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# Stretched Horizon as a Quantum Gravity Beam Splitter

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The disentanglement of a black hole with its Hawking radiation is a form of CNOT operation that demolishes entanglements. This mechanism is due to boundary condition set up on the stretched horizon in holography. This is reconsidered here as an entanglement swap with the transfer of entanglement, where aged Hawking radiation is not entangled with the black hole (BH), but rather with gravitons or BMS charges at $I^+$.

**Keywords: event horizon, hawking radiation, firewall, entanglement, BMS symmetries**

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## INFORMATION, FIREWALLS AND DISENTANGLEMENT

A central canon of wave physics is Huygens' principle. This says that a wave at any point in space evolves from that point as a spherical wave. How the entire wave behaves is a result of constructive and destructive interference. Hence an elementary plane wave is a Fourier sum of an infinite number of Bessel functions for spherical wave fronts. This means for a spacetime with Lorentzian metric that a field at a point is determined by data on a spatial surface that intersects the past light cone and its interior. Similarly, data in the future region of a spatial surface in the future light cone are determined by the data at this point. Hence data on the past region $I^-(x)$ is equivalent to data on the future $I^+(x)$. If the field data evolves according to the conformal equation $\varphi - {}^{1/6} R\varphi = 0$ this means data is carried to conformal boundaries. We then expect that.

$$data \in I^+ = data \in I^-$$

Hence data that enters a local region from will then scatter to +, which is remarkably similar to the idea of the S-matrix. It also is something we would expect in a universe where quantum information is conserved, such as with the holographic principle.

Consider the hypothesis advanced by Hossenfelder that disentanglement of Hawking radiation by Bogoliubov transformations can address the firewall problem [1]. In this analysis and in what follows in this paper we consider only the Schwarzschild BH. The AMPs thesis [3] is for an inconsistency between unitarity of quantum mechanics and the equivalence principle of relativity. The emission of Hawking radiation means there is an entanglement with an emitted boson and the BH. After the BH has emitted half its mass, or equivalently it has emitted about half its quantum information, Hawking radiation that is emitted is entangled with both the BH and Hawking radiation emitted in the past. From the perspective of the old Hawking radiation in a bipartite entanglement with the black hole is transformed into a triparite entanglement by a quantum process. This is a violation of quantum monogamy, which is a violation not permitted by unitarity of quantum mechanics. This suggests some incompatibility between gravitation and quantum mechanics still unaddressed [3]. In addition, the entanglement entropy of the black hole continues to increase and surpasses the Bekenstein bound. The firewall is an artifact put on the black hole to preserve unitarity and that violates the equivalence principle; it is a form of singularity that seals the interior of the black hole from entry by any quantum state from the exterior or exit from the interior. The proposal by Hossenfelder is there is a disentanglement of such Hawking radiation that prevents this, where Bogoliubov transformed operators $A = a\ cosh(gs) + a^\dagger\ sinh(gs)$

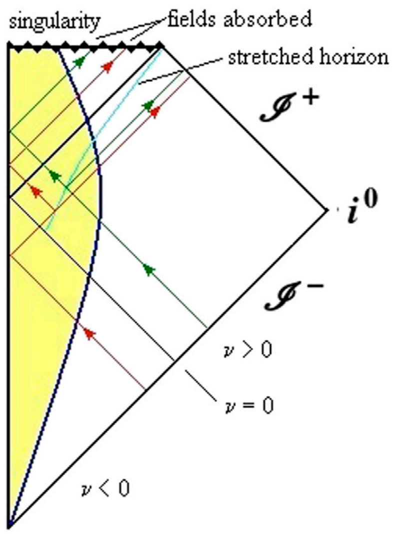

**FIGURE 1 |** Penrose diagram for black hole and the stretched horizon.

disentangle with $sinh(gs) \sim e^{-E\beta}$, with $s < 0$ and for $g \propto kT$ and $T >> 0$ and representing the loss of entanglement.

The bipartite entanglement of the system $AB$ and $C$ is $\delta I(A{:}\, B\, C)$. The absorption or emission of a quantum particle by a BH has a metric response in a back reaction. This response can be a gravitational wave, though that is not well understood. This quantum mutual information is then a graviton produced by the black hole. Ignoring this term means this is just a bipartite entanglement. This ignored information carried away or embossed onto spacetime itself is a form of a BMS supertranslation or charge. Hossenfelder illustrates how fields that enter the BH with $\nu > 0$ interact with the stretched horizon as a surface of boundary conditions, as seen in **Figure 1**. The Bogoliubov transformation defines and is determined by a local operator, thus the boundary condition sending a field amplitude to $I^+$ is locally determined. Yet a graviton emitted by a black hole is also entangled with the black hole, which in turn is entangled with the Hawking radiation. Hence, this process as a local operation is only an approximation. This approximation is accurate to the extent the graviton is far more weakly interacting than the field of interest. The local operation is then a re-entanglement that establishes a non-local entanglement with gravitational information in the limit $\nu \to \infty$ and approaching $I^+$.

The in and out directed modes in Hawking radiation denoted as $|\Phi(k)_\pm\rangle$ are

$$|\Phi(k) \pm\rangle = A^T|\phi \pm\rangle =: |A \pm\rangle - |B \pm\rangle$$

where the matrices giving the exterior and interior states are

$$A = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 - \mathrm{i}w^2 & 1 - iw^2 \\ 1 + w^2 & -1 - w^2 \end{pmatrix}$$
$$B = \frac{w}{\sqrt{2}}\begin{pmatrix} 1 - \mathrm{i} & 1 - i \\ 1 + w & -1 - i \end{pmatrix}$$

Here $w^2 = 1/(e^{2\pi\omega(k)/g} - 1)$, for $g$ the gravity computed from $\xi^\nu\nabla_\nu\xi^\mu = g\xi^\mu$ and $\xi$ the killing vector for the BH coordinates. These then define the $\pm$ states that reach $\mathrm{I}^+$ or that fall across the horizon. The state entanglement between the exterior $A_\pm$ and interior $B_\pm$ is

$$|\Psi\rangle \to \frac{1}{\sqrt{2}}\left(|A_+\rangle|B_+\rangle + |A_-\rangle|B_-\rangle\right) \tag{1}$$

However, the reflection off the boundary condition on the stretched horizon induces the transformations.

$$\begin{aligned} |A_\pm\rangle &\to \frac{1}{\sqrt{2}}\left(|A_\pm\rangle + i|B_\pm\rangle\right) \\ |B_\pm\rangle &\to \frac{1}{\sqrt{2}}\left(|A_\pm\rangle - i|B_\pm\rangle\right) \end{aligned} \tag{2}$$

This transforms the entangled state into

$$|\Psi\rangle \to \frac{1}{4}\left(|A_+\rangle|A_+\rangle + |B_+\rangle|B_+\rangle + |A_-\rangle|A_-\rangle + |B_-\rangle|B_-\rangle\right) \tag{3}$$

which is no longer an entanglement of states exterior and interior to the black hole. This is effectively the operation of a CNOT gate, a local operation that destroys entanglements.

If quantum information is ultimately conserved this operation violates unitarity and is some semi-classical approximation. Hawking radiation also result in a metric back reaction, which is a classical effect of adjusting the metric to account for the loss of mass-energy in the emission of a Hawking boson. Consider this as a classical system behind the CNOT gate. Decoherence is the loss of entanglement to the environment [4]. To account for this, consider this non-local entanglement phase as carried off by gravitons or as BMS supertranslations.

## HORIZON AS BEAM SPLITTER; ENTANGLEMENT OF STATES AND BMS DYNAMICS

The BMS symmetry describes motion of test charges due to gravitational radiation from a perturbed gravitating source or black hole [5]. Gravitational memory is a measure of the final positions of the masses not being the same necessarily as their initial positions. This is then a set of translations that carry information about the gravitational radiation. The Bondi metric for gravitational memory is

$$\begin{aligned} ds^2 = \; & du^2 - 2dudr + 2r^2\gamma_{z\bar{z}} + \frac{2m}{r}du^2 + rC_{zz} + rC_{\bar{z}\bar{z}}d\bar{z}^2 \\ & + D^zC_{zz}dudz + D^{\bar{z}}C_{\bar{z}\bar{z}}dud\bar{z} + \ldots \end{aligned}$$

for $\gamma_{z\bar{z}} = 2(1 + z\bar{z})^{-2}$ the metric on the unit $\mathrm{S}^2$ sphere. The term $m_B$ is the Bondi mass term, say for and BH and source of mass-energy propagating out to $\mathrm{I}^+$, where the coordinate $u$ is defined. The terms $C_{zz}$ and $C_{\bar{z}\bar{z}}$ determine Weyl curvature terms for gravitational wave propagating out. An Einstein field equation is

$$D_{\bar{z}}^2C_{zz} + D_z^2C_{\bar{z}\bar{z}} = 0$$

which gives the simple solution $C_{zz} = D^2C(z, \bar{z})$. Here $C(z, \bar{z})$ is a scalar potential. The change in this potential is a change in Weyl curvature with the passage of a gravitational wave.

The curvature has two parts, one that is conformal and a source term that is not. These define the Bondi mass, and the rate this changes in time, or the parameter $u$ at $I^+$ is

$$\frac{\partial m_B}{\partial u} = \frac{1}{4}\left(D_z D_z N^{zz} + cc\right) - \frac{1}{4}\left(N_{zz}N^{zz} + c.c\right) + 4\Pi G T_{uu}(matter)|r \rightarrow \infty$$

where $N_{zz} = \partial_u C_{zz}$ is the Bondi news [6]. The term $^1\ N_{zz}N^{zz}$ is the flux of gravitational radiation. The stationary spacetime has $M$, $Q$, $J$ as Noether charges or conserved quantities. This system has a single set of local symmetries. These are the Lorentz or Poincare symmetries on a spatial surface, which is defined on $i_0$ since all spatial surfaces contact there. The evolution of the Bondi mass is then a manifestation of these plus abelian symmetries of supertranslations that reach $I^+$.

The supertranslations in the variables $u, r, z. \bar{z}$, are

$$u \rightarrow u + f(z, \bar{z})$$
$$r \rightarrow r - D^z D_z f(z, \bar{z})$$
$$z \rightarrow z + \frac{1}{r} D^z f(z, \bar{z})$$

for a function $f(z, \bar{z})$, and the translation for $\bar{z}$ evident. A general infinitesimal supertranslation can be easily seen from these

$$\xi = f(z, \bar{z})\frac{\partial}{\partial u} + D^z D_z f(z, \bar{z})\frac{\partial}{\partial r} - \frac{1}{r}\left(D^z f(z, \bar{z})\frac{\partial}{\partial z} + c.c\right)$$

Now compute the Lie derivative of the Bondi mass and Weyl curvature and the Bondi mass

$$L_\xi m_B = f(z, \bar{z})\frac{\partial m_B}{\partial u}$$

where $\partial m_B/\partial u$ given above, and the Weyl curvature

$$L_\xi C_{zz} = f(z, \bar{z}) N_{zz} - 2D\frac{2}{z} f(z, \bar{z})$$

The supertranslations are additive, where for $\xi$ and $\xi'$ we have additive properties $\xi'' = \xi + \xi'$, and these are generators of a group with $g = e^{pa\xi a}$ with the index summed over $u, r, z, \bar{z}$. Clearly for $g' = e^{pa\xi'}$ we have that $gg' = g'g$ from the additive nature of the supertranslation vectors and that metric elements are commutative. This is then an infinite dimensional abelian group. The BMS symmetries are then a semi-direct product of the Poincare symmetries at $i^0$ with a group A of abelian symmetries $BMS = SO(3, 1)$ u A. An elementary realization with one unitary symmetry is $O(3, 1) = SO(3, 1) \times U(1)$ [7].

This gravitational information is carried away by $C_{zz}$ and $C_{\bar{z}\bar{z}}$ and the potential $C(z, \bar{z})$ is considered a quantum state for a single graviton. We then write this as $|C_{\pm,\pm}\rangle = |C^{(1)}\rangle|C^2\ \rangle$, so the operator consider the exterior states as entangled with one of these. The Hawking radiation is considered to have one degree of freedom that is only entangled with one polarization direction as a gravitational degree of freedom. The initial eigenstates for the Weyl state are $C(+,-)$ and $C(-, +)$ which has zero helicity. This is a scalar field or a model for the graviton vacuum state. This is then included in the entangled state so **Eq. 1** becomes

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|A_+\rangle|B_+\rangle|C_-\rangle|C_+\rangle + |A_-\rangle|B_-\rangle|C_+\rangle|C_-\rangle\right) \quad (4)$$

The scalar field or vacuum is in a singlet entanglement with the exterior state $A_\pm$. The exterior and interior states are now transformed with a new equation instead of **Eq. 2**.

$$|A_\pm\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|A_\pm\rangle + i|B_\mp\rangle\right)$$
$$|B_\pm\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|B_\pm\rangle + i|A_\mp\rangle\right)$$

with the additional transformation that will generate the graviton

$$|C_\pm^{(1)}\rangle \rightarrow \frac{1}{\sqrt{2}}|C_\pm^{(1)}\rangle + i|C_\pm^{(2)}\rangle$$
$$|C_\pm^{(2)}\rangle \rightarrow \frac{1}{\sqrt{2}}|C_\pm^{(2)}\rangle + i|C_\pm^{(1)}\rangle$$

The entangled state is transformed into

$$|\Psi\rangle \rightarrow \frac{1}{2}\left((1-i)|A_+\rangle|A_-\rangle + (1+i)|B_+\rangle|B_-\rangle\right)\left(|C_+^{(1)}\rangle|C_+^{(2)}\rangle + |C_-^{(1)}\rangle|C_-^{(1)}\rangle\right) \quad (5)$$

What is evident is the entanglement between the interior and exterior states of the black hole is removed. If the observer fails to account for the graviton it will then appear that there has been a disentanglement of the black hole with a loss of quantum phase. However, the four-way entanglement between the interior and exterior states of the black hole in addition entangled with the vacuum is swapped so now the exterior and interior states of the black hole are entangled with a quantum gravitational qubit or a graviton that carries information off to $^+$. Classically $N_{zz} = \partial_u C_{zz}$ is the Bondi news, and in this quantum setting the Bondi news has two states, or is equivalent to a triplet entanglement of helicity one states, that carry half of the 4-way entanglement information. The remaining exterior and interior state of the black hole are then entangled with the gravitons at $^+$. The exterior states are the Hawking radiation emitted by the black hole.

The graviton may be thought of as an entanglement built from operators $a_r^\dagger a_l^\dagger + a_l a_r$, in a string con-text of left and right modes, to construct the graviton as a triplet state of the form $^{1/\sqrt{2}}\ (|+, +\rangle + |-, -\rangle)$.

The entanglement swap seen in **Eq. 5** transforms the gravity vacuum state into a graviton of this sort. In a gauge-like construction a graviton is a bound state, pairing or entanglement between two gluon-like gauge bosons in a colorless spin-2 state. The transformation then sets the entanglement into a 4-fold entanglement. This is the maximal entanglement and correspondingly the maximum entanglement entropy [7].

This has some similarities with Susskind's $ER = EPR$ [8] hypothesis that entangled particles are connected by a non-traversable wormhole, such as a black hole. The entanglement between particles inside and outside of a black hole are converted into an entanglement at $I^+$, where we may say in some sense this entanglement is equivalent to a connection by an Einstein-Rosen bridge. This entanglement swap is also a type of map between states on a black hole to states on a cosmological horizon. The hydrogen-like states of a BH using the de Sitter metric is another form of this equivalency between entangled states and those in an ER bridge.

The essential feature of this is that the system is open. The transfer of quantum information from – to + is not restricted to a closed system with diffeomorphisms of spatial surfaces according to local Lorentz symmetries at $i^0$. This is then a scattering problem that obeys a form of the Huygens' principle. This holds, at least to a good degree of approximation, even though spacetime shearing may complicate this Huygens' principle. For vacuum spacetimes the self-dual and anti self-dual Weyl curvatures in complex [9] variables preserve the phase space volume in general relativity [10]. This holds if the shear curvature is conformal. The duality of the Weyl tensor $C^+_{abcd} + C^-_{abcd}$, a complex part plus its complex conjugate is under the Hodge star operation

$$*C^{\pm}_{abcd} = \epsilon^{ef}_{ab} C^{\mp}_{efcd}$$

such that $C^{\pm}_{abcd}$ are independent tensors, and the BMS group is conformal [11]. These then can contain the shear in a chiral manner with $C^{\pm}$ left and right handed chiralities. The self duality and anti-self duality of the Weyl tensor then means the shearing does not change the phase space volume. Now identify $C_{abcd}{}^+$ with $C^+_{abcd}$ and $C_{\bar{z}\bar{z}}$ with $C^-_{abcd}$. The evolution of the Bondi mass is governed by the term $1/4(D_z D_z N^{zz} + cc) - 1/4\ (N_{zz}N^{zz} + c.c)$ that clearly will satisfy the Penrose condition on shear. The source term $4\pi G T_{uu}(matter)\ _{r\to\infty}$ is of less concern if the matter is in a localized region far from the asymptotic $I^{\pm}$.

The contribution of the matter term may be handled in a perturbation type series. The function $f\ (z,\ \bar{z})$ for the supertranslation may be approximated as

$$f(z,\bar{z}) = f_0(z,\bar{z}) + G(k + i\epsilon)Vf(z,\bar{z})$$

for $V$ a potential $V'\ T^{00}$. This potential will then largely be the Newtonian gravitational potential of the black hole. We may then construct a series with the first $f_0(z, \bar{z})$ and this is used to compute the first term

$$f_1(z,\bar{z}) = f_0(z,\bar{z}) + G(k + i\epsilon)Vf_0(z,\bar{z})$$

We may then write the perturbed function as $f_1(z, \bar{z}) = f_0(z, \bar{z}) + {}^1 \int d^3qe^{ikq}V(q)$. We may then replace the non-conformal matter term with a complex function that satisfies the Cauchy-Riemann conditions. In this manner what shearing occurs locally to the black hole may be expressed in a conformal manner. This treatment is similar to the Lippman-Schwinger method leading to the Born scattering approximation and series.

The holographic screen as a beam splitter means an entanglement shift, disentanglement between old Hawking radiation and a black hole and re-entanglement of that radiation with data on $^+$. The fly in the ointment is the source term. It is then argued that what difficulties exist with quantum error correction lies with the non-conformal nature of this term. However, with suitable perturbation series this difficulty may be reduced. This then suggests a perfect quantum error correction code would exists where this series is convergent to conformal physics and the holographic principle [12]. This may not be entirely possible, but this may proved a better understanding. The complete convergence might then be equivalent to finding a method for the renormalization of quantum gravitation to all orders.

This physics proposes the disentanglement of a black hole with Hawking radiation is a non-local entanglement swap. The old Hawking radiation is entangled with gravitons at, or for practical concerns near, $^+$. This process may be associated with a perfect quantum error correction code. It is in line with the requirement that Verlinde and Verlinde laid out with the requirement for an open world [13]. The source term is of course still an open problem. The procedure suggested with a perturbation series may converge to some solution where in the limit the loss of conformal structure is zero. However, this may not happen, but it might provide a better understanding of where a quantum error correction code lies. Conformal invariance is broken with mass, for a massive particle has a Compton wavelength that defines a scale where the particle is surrounded by a virtual cloud that is probed at high energy to generate other particles. The occurrence of mass with particles is with the coupling of the Higgs field with particle states. The Higgs particle may in fact be a source of the zitterbewegung motion of a massless particle within a region defined by the Compton wavelength. Elementary particles have extremely low masses compared to the Planck scale, which is why gravitation is such a weak field. It also means the influence of conformal invariance violations by mass on quantum gravitation is proportionately the same.

The ratio of the mass of the Higgs with the Planck mass defines a form of the gravitational coupling $\alpha_g = 1.0478 \times 10^{-34}$. The weakness of the gravitational interaction at the IR scale or with the Higgs particle reflects the degree to which the masses of elementary particles have a tiny influence on conformal quantum gravitation. This means the Huygens' principle is a good approximation since quantum gravitation is conformal, or at least almost conformal.

## CONNECTION TO ER = EPR

Susskind has proposed a solution to the violation of quantum monogamy by indicating how the EPR result of entanglement is related to or equivalent to the Einstein-Rosen bridge. This hypothesis emerged after Raamsdonk's observation [14] that an AdS-Schwarzschild black hole is dual to an entanglement between conformal field theories in the AdS/CFT correspondence. The Schwarzschild black hole is entangled with another black hole connected by a spacelike region that forms the non-traversable wormhole. The two black holes can be thought to have been produced with a huge number of entangled states, where in this idealization the two black holes are also entangled. The emission of Hawking radiation means that radiation is entangled with the black hole. This continues until the Page time, where the black hole has emitted half its mass or quantum numbers. At this point emitted Hawking radiation is now entangled with previously emitted Hawking radiation and the black hole. This would be a process that transforms the old Hawking radiation in a bipartite entanglement into a tripartite entanglement. This cannot be a unitary process. However, if this black hole is connected by an ER bridge to an entangled black hole then this third entanglement can be taken up that way [8]. There is then no claim of a unitary evolution that changes a bipartite entanglement to a tripartite entanglement.

The observable physical universe does not have entangled black holes. Within a vast multiverse setting this might be the case, but there is no manner by which we can ever show a black hole in our spacetime is entangled with a black hole in another cosmology. We might though be able to show an equivalency to gravitational waves. The BMS metric connects black holes with gravitational memory, where information in a black hole can be transformed to gravitational information at $I^+$.

A near transformation of a black hole to a gravitational wave is to put the BH on an extreme Lorentz boost. For a passage close to an observer at velocity extremely close to the speed of light it will appear similar to a gravitational wave. Now the transformation is not 100%, and this is because the BH is classically not destructible. We can see this with the transformation of the Schwarzschild metric with $g_{tt}$ = 1 $2m/r$ and $g_{rr}$ = (1 $2m/r)^{-1}$. In a weak field approximation or where the moving black hole passes some distance from the observer we can set $g_{rr}$ 1 with $g = \Lambda^{-1}g\Lambda$ the metric terms in Cartesian coordinates transform as

$$\begin{aligned} g_{tt} &\to \gamma^2 (g_{tt} + \beta^2) \\ g_{xx} = 1 &\to \gamma^2 (1 + \beta^2 g_{tt}) \\ g_{tx} = 0 &\to \beta\gamma^2 (1 + g_{rr}) \end{aligned}$$

with $\beta = v/c$. Now simplify things by considering a weak field approximation with $g_{rr} = 1$, so the observer is not too close to where the black hole passes by. The line element with $\beta \to 1$ is then

$$ds^2 = \gamma^2 \left[ \left(1 - \frac{2m}{r} - \beta^2\right) dt^2 - \left(1 + \beta^2 \left(1 - \frac{2m}{r}\right)\right) dx^2 - 2\left(1 + \beta^2 \left(1 + \frac{m}{r}\right)\right) dx dt \right] - r^2 d\Omega^2$$

Since the $dt$ has an implicit $c$ multiplied by it this metric is approximately the Brinkman metric for pp-waves. A black hole passing an observer near the speed of light approximates a gravitational wave.

With BMS symmetry we have Weyl tensor terms associated with disturbance of a black hole. The Weyl tensor for a black hole, eg $C_{\theta\varphi\theta\varphi} = 2mr\ sin^2\theta$, is adjusted to

$$C_{\theta\phi\theta\phi} \to C_{\theta\phi\theta\phi} + \delta C_{\theta\phi\theta\phi} = 2mr \sin^2\theta + C_{\theta\phi\theta\phi}$$

Here $C_{\theta\varphi\theta\varphi}$ contains the same information as $C_{zz}$ and $C_{\overline{zz}}$. The type D solution satisfies the condition that for a vectors $V_\varphi$ and $U_\theta$ then $C_{\theta\varphi\theta\varphi} V_\varphi V_\varphi = c V_\theta V_\theta$ and $C_{\theta\varphi\theta\varphi} U_\varphi U_\varphi = c U_\theta U_\theta$, for inward and outward geodesics. The generation of a gravitational wave means $C_{\theta\varphi\theta\varphi} V_\varphi = 0$. The change in the black hole horizon area $\delta A = 32\pi m \delta m$ is compensated for by the Weyl tensor term $C_{\theta\varphi\theta\varphi}$ [15].

In this way the entanglement pair of a black hole can be replaced with a black hole entangled with gravitons. Hence the generation of a Hawking photon by a black hole with no associated quanta across the ER bridge may be instead associated with a graviton approaching $^+$. Generally black holes we observe from astrophysical processes are not entangled with other black holes. Such entanglements can only happen in type I multiverse or MWI settings, but these are not observable aspects of the universe. The generation of BMS symmetries and their connection to quantum numbers for black holes is potentially observable. Such detection may occur with the permanent deformation of spacetime that occurs with gravitational memory [17]. If these BMS symmetries exhibit non-classical properties, like black body radiation or a discrete structure, it is then reasonable to conclude they are quantum mechanical in nature. It is reasonable to propose properties analogous to the Einstein coefficients for the emission of photons [16].

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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