B}\,, \tag{16}$$

where M is the black hole mass, k_B is the Boltzmann constant, and $\kappa = c^4/(4GM) = c^2/(2r_s)$ is the surface gravity at the event horizon r_s. This temperature arises from quantum field theory calculations in the curved spacetime.

For the Gaia BH1 black hole, with a mass $M \approx 9.62M_\odot \approx 1.913 \times 10^{31}$ kg, the Hawking temperature can be obtained as

$$T_H \approx \frac{(1.054 \times 10^{-34})(3 \times 10^8)^3}{8\pi(6.674 \times 10^{-11})(1.913 \times 10^{31})(1.38 \times 10^{-23})} \approx 6.41 \times 10^{-9}\ \mathrm{K}\,. \tag{17}$$

This temperature looks too low and it exists far below the cosmic microwave background temperature. Hence direct observation of Hawking radiation from stellar-mass black holes currently looks impossible.

In Loop Quantum Gravity, the classical singularity at $r = 0$ is resolved, and the geometry near the classical horizon r_s is expected to be modified. Here we work with a quantum-corrected effective boundary existing at $r_q = (7/6)r_s$. The presence of this quantum boundary provides the transition from classical spacetime to a quantum geometry regime, and this could be able to affect the thermal properties of the black hole.

While a full LQG derivation of the temperature in the presence of such a boundary is complex and model-dependent, one might expect corrections to the standard Hawking temperature T_H. These corrections will modify the spacetime structure near r_q and change the conditions for particle creation or the effective surface gravity that is meant for the thermal emission. For massive black holes where r_q is slightly larger than r_s, any such corrections to the temperature are possibly suppressed by powers of the Planck length over the horizon radius (l_p/r_s). Also, this will be extremely small. For the Kerr case, the standard Hawking temperature is determined by the surface gravity κ_+ at the outer event horizon r_+.

$$T_K = \frac{\hbar \kappa_+}{2\pi c k_B},\ \text{where}\ \kappa_+ = \frac{c^2(r_+ - r_-)}{2(r_+^2 + a^2)}\,. \tag{18}$$

Using the Gaia BH1 parameters with assumed spin $a = 0.5GM$ ($r_+ \approx 2.66 \times 10^4\,\mathrm{m}, \mathrm{r}_- \approx 1.19 \times 10^4\,\mathrm{m}$), the standard Kerr temperature is obtained as

$$T_K \approx 6.0 \times 10^{-9}\ \mathrm{K}\,. \tag{19}$$

As in the Schwarzschild case, the existence of the LQG-corrected radius $r_q(a)$ derived from area quantization [see later sections of this paper] might lead to smaller corrections to this temperature, although T_K remains dominant.

Due to the extremely low values of T_H and T_K for Gaia BH1, direct thermal observations are not feasible to probe these LQG modifications. Hence, this work focuses on other possible observational signatures regarding the quantum-corrected radius r_q, such as orbital perturbations and gravitational wave effects.

4 LQG and observable quantum gravitational effects

The quantum gravitational effects of those black holes will be observed from the least distance toward the horizon of the black hole. As a result, its quantum gravitational effects can be studied using loop quantum gravitational perspectives. The entropy defined from LQG is [Rovelli (1996)]

$$S_{lqg} = \frac{A}{B_{j_m} l_p^2} \ln(2j_m + 1)\,. \tag{20}$$

As suggested by LQG, the Barbaro–Immirizi parameter is defined as

$$\gamma = \frac{\ln 2}{\pi\sqrt{3}}\,. \tag{21}$$

The area of the black hole is represented by

$$A = 16\pi^2 \left(\frac{Gm}{c^2}\right)^2\,. \tag{22}$$

$$S_{bh} = \frac{A}{4l_p^2}\,. \tag{23}$$

The LQG correction on black hole entropy is presented as

$$S_{lqg} = \frac{A}{B_{jm} l_p^2} \ln(2j_m + 1)\,. \tag{24}$$

The LQG parameters are to be considered for any experiment which is intended to observe the quantum gravitational effects. Hence, in addition to generalized entropy, quantized entropy calculations have been developed.

$$T^{-1} = \frac{\Delta S}{\Delta m}\,, \tag{25}$$

$$\Delta S = T^{-1} \Delta M\,, \tag{26}$$

$$S = \frac{M}{T}\,. \tag{27}$$

For the lower curvatures, the quantized entropy becomes classical as $j \to j_{max}$. As a result, Eq. 24 is reduced to Eq. 27. In view of the AdS/CFT conjecture, the area variable is obtained [Silva (2020)] and it is related to the radial parameter obtained in Eq. 1. The area gauge is obtained as

$$A = 4\pi \left(r_s(1 + \frac{b}{6}) \right)^2 . \tag{28}$$

This extended area is found just outside the horizon and exhibits quantum gravitational properties.

4.1 Gaia BH1 as Kerr black hole

We can discuss the Gaia BH1 as a Kerr black hole. For such a discussion, the spin parameter a is taken into the calculations. This will modify both the quantum-corrected radius $q(r)$ as well as temperature.

For a Kerr black hole, the horizons are given by

$$r_\pm = GM \pm \sqrt{(GM)^2 - a^2}, \tag{29}$$

where $a = \dfrac{J}{M}$ is the spin parameter ($0 \leq a \leq GM$), J is the angular momentum, r_+ is the outer horizon (event horizon), and r_- is the inner horizon.

The Schwarzschild radius for a non-rotating black hole is $R_s = 2GM/c^2$. For a Kerr black hole, the outer horizon r_+ replaces R_s.

The quantum-corrected radius $q(r, a)$ for a Kerr black hole also addresses the role of the spin. The area from LQG is obtained as [Ashtekar & Bianchi (2021)]

$$A_{\text{lqg}} = 8\pi\gamma\ell_p^2\sqrt{j(j+1)}\,, \tag{30}$$

$$A_{\text{classical}} = 4\pi(r_+^2 + a^2)\,. \tag{31}$$

Equating these equations leads to

$$j \simeq \frac{(r_+^2 + a^2)}{(2\gamma l_p^2)} \simeq 10^{80}\,. \tag{32}$$

To connect this quantized calculation to the macroscopic black hole, we map the LQG area with the classical Bekenstein–Hawking area $A_{BH} = 4\pi(r_+^2 + a^2)$. This provides $8\pi\gamma l_p^2\sqrt{j(j+1)} = 4\pi(r_+^2 + a^2)$. For large j, $\sqrt{j(j+1)} \approx j$. Hence $j \approx (r_+^2 + a^2)/(2\gamma l_p^2)$. For Gaia BH1, with $M \approx 9.62 M_\odot$ and moderate spin $a = 0.5GM$, $r_+ \approx 2.66 \times 10^4$ m. Using $l_p \approx 1.6 \times 10^{-35}$ m and $\gamma \approx 0.2$–0.3, this requires $j \sim 10^{80}$. This huge value shows the necessity of a vast number of Planck-scale quanta needed to implement the macroscopic horizon area.

This shows that spin reduces the quantum radius.

We generalize the Schwarzschild result by assuming the quantum boundary for Kerr is $r_q(a) \approx \dfrac{7}{6} r_+$. In general, the Hawking temperature for a Kerr black hole is written as

$$T_{\text{Kerr}} = \frac{\hbar\kappa}{2\pi k_B}, \tag{33}$$

where κ is the surface gravity that can be written as

$$\kappa = \frac{r_+ - r_-}{2(r_+^2 + a^2)}. \tag{34}$$

Substituting $r_\pm = GM \pm \sqrt{(GM)^2 - a^2}$ leads to

$$\kappa = \frac{\sqrt{(GM)^2 - a^2}}{2GM\left(GM + \sqrt{(GM)^2 - a^2}\right)}. \tag{35}$$

For $a \ll GM$, this reduces to the Schwarzschild case as

$$\kappa \approx \frac{1}{4GM}. \tag{36}$$

The Gaia BH1 has the mass of $M = 9.62\,M_\odot = 1.913 \times 10^{31}$ kg. Its spin parameter a is assumed to be $a = 0.5GM$ (moderate spin), the Barbero–Immirzi parameter is $\gamma = \dfrac{\ln(2)}{\pi\sqrt{3}}$, the Planck length is $\ell_p = 1.616 \times 10^{-35}$ m. We can numerically calculate its kinetics.

For $a = 0.5GM$ the r_+ becomes

$$r_+ = GM + \sqrt{(GM)^2 - (0.5GM)^2} = GM\left(1 + \sqrt{0.75}\right) \approx 1.866GM. \tag{37}$$

Using the relation $GM = 1.913 \times 10^{31} \times 6.674 \times 10^{-11}/(3 \times 10^8)^2 \approx 1.424 \times 10^4$ m, then

$$r_+ \approx 1.866 \times 1.424 \times 10^4\,\text{m} \approx 2.656 \times 10^4\,\text{m}. \tag{38}$$

Using the relation $r_q(a) = r_+\left(1 - \frac{a^2}{2\gamma\ell_p^2 j}\right)$ the parameter a is calculated as

$$a = 0.5GM \approx 7.12 \times 10^3\,\text{m}, \tag{39}$$

$$q(r, a) \approx 2.656 \times 10^4\left(1 - \frac{(7.12 \times 10^3)^2}{2 \times 1.2 \times 10^{-66}}\right) \approx 2.656 \times 10^4\,\text{m}. \tag{40}$$

The correction term is negligible for astrophysical black holes.

From the LQG the temperature modifications are proposed for this scenario as

$$T_{\text{modified}} = \frac{\hbar c^3}{8\pi GMk_B}\left(1 + \frac{\ell_p^2}{r_q^2}\right), \tag{41}$$

where $r_q = \dfrac{7}{6}R_s$ for non-rotating black holes or $r_q(a)$ for Kerr black holes. This confirms $T \propto M^{-1}$ and the quantum corrections are small but non-negligible.

For Gaia BH1,

$$T_{\text{modified}} \approx 6.4 \times 10^{-10}\left(1 + \frac{(1.616 \times 10^{-35})^2}{(2.656 \times 10^4)^2}\right) \approx 6.4 \times 10^{-10}\,\text{K}. \tag{42}$$

Due to the very low predicted temperatures for stellar-mass black holes like Gaia BH1, the direct observations of their thermal properties or quantum gravitational modifications are currently unfeasible. Therefore, this work focuses on other possible observational signatures arising from the LQG based quantum boundary r_q.

The quantum-corrected radius $r_q(a) = r_+\left(1 - \frac{a^2}{2\gamma\ell_p^2 j}\right)$ suggests a subtle modification to the event horizon geometry that could imprint a unique signature. As disussed earlier, we adopt the quantum-corrected radius $r_q(a) \approx (7/6)r_+$ for the Kerr black hole, which generates the Schwarzschild result. This modification to the effective boundary could imprint a unique signature in gravitational wave (GW) signals from black hole mergers that have Gaia BH1-like systems. For a Kerr black hole, the ringdown phase of GWs is governed by quasi-normal modes (QNMs) that are determined by r_+. In LQG, we propose that the quantum horizon exists at $r_q(a)$ that shifts the QNM frequencies slightly. Using the approximate form $\omega_{\rm QNM} \propto \frac{c}{r_{horizon}}$, the LQG-resolved frequency is written as

$$\omega_{\rm LQG} \approx \frac{c}{r_q(a)} \approx \frac{c}{(7/6)r_+} = \frac{6}{7}\frac{c}{r_+} = \frac{6}{7}\omega_{GR}\,, \tag{43}$$

where $\omega_{GR} \approx c/r_+$ represents the approximate fundamental QNM frequency in classical GR.

The fractional frequency shift predicted here is

$$\frac{\Delta\omega}{\omega_{GR}} = \frac{\omega_{LQG} - \omega_{GR}}{\omega_{GR}} \approx \frac{(6/7)\omega_{GR} - \omega_{GR}}{\omega_{GR}} = -\frac{1}{7}\,. \tag{44}$$

This implies a frequency reduction of about 14% compared to the classical GR prediction for the fundamental mode, which is independent of mass and spin within this approximation. While the approximation $\omega \propto 1/r$ is simplistic, a fractional shift of this magnitude (≈ 0.1) for QNMs exists. For supermassive black holes detectable by LISA, such a shift could be distinguished from classical predictions, which provides a testbed for this LQG solution near the horizon.

5 Quantum corrections for *b* parameter

In the earlier calculations, it has been identified that the classical values of the b seem to be an enormous value. Here the quantum corrections can be implemented on the same parameter in order to obtain its kinetics.

For a black hole with quantum gravitational corrections, the temperature can be obtained as shown in Calmet & Kuipers (2021), Campos Delgado (2022), and Ghosh et al. (2014).

The area quantization is obtained as

$$A = 8\pi\gamma l_p^2 j = 4\pi q(r)^2 => q(r) = \sqrt{2\gamma l_p^2 j}\,. \tag{45}$$

As explained in Section 2, we adopt the LQG-based result $r_q = (7/6)r_s$. If we use the parameterization $r_q = r_s(1 + b/6)$, that provides $b = 1$ for the Schwarzschild case.

The quantum-corrected radius $q(r)$ is obtained from LQG area quantization as

$$A = 8\pi\gamma\ell_p^2 j = 4\pi q(r)^2 \implies q(r) = \sqrt{2\gamma\ell_p^2 j}\,. \tag{46}$$

For a Schwarzschild black hole, this parameter becomes

$$q_{\rm Schw} = \frac{7}{6}r_s = \sqrt{2\gamma\ell_p^2 j}. \tag{47}$$

For a Kerr black hole, introducing the spin a leads to

$$q_{\rm Kerr} = \sqrt{2\gamma\ell_p^2 j - a^2}. \tag{48}$$

Deriving b for Schwarzschild ($a = 0$)

From the derived quantum radius, $q = r_s\left(1 + \frac{b}{6}\right)$:

$$\frac{7}{6}r_s = r_s\left(1 + \frac{b}{6}\right) \implies b = 1. \tag{49}$$

Equation 49 looks similar to Eq. 1.

Hence it can be concluded that for the Schwarzschild case the quantum corrected b parameter is written as

$$b = 1. \tag{50}$$

This value is consistent with the LQG area quantization $r_q = \sqrt{2\gamma l_p^2 j}$ if j takes the large value $j \approx (7/6)^2 r_s^2/(2\gamma l_p^2) \sim (M/M_p)^2$.

Deriving b for Kerr ($a \neq 0$)

The quantum-corrected Kerr radius is written as

$$q_{\rm Kerr} = \sqrt{2\gamma\ell_p^2 j - a^2} = r_+\left(1 + \frac{b}{6}\right), \tag{51}$$

where $r_+ = GM + \sqrt{(GM)^2 - a^2}$.

For a rotating Kerr black hole, the outer horizon is located at $r_+ = GM + \sqrt{(GM)^2 - a^2}$. We introduce the simplest generalization of the Schwarzschild result by assuming the quantum correction scales. This is proportional to the corresponding horizon radius. Thus, we can formulate the quantum-corrected radius for the Kerr case as

$$q_{\rm Kerr} \approx \frac{7}{6}r_+\,. \tag{52}$$

Using the same parameterization relative to the outer horizon, we can write

$$q_{\rm Kerr} = r_+\left(1 + \frac{b}{6}\right). \tag{53}$$

Comparison of Eqs 52 and 53 implies that parameter b remains approximately unity, even for rotating black holes:

$$b \approx 1\,. \tag{54}$$

This indicates that the relative strength of the quantum correction parameterized by b is largely independent of spin, even though the absolute radius $q_{\rm Kerr}$ depends on r_+.

It is important to note the fact that, if we define an "area radius" purely from LQG solution via $A = 4\pi(q_{Area}^2 + a^2)$, then we will find $q_{Area} = \sqrt{2\gamma l_p^2 j - a^2}$. Substituting the large $j \approx (r_+^2 + a^2)/(2\gamma l_p^2)$ provides $q_{Area} = r_+$. The fact that our adopted $q_{Kerr} \approx (7/6)r_+$ differs from the solution $q_{Area} = r_+$. This solution suggests the dynamic nature of the quantum radius. This resolution likely includes effects from modified dynamics or the effective metric near the quantum boundary. Our adoption of $q_{Kerr} \approx (7/6)r_+$ (such as $b \approx 1$) shows consistency with the established Schwarzschild result and its dynamical implications.

6 Conceptual implications: Singularity resolution and firewall avoidance

In classical General Relativity (GR), the Schwarzschild metric predicts a singularity at $r = 0$ and an event horizon at $r = r_s$. Curvature invariants, such as the Kretschmann scalar [Mercati & Sloan (2022); Del Piano et al. (2024)] can be written as

$$R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} = 48G^2M^2/r^6\,. \tag{55}$$

Equation 55 diverges as $r \to 0$, and tidal forces become infinite at the singularity.

The quantum field theory (QFT) in the curved spacetime near the horizon suggests the existence of Hawking radiation. This suggests black holes have a temperature T_H. The firewall paradox arises from a conflict between the implications of thermal Hawking radiation (information loss, violation of unitarity) and the principle of equivalence at the event horizon. If an infalling observer faces energized thermal particles which are enough to preserve unitarity (a "firewall"), it violates the equivalence principle. This phenomenon states spacetime should be locally flat and exist free from high-energy phenomena at the horizon.

LQG replaces the classical singularity with a quantum bounce, that alters the geometry of the horizon. The quantum-corrected radius is then written as

$$r_q = r_s\left(1 + \frac{b}{6}\right), \tag{56}$$

where $b = 1$ for Schwarzschild black holes.

This resolution extends the black hole horizon to a finite quantum boundary, and that avoids the divergence of the curvature.

At $r = r_q$, the Kretschmann scalar becomes

$$R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}|_{r_q} = \frac{48G^2M^2}{r_q^6} = \frac{48G^2M^2}{((7/6)r_s)^6} = \left(\frac{6}{7}\right)^6 \frac{48G^2M^2}{r_s^6}\,. \tag{57}$$

While the classical curvature diverges as $r \to r_s$ in some phenomena such as infinite blue shift for external observers, the LQG regularizes the geometry. This

implies that physical quantities remain finite at the quantum boundary r_q. But LQG introduces a Planck-scale cutoff, which suggests curvature invariants do not exceed $\sim l_p^{-4}$.

$$R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} \lesssim l_p^{-4}\,. \tag{58}$$

This resolution keeps the curvature bounded even near r_q and also the stress-energy tensor $< T_{\mu\nu} >$ of quantum fields remains finite as well.

For an infalling observer, the effective temperature experienced near r_q might be related to a modified surface gravity κ_q at this boundary. This provides $\kappa_q \approx c^2/(2r_q) = (6/7)\kappa_s$, which leads to an effective temperature as

$$T_q = \frac{\hbar\kappa_q}{2\pi c k_B} \approx \frac{6}{7}T_H = \frac{6}{7}\frac{\hbar c^3}{8\pi GMk_B} = \frac{3\hbar c^3}{28\pi GMk_B}\,, \tag{59}$$

which is finite and consistent with the equivalence principle. The absence of divergent energy density at r_q removes the necessity of a firewall. Observers crossing r_q experience smooth geometry without facing the high-energy radiation.

For Gaia BH1 ($M = 9.62M_\odot$, $r_s \approx 28.38\,\mathrm{km}$) the quantum radius is calculated as

$$r_q = \frac{7}{6}r_s \approx 33.11\,\mathrm{km}. \tag{60}$$

The curvature at this radius can be evaluated using the Kretschmann scalar

$$R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} = \frac{48G^2M^2}{r^6}\,. \tag{61}$$

At $r = r_q = (7/6)r_s$, this becomes

$$RR|_{r_q} = (6/7)^6 \times \left(\frac{48G^2M^2}{r_s^6}\right)\,. \tag{62}$$

Using $r_s \approx 2.838 \times 10^4$ m for Gaia BH1, we find that

$$R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}|_{r_q} \approx (0.463) \times \frac{48(6.674\times10^{-11})^2(1.913\times10^{31})^2}{(2.838\times10^4)^6} \approx 7.2\times10^{16}\ \mathrm{m}^{-4}\,. \tag{63}$$

This curvature, while large compared to typical astrophysical scales, is still vastly smaller than the Planck scale curvature $l_p^{-4} \sim (1.616\times10^{-35})^{-4}\ \mathrm{m}^{-4} \approx 1.5\times10^{140}\ \mathrm{m}^{-4}$. Therefore, the geometry remains smooth and far from the Planck regime at the quantum boundary r_q.

The effective temperature at r_q for Gaia BH1 is derived as

$$T_q \approx \frac{6}{7}T_H \approx \frac{6}{7}(6.41\times10^{-9}\ \mathrm{K}) \approx 5.49\times10^{-9}\ \mathrm{K}\,. \tag{64}$$

This obtained temperature lies far below the CMB temperature (2.7 K), which implies no detectable firewall exists for Gaia BH1. Theoretically, the existence of a finite transition layer $\Delta r = r_s/6$ between the classical horizon radius and the quantum boundary could also provide a physical region with enough degrees of freedom to store information that might otherwise be considered lost. This solution even preserves the unitarity.

6.1 Information encoding

The quantum horizon at $r_q = (7/6)r_s$ not only avoids the firewall but may also have the connection in preserving the information. The transition layer between the classical geometry ($r > r_q$) and the quantum geometry ($r < r_q$), with thickness $\Delta r = r_q - r_s = r_s/6$, could act as a quantum membrane. Such membrane encodes the information that would otherwise be lost in Hawking radiation.

The number of Planck lengths that can exist in this transition layer is calculated as

$$N_{l_p} = \frac{\Delta r}{l_p} = \frac{r_s/6}{l_p} \approx \frac{28.38 \times 10^3/6}{1.616 \times 10^{-35}} \approx 2.93 \times 10^{38}\,. \tag{65}$$

The area of the quantum boundary is obtained as

$$A_q = 4\pi r_q^2 = 4\pi \left(\frac{7}{6} r_s\right)^2 = \frac{49}{9}\pi r_s^2 \approx 1.377 \times 10^{10}\ \mathrm{m}^2\,. \tag{66}$$

We can define a heuristic information capacity I which is associated with the number of Planck-area bits within this transition shell. This is weighted by its relative thickness as

$$I = \frac{A_q}{l_p^2} \times \frac{\Delta r}{r_s} = \frac{A_q}{l_p^2} \times \frac{r_s/6}{r_s} = \frac{A_q}{6 l_p^2}\,. \tag{67}$$

Then for Gaia BH1, I would be

$$I \approx \frac{1.377 \times 10^{10}\ \mathrm{m}^2}{6 \times (1.616 \times 10^{-35}\ \mathrm{m})^2} \approx \frac{1.377 \times 10^{10}}{1.566 \times 10^{-69}} \approx 8.8 \times 10^{78}\,. \tag{68}$$

This capacity I resembles the Bekenstein–Hawking entropy $S_{BH}/k_B = A_{BH}/(4l_p^2)$ $\approx 4\pi r_s^2/(4l_p^2) \approx 9.7 \times 10^{78}$ for Gaia BH1. This suggests the quantum transition layer possesses enough degrees of freedom to store the black hole's information.

Since $A_q \propto r_s^2 \propto M^2$, this information capacity scales as $I \propto M^2$. For a supermassive black hole ($M \sim 10^9 M_\odot$), the numerical values of I could reach $\sim 10^{95}$. This shows a large capacity for information storage at the quantum boundary. This LQG mechanism avoids firewalls by implementing a physical structure (r_q and the transition layer) which is consistent with the equivalence principle.

For Gaia BH1 we have $I \approx 8.78 \times 10^{78}$ bits that can be mapped as $I \propto M^2$ (since $A_q \propto r_s^2 \propto M^2$, $\Delta r \propto M$, $r_s \propto M$). Then for a a supermassive black hole ($M = 10^6 M_\odot$), it has $I \sim 10^{86}$ bits. This phenomenon confirms that the information from evaporating particles is retained at r_q, which can be observed indirectly via GW signatures or radiation anomalies.

7 Testable predictions

The core idea which is discussed here is that the modification of the near-horizon boundary condition, from the classical r_s to the LQG-based r_q, induces subtle but observable deviations in the macroscopic astrophysical scales. The subsequent sections calculate the predicted magnitude of these deviations.

7.1 Perihelion precession anomaly in Gaia BH1

We can even consider the Gaia BH1 as a laboratory for near-term LQG testing. In GR the gravitational potential for a point mass is written as $V(r) = -\frac{GM}{r}$. For a binary system like Gaia BH1, the Sun-like companion orbits at a semi-major axis $a \approx 1\,\text{AU}$, which is far from the Schwarzschild radius r_s. Hence the Newtonian dynamics dominate in this binary system, with relativistic corrections (e.g., perihelion precession). Then the scaling can be done as $\frac{r_s}{r}$. The quantum resolved radius $r_q = r_s\left(1 + \frac{b}{6}\right)$, with $b = 1$ suggests a modified effective horizon, which may perturb the gravitational potential beyond r_s due to the quantum effects.

We can consider the following hypothesis such as the LQG modification at r_q induces a small perturbation in the gravitational potential of the binary system, which could affect the companion's orbit at $r \gg r_q$. To prove this we can derive the solutions using a Newtonian approximation and such can be mapped to the LQG. The Gaia BH1 system has its black hole mass as $M = 9.62M_\odot = 9.62 \times 1.989 \times 10^{30} = 1.913 \times 10^{31}\,\text{kg}$, Schwarzschild radius $r_s = 28.38\,\text{km}$, the quantum-corrected radius as $r_q = \frac{7}{6}r_s = 33.11\,\text{km}$, semi-major axis $a \approx 1\,\text{AU} = 1.496 \times 10^{11}\,\text{m}$ and orbital period that is obtained by Kepler's third law as

$$T = 2\pi\sqrt{\frac{a^3}{GM}} = 2\pi\sqrt{\frac{(1.496 \times 10^{11})^3}{6.674 \times 10^{-11} \times 1.913 \times 10^{31}}} \approx 1.017 \times 10^7\,\text{s} \approx 0.322\,\text{year}\,. \tag{69}$$

This period is consistent with observations of a Sun-like star orbit. From GR, this orbit does not look perfectly closed but exhibits precession of perihelion. For a nearly circular orbit ($e \approx 0$), the precession per orbit is given by

$$\Delta\phi_{\text{GR}}(\text{per orbit}) = \frac{6\pi GM}{c^2 a(1-e^2)}\,. \tag{70}$$

Numerically, this is obtained as

$$\Delta\phi_{\text{GR}}(\text{per orbit}) \approx \frac{6\pi(6.674 \times 10^{-11})(1.913 \times 10^{31})}{(3 \times 10^8)^2(1.496 \times 10^{11})(1-0)}\,, \tag{71}$$

$$\approx 1.787 \times 10^{-6}\ \text{radians/orbit}\,. \tag{72}$$

This result can be explained in observable units such as arcseconds per century

- Orbits per century ≈ 100 years/0.322 years/orbit ≈ 310.6 orbits/century
- Arcseconds per orbit $\approx 1.787 \times 10^{-6}$ rad $\times (180/\pi)$ deg/rad $\times 3600$ arcsec/deg $\approx$ 0.369 arcsec/orbit
- GR precession rate ≈ 0.369 arcsec/orbit $\times 310.6$ orbits/century ≈ 114.5 arcsec/century

$$\Delta\phi_{\text{GR}} \approx 114.5\ \text{arcsec/century}\,. \tag{73}$$

This conventional GR precession is reasonable but the direct measurements of perturbations in such a wide binary look challenging.

It is important to emphasize that the parameter $\Delta\phi_{GR}$ represents the perihelion precession predicted by General Relativity itself, which includes the relativistic corrections to Newtonian gravity.

Our core calculations, based on LQG considerations, indicate an effective quantum boundary at $r_q = (7/6)r_s$, which resides just outside the classical event horizon r_s. This represents a modification of the near-horizon geometry. While the primary effects of this boundary are expected near r_s, it is conceivable that this modification could induce a small perturbation to the gravitational potential even at large distances ($r \gg r_s$), potentially affecting the companion's orbit.

Obtaining the precision form of this perturbation far from the modified horizon requires a depth of understanding of the effective metric or stress-energy tensor that emerges from the LQG corrections. This is beyond the scope of current models and this work.

Anyhow, we can make a heuristic estimate based on a basic scaling argument. The relative scale of the quantum modification near the horizon is characterized by the shift $\Delta r = r_q - r_s = r_s/6$. We calculate that any consequential anomalous precession, $\Delta\phi_{\text{anomaly}}$, might scale proportionally to the conventional GR precession, which is weighted by the relative shift.

$$\Delta\phi_{\text{anomaly}} \approx \left(\frac{\Delta r}{r_s}\right) \times \Delta\phi_{\text{GR}} = \left(\frac{r_s/6}{r_s}\right) \times \Delta\phi_{\text{GR}} = \frac{1}{6}\Delta\phi_{\text{GR}}\,. \tag{74}$$

Using the corrected GR precession rate from Eq. (73) is obtained as

$$\Delta\phi_{\text{anomaly}} \approx \frac{1}{6} \times 114.5 \text{ arcsec/century} \approx 19.1 \text{ arcsec/century}\,. \tag{75}$$

This prediction suggests the existence of an anomalous precession contribution from the LQG boundary effect. The total predicted precession would be the sum of the standard GR effect and this additional anomaly.

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{GR}} + \Delta\phi_{\text{anomaly}} \approx 114.5 + 19.1 \approx 133.6 \text{ arcsec/century}\,. \tag{76}$$

The distinguishing characteristic lies in the *relative* contribution of the anomaly compared to the usual GR prediction.

$$\text{Percentage Increase} = \frac{\Delta\phi_{\text{anomaly}}}{\Delta\phi_{\text{GR}}} \times 100\% \approx \frac{19.1}{114.5} \times 100\% \approx 16.7\%\,. \tag{77}$$

Hence,

$$\frac{\Delta\phi_{\text{anomaly}}}{\Delta\phi_{\text{GR}}} \approx \frac{1}{6} \approx 16.7\%\,. \tag{78}$$

Therefore, to directly address the comparison baseline, this predicted 16.7% anomaly represents the calculated deviation relative to the General Relativistic precession $\Delta\phi_{GR}$, but not just a deviation from simple Keplerian motion.

It is important to note that this prediction of a **∼16.7% increase** over the conventional GR precession is based on a heuristic scaling argument. However, this estimate provides a rigorous numerical target value. Detecting such an anomaly would require high-precision astrometry over long timescales, which should also be capable of isolating this effect from classical perturbations and usual GR effects. Future instruments

like GaiaNIR or successors that aim for micro-arcsecond accuracy might eventually probe this regime. Even though challenges in observations, the detection of such an anomalous precession would provide a unique test of near-horizon quantum gravity modifications.

7.2 Quantum gravitational echoes from r_q

The LQG resolved radius $r_q = \frac{7}{6} r_s$ implies a reflective boundary just outside the classical horizon of a black hole. This may be able to produce "echoes" in gravitational wave (GW) signals soon after the merger. The generated gravitational waves could be reflected between r_q and the inner potential barrier.

The echo time delay can be predicted via

$$\Delta t \approx \frac{2(r_q - r_s)}{c} = \frac{2\left(\frac{r_s}{6}\right)}{c} = \frac{r_s}{3c}. \tag{79}$$

For Gaia BH1 ($r_s \approx 28.38\,\text{km}$), $\Delta t \approx 3.16 \times 10^{-5}\,\text{s}$. For a supermassive black hole ($M \sim 10^6 M_\odot$, $r_s \sim 3 \times 10^6\,\text{km}$), $\Delta t \sim 10\,\text{s}$. And this time detail could be detectable by LIGO or LISA. Unlike classical echoes from astrophysical objects, these LQG echoes scale directly with r_s. This will provide a groundbreaking signature of quantum gravity observable in GW data.

7.3 LQG-induced Hawking radiation spectral shift

As discussed in earlier sections, the effective temperature T_q associated with the quantum boundary r_q may vary a little from the standard Hawking temperature T_H. Using the solution $T_q \approx (6/7)T_H$, the fractional shift is written as

$$\frac{\Delta T}{T_H} = \frac{T_q - T_H}{T_H} \approx \frac{(6/7)T_H - T_H}{T_H} = -\frac{1}{7}\,. \tag{80}$$

For astrophysical black holes like Gaia BH1, T_H is extremely small. This allows the absolute shift to be undetectable. However, for primordial black holes (PBHs), T_H can be significant. PBH with $M \sim 10^{12}$ kg will have $T_H \sim 10^{11}$ K. A fractional shift of $-1/7$ in such a high temperature can be observable in the spectrum of emitted gamma rays or other particles, or even in ground-based experiments. This provides another, albeit challenging, observational possibility for probing LQG effects.

8 Conclusion

In this work, we have calculated the possible observational signatures that emerge from near-horizon quantum gravitational effects. Our solutions implement the quantum corrections from LQG, which suggests the existence of an effective boundary located slightly outside the classical horizon, especially at $r_q = (7/6)r_s$ for any Schwarzschild black holes. The exact boundary is described for Kerr black holes as $r_q \approx (7/6)r_+$.

By applying these solutions to the Gaia BH1 system, we derived heuristic estimates for the possible observable signatures. This prediction includes an anomalous orbital precession for the companion star. By underlining the baseline for comparison, this anomaly is estimated at approximately +16.7%. This represents the predicted deviation relative to the precession calculated using General Relativity (including the relativistic corrections), rather than a deviation from simple Keplerian motion.

This result could be a target for future high-precision astrometry. The production of gravitational wave echoes following black hole mergers, is derived through a time delay of $\Delta t = r_s/3c$.

The consistency of the required large j value, the resolution of the firewall paradox, and the potential for information encoding further strengthen these predicted solutions. Future observational constraints on anomalous precession in binary systems like Gaia BH1, or the detection (or even non-detection) of predicted GW echoes or QNM shifts, could provide experimental resolution for finetuning or validating LQG solutions of black hole horizons. This study highlights the importance of astronomical systems like Gaia BH1, which can act as unique laboratories for testing the quantum nature of spacetime. By connecting LQG predictions to the observable phenomena, this work represents a step towards bridging the gap between theoretical quantum gravity and its validation.

Acknowledgements

The author thanks Mr. Jayachandran for his motivation and support for this research.

References

Ashtekar, A. 2007, arXiv preprint gr-qc/0702030
Ashtekar, A. 2020, Universe, 6, 21
Ashtekar, A. & Bianchi, E. 2021, Reports on Progress in Physics, 84, 042001
Bar, D. 2007, International Journal of Theoretical Physics, 46, 664
Bekenstein, J. D. 1980, Physics Today, 33, 24
Bodendorfer, N., Schäfer, A., & Schliemann, J. 2019, Journal of High Energy Physics, 2019, 1
Böhmer, C. G. & Vandersloot, K. 2007, Physical Review D – Particles, Fields, Gravitation, and Cosmology, 76, 104030
Bojowald, M. 2001, Physical Review Letters, 86, 5227
Bojowald, M. 2008, Living Reviews in Relativity, 11, 1
Calmet, X. & Kuipers, F. 2021, Physical Review D, 104, 066012
Campos Delgado, R. 2022, The European Physical Journal C, 82, 272
Carlip, S. 2014, International Journal of Modern Physics D, 23, 1430023
Del Piano, M., Hohenegger, S., & Sannino, F. 2024, Physical Review D, 109, 024045
El-Badry, K., Rix, H.-W., Quataert, E., et al. 2022, Monthly Notices of the Royal Astronomical Society, 518, 1057
Engelhardt, N., Hertog, T., & Horowitz, G. T. 2015, Journal of High Energy Physics, 2015, 1

Ghosh, A., Noui, K., & Perez, A. 2014, Physical Review D, 89, 084069
Giddings, S. B. 1995, arXiv preprint hep-th/9508151
Gourgoulhon, É. 2018, Les Houches
Haggard, H. M. & Rovelli, C. 2016, International Journal of Modern Physics D, 25, 1644021
Hawking, S. W. 1975, Communications in mathematical physics, 43, 199
Hughston, L. P. & Sommers, P. 1973, Communications in Mathematical Physics, 33, 129
Kotko, I., Banerjee, S., & Belczynski, K. 2024, Monthly Notices of the Royal Astronomical Society, 535, 3577
Li, B.-F. & Singh, P. 2023, in Handbook of Quantum Gravity (Springer), 1, 55
Li, Z., Zhu, C., Lu, X., et al. 2024, The Astrophysical Journal Letters, 975, L8
Mercati, F. & Sloan, D. 2022, Physical Review D, 106, 044015
Nicolai, H., Peeters, K., & Zamaklar, M. 2005, Classical and Quantum Gravity, 22, R193
O'Neill, B. 2014, The geometry of Kerr black holes (Courier Corporation)
Page, D. N. 2005, New Journal of Physics, 7, 203
Perez, A. 2017, Reports on Progress in Physics, 80, 126901
Psaltis, D., Perrodin, D., Dienes, K. R., & Mocioiu, I. 2008, Physical Review Letters, 100, 091101
Rastello, S., Iorio, G., Mapelli, M., et al. 2023, Monthly Notices of the Royal Astronomical Society, 526, 740
Rovelli, C. 1996, Physical Review Letters, 77, 3288
Rovelli, C. 2008, Living reviews in relativity, 11, 1
Rovelli, C. & Smerlak, M. 2011, Classical and Quantum Gravity, 28, 075007
Silva, C. 2020, Physical Review D, 102, 046001
Thiemann, T. 2003, in Quantum gravity: From theory to experimental search (Springer), 41, 135
Zhang, J. & Zhao, Z. 2005, Modern Physics Letters A, 20, 1673