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Non-Renormalization Singularity Resolution and Black Hole Shadow Verification

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Abstract

We propose a non-perturbative quantum gravity framework using quantum vortices (statistical average topological structures of microscopic particles) embedded in AdS/CFT holographic duality, resolving black hole singularities without renormalization. Thus, this constitutes a singularity-resolution mechanism grounded in physical processes rather than mathematical techniques. The quantum vortex field generates a repulsive potential within the critical radius $r_* \approx 8.792 \times 10^{-11}$m, dynamically preventing matter from reaching $r = 0$ and avoiding curvature divergence. The derived Huang metric (Schwarzschild metric with quantum corrections) enables parameter-free prediction of black hole shadow angular diameters, without post-observation fitting of Kerr black hole spin. Observational verification shows: the theoretical shadow of Sgr A* is 53.3 μas (EHT: 51.8 ± 2.3 μas), and that of M87* is 46.2 μas (EHT: 42 ± 3 μas), resolving contradictions of the Kerr model. This framework unifies singularity elimination, information conservation, and shadow prediction, providing a testable quantum gravity paradigm.

Keywords: quantum gravity; black hole; singularity; metric; Einstein field equation; general relativity; AdS/CFT duality; EHT; SgrA*; M87*

I. Introduction.

The "singularity problem" has long hindered the unification of classical gravity and quantum mechanics: under the Schwarzschild metric, black hole singularities exhibit infinite curvature, violating quantum mechanics' requirement for finite physical quantities. Traditional quantum gravity approaches (e.g., string theory, loop quantum gravity) rely on perturbative quantization or discrete spacetime, lacking direct observational support. This work adopts an approach distinct from traditional perturbative methods or pure mathematical constructions. We prioritize building a physical framework that can directly engage with key astronomical observations. At its core lies the introduction of "quantum vortices"—as unified microscopic carriers with a clear physical picture—which are embedded in AdS/CFT duality to realize non-locality. The primary goal of this work is to demonstrate the framework's ability to simultaneously resolve the singularity problem and make parameter-free predictions of black hole shadows (without retrofitting black hole spin through observations). The consistency between theoretical predictions and EHT observational data provides strong preliminary support for the validity of this physical picture.

The Event Horizon Telescope (EHT)'s images of Sgr A* and M87* reveal discrepancies between Kerr black hole predictions and observations (e.g., M87*'s shadow exceeds the Kerr upper limit). To address these issues, we introduce quantum vortices—topological solitons from statistical averages of fermions, bosons, and gauge fields—and embed them in AdS/CFT duality. This non-perturbative approach generates an internal repulsive potential, eliminating singularities at the source and enabling parameter-free shadow calculations.

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II. Theoretical Framework

A. Quantum Vortices and AdS/CFT Duality

A quantum vortex is defined as the statistical average quantum topological structure of microscopic particles, with the operator:

$$\mathcal{O}_{vortex}(x,y) \sim \langle \bar{\psi}\psi\phi\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}\rangle^{1/2} e^{iC\theta(x,y)} \quad (1)$$

Superfluid helium experiments [1] (e.g., quantum vortex lattices) confirm this topological structure.

Quantum vortex field operator:

$$\Phi_{vortex}(x,y) = \mathcal{O}_{vortex}(x,y)\int d^4\,y\sqrt{-g(y)}K(x,y)$$

$$= \langle \bar{\psi}\psi\phi\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}\rangle^{1/2} e^{iC\theta(x,y)}\int d^4\,y\sqrt{-g(y)}\frac{e^{iC\theta(x,y)}}{(|x-y|^2+\ell^2)^2} \quad (2)$$

Where:

$\bar{\psi}\psi$: fermion field, $[\bar{\psi}\psi] = L^{-3}$.

ϕ: boson field, $[\phi] = L^{-1}$.

$\mathcal{A}_{\mu\nu} \equiv (B_{\mu\nu}, W^a_{\mu\nu}, G^a_{\mu\nu})$: unified field strength tensor, $[\mathcal{A}_{\mu\nu}] = [\mathcal{A}^{\mu\nu}] = L^{-2}$.

$e^{iC\theta(x,y)}$: vortex phase, which connects to non-local entanglement (quantum entanglement).

C: Central charge (topological charge number)

$\theta(x,y) \sim \arctan\left(\frac{y_2-x_2}{y_1-x_1}\right)$: topological phase.

The vortex winding number W is derived from the central charge C and topological phase $\theta(x,y)$ as $W = \oint_C \nabla\theta \cdot dl$.

$K(x,y) = \frac{e^{iC\theta(x,y)}}{(|x-y|^2+\ell^2)^2}$: non-local kernel function, ℓ: minimal characteristic length (Planck length).

It should be noted that the quantum vortex (field) operator does not violate the Pauli exclusion principle. First, the vortex phase $e^{iC\theta(x,y)}$ in the operator already indicates a non-local (entangled) statistical average. Second, the apparent structure of this microscopic topology primarily resides in regions of immense spacetime curvature—"near the black hole"—where the Pauli exclusion principle is weakened by the extreme curvature. This assumption also finds indirect support from simulations of superfluid helium "quantum tornados" near analog black holes [1].

We use AdS/CFT nested duality ($AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$ [2,3]): the black hole's external 4D AdS_4 bulk spacetime is dimensionally reduced to its internal 3D CFT_3 boundary (2D CFT_2 boundary → 1D CFT_1 boundary), where quantum vortices generate a discrete mass density. The nested AdS/CFT duality [2,3] adopted in this work ($AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$) is based on the core holographic correspondence of standard AdS/CFT, which establishes an equivalence between gravitational theories in AdS bulk spacetime and conformal field theories on the boundary. The standard AdS/CFT duality reveals that the strongly coupled CFT on the boundary can be equivalently described by the weakly coupled gravity theory in the AdS bulk, and this core logic is retained in our nested structure. We only extend the single-level duality to a multi-level hierarchy [2,3] according to the spacetime property transition (classical outside the black hole, quantum inside) and the distribution of quantum vortices, which is consistent with the flexible adaptation of AdS/CFT duality to different spacetime scenarios.

B. Corrected Poisson Equation

In standard flat spacetime, the d'Alembert operator for scalar fields is: $\Box\phi = \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi$. The time inside a black hole is spacelike (metric $g_{tt} > 0$), and time is extremely dilated near the horizon (the internal timelike radial coordinate $r_t \to \infty$). Similar to flat spacetime, AdS/CFT duality is used to reduce the dimension of the four-dimensional (AdS_4) bulk spacetime to a three-dimensional (CFT_3)

boundary—i.e., the black hole's external spacetime is dualistically dimensionally reduced to its interior (AdS_4/CFT_3). The quantum vortex field satisfies the quantized d'Alembert operator (with the scalar field ϕ replaced by the quantum vortex field ϕ_{vortex}): $\Box\phi_{vortex} = \frac{kh}{c^2}\partial_t^2\phi_{vortex} - \nabla^2\phi_{vortex}$. The quantum vortex field ϕ_{vortex} can be treated as a free scalar field: $\Box\phi_{vortex} = 0 \Rightarrow \nabla^2\phi_{vortex} = \frac{kh}{c^2}\partial_t^2\phi_{vortex}$.

According to the definition of quantum vortices: $\phi_{vortex} = \langle\phi_{micro}\rangle_{stat}$, where ϕ_{micro} is the topological field of a single microscopic particle (e.g., the local phase field of a vortex line), and $\langle\cdot\rangle_{stat}$ denotes the discrete statistical average of a large number of particles. The topological field of a single particle satisfies linear dynamics (e.g., the free field equation $\partial_t^2\phi_{micro} = \nabla^2\phi_{micro}$), but topological entanglement between particles produces non-linear coupling.

When taking the statistical average of these microscopic fields, the expected value of the cross term is converted into a non-linear term of the macroscopic field: $\langle\partial_t^2\phi_{micro}\rangle_{stat} = \langle\nabla^2\phi_{micro}\rangle_{stat} + \langle\lambda\phi_{micro}\,\partial_t\phi_{micro}\rangle_{stat}$, where λ is the coupling constant. For "high-density vortex systems" (e.g., regions with extremely high quantum vortex density inside black holes), the statistical average of the cross term dominates the linear term, i.e., $\partial_t^2\phi_{vortex} \approx \lambda\langle\phi_{micro}\,\partial_t\phi_{micro}\rangle_{stat} \sim \lambda\phi_{vortex}\,\partial_t\phi_{vortex}$. It can be assumed that the temporal evolution of the vortex field exhibits "self-similarity" (i.e., $\phi_{vortex} \sim \partial_t\phi_{vortex}$, where the rate of change of the topological structure with time is comparable to its own intensity). This simplifies to (setting $\lambda \sim a^2$):$\partial_t^2\phi_{vortex} \sim \lambda(\partial_t\phi_{vortex})^2 \sim a^2(\partial_t\phi_{vortex})^2$ (similar to the statistical average logic of "Reynolds stress" in turbulence: the linear motion of microscopic molecules accumulates into non-linear stress of the macroscopic fluid through collisions ($\langle u_i u_j\rangle \sim \partial_i U_j$); here, the linear evolution of microscopic topological fields accumulates into the non-linear time derivative of the macroscopic vortex field through non-local entanglement):

$$\nabla^2\phi_{vortex} \approx \frac{kh}{c^2}(a\cdot\partial_t\phi_{vortex})^2 = \frac{khc^2G^2M^2}{64\pi^2t^2} \qquad (3)$$

(Substituting the black hole mass M, the "self-similarity" is further transformed into: $\partial_t\phi_{vortex} = \frac{M}{t}$. $a \approx \frac{Gc^2}{8\pi}$ is the phase density coupling constant for non-local entanglement at the CFT_3 boundary, the winding number $W=8\pi$)

B.1 Derivation of Key Constants: Winding Number and Coupling Constant

The core of our non-perturbative framework lies in the physical determination of the winding number W and the phase density coupling constant a, which are crucial for the quantum vortex operator and the subsequent correction to the Poisson equation. Their values are not ad hoc but are derived from the consistency conditions of the nested AdS/CFT duality.

1. Winding Number $W=8\pi$:

The winding number $W=\oint_C \nabla\theta\cdot d\mathbf{l}$ is a topological invariant characterizing the quantum vortex. Within the CFT_3 boundary inside the black hole, the quantum vortex operator O_{vortex} possesses a definite conformal dimension Δ_{vortex}. For a scalar operator like ours, $\Delta_{vortex}\approx 2$ is a natural and consistent choice. The central charge C of the boundary CFT_3 is determined by the symmetry of the quantum vortex field. The internal spacetime of the black hole exhibits a high degree of symmetry, which can be effectively described by $U(2)_F \times U(2)_B$.

- $U(2)_F$, associated with fermionic degrees of freedom, corresponds to the electroweak symmetry $U(1)_Y \times SU(2)_L$, contributing 4 generators.
- $U(2)_B$, associated with bosonic degrees of freedom, corresponds to a pre-color symmetry $U(1)_C \times SU(2)_P$ (related to hyper-color charge and polarization), also contributing 4 generators.

This gives a total central charge $C = 4 + 4 = 8$. The conformal dimension Δ of an operator is related to its topological charge (winding number W) in this setup by the approximate relation $\Delta_{vortex} \sim \frac{W^2}{4\pi^2 C}$. Substituting $\Delta_{vortex} \approx 2$ and $C = 8$ yields:

$$W^2\approx 2\times 4\pi^2\times 8=64\pi^2 \quad\Rightarrow\quad W\approx 8\pi$$

This derivation roots the winding number in the conformal data of the holographic dual theory.

2. Coupling Constant $a \approx \frac{Gc^2}{8\pi}$:

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The constant a represents the phase density coupling constant for non-local entanglement at the CFT_3 boundary, normalized per unit winding phase. Given that the winding number W is now established as 8π, the coupling constant naturally inherits the factor $1/(8\pi)$ when considering the coupling per unit phase. Furthermore, to account for the strong coupling between fermionic and bosonic degrees of freedom on the CFT boundary, the combination of the gravitational constant G and the speed of light c is necessitated. Thus, the expression $a \approx Gc^2/8\pi$ emerges naturally as the coupling strength per unit winding phase within the gravitational context. This is not an arbitrary choice but a consequence of the topological structure (W) and its interaction with gravity (G, c).

With W and a physically motivated, the term $\nabla^2\phi_{vortex} \approx \frac{kh}{c^2}(a \cdot \partial_t\phi_{vortex})^2$ in Eq. (3) of the original text loses its ad hoc nature. It becomes a result of the statistical averaging of microscopic topological fields and the specific holographic embedding we have employed.

B.2 Singularity Resolution

It can be inferred from the quantum vortex operator $(O_{vortex}(x,y) \sim \langle\bar{\psi}\psi\phi\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}\rangle^{1/2}e^{iC\theta(x,y)})$ that: the quantum vortex field is essentially a scalar field coupled by other interactions (excluding classical gravity), and physically possesses the properties of other fundamental forces. For example, for the "Yukawa potential" representing the strong force, as long as the system satisfies $am\sqrt{\langle r^2\rangle}\ll 1$ (i.e., under "extremely short distances"), this approximation is statistically reliable (via Taylor expansion) [4,5]: $\langle e^{-amr}\rangle \approx \langle 1+\ln(1-amr)\rangle = 1-am\langle r\rangle - \frac{(am)^2}{2}\langle r^2\rangle + \cdots$. It can be seen that under the "extremely short distances" of statistical averaging, the Yukawa potential exhibits a "logarithmic dependence" $(\ln(1-amr))$, and this "logarithmic dependence" inherently possesses a "sign reversal property" (reversal of force direction). If extended to the quantum vortex field, it can generate a quantum repulsive barrier counteracting classical gravity under the "extremely short distances" of statistical averaging, achieving non-perturbative "singularity resolution" (rather than "smoothing" or "erasing" the singularity). The divergent behavior of the Riemann tensor component R^r_{trt} near the singularity ($R^r_{trt} \propto r^{-3}$) naturally provides the quantum effect source term for this "logarithmic dependence". Therefore, through the spacelike property of the internal time of the black hole (due to $g_{tt}>0$), r^{-3} can be approximately replaced by t^{-2} to construct a "logarithmically dependent" quantum gravitational potential (generated by the quantum vortex field ϕ_{vortex}) that counteracts the classical gravitational potential, thereby achieving "singularity resolution":

$$\nabla^2\phi_{vortex} \approx \frac{khc^2G^2M^2}{64\pi^2t^2} \approx \frac{khc^2G^2M^2}{64\pi^2r^3} \qquad (4)$$

This substitution implies that the divergent behavior of classical general relativity near the singularity—exemplified by the Riemann tensor component $R^r_{trt} \propto r^{-3}$—intrinsically contains the source term $(\frac{khc^2G^2M^2}{64\pi^2r^3})$ that prevents its own curvature divergence. Integrating this source term (by solving the Poisson equation) naturally generates a logarithmic term, which in turn counteracts classical gravitational collapse into a singularity. In other words, spacetime spontaneously forms a response to the divergence of $R^r_{trt} \propto r^{-3}$, and this response non-perturbatively yields a finite observable result—such as the black hole shadow. Thereby, without introducing extrinsic entity assumptions—such as the “strings” in 11-dimensional string theory or “discretized spacetime” in loop quantum gravity—the “singularity” is naturally and physically screened.

For the CFT boundary spacetime inside the black hole, the Poisson equation is corrected to include quantum gravity effects:

$$\nabla^2\Phi = 4\pi G\left(M\delta^3(r) + \frac{khc^2G^2M^2}{64\pi^2r^3}\right) \qquad (5)$$

Or

$$\nabla^2\Phi = 4\pi G\left(M\delta^3(r) + \frac{kG_hM^2}{4\pi Gr^3}\right) \qquad (6)$$

where:

$M\delta^3(r)$: classical point mass source;

The quantum gravitational constant G_h is defined as

$$G_h = \frac{hc^2G^3}{16\pi} = \frac{\hbar c^2 G^3}{8} \qquad (7)$$

(dimensionality: $kg^{-2}m^3s^{-2}$)

Dimensional Transmutation and the Quantum Gravitational Constant G_h:

The definition of the quantum gravitational constant $G_h = \frac{hc^2G^3}{16\pi}$ implies a profound dimensional transmutation. This arises naturally from the complete nested AdS/CFT duality structure, $AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$, which describes the gravitational transition from the classical exterior to the deeply quantum interior of the black hole.

The effective Planck constant at the innermost boundary, denoted h_{CFT_1}, undergoes a radical dimensional change due to the holographic spacetime compression toward the CFT_1 boundary. The compression factor $k_{\dim}^{CFT_1}$ with dimensions $[L]^{-10}[T]^7$ is a direct consequence of this hierarchical duality.

Derivation of the Compression Factor $k_{\dim}^{CFT_1}$:

The external AdS_4 bulk spacetime (4 dimensions) is coupled with the internal phase dimensions associated with the gauge symmetries of the Standard Model fields. The symmetry group $U(1)_Y \times SU(2)_L \times SU(3)_c$ corresponds to a total of $1 + 2 + 3 = 6$ internal phase dimensions (complex space), forming a coupled 10-dimensional structure $(4 + 6 = 10)$.

The complete nested duality $AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$ maps this 10-dimensional bulk structure onto the ultimate CFT_1 boundary. The CFT_1 boundary, being 1-dimensional, inherits the description of all 6 internal phase dimensions, resulting in an effective 1 + 6 = 7-dimensional description. The dimensional discrepancy between the original 10-dimensional bulk and the final 7-dimensional boundary description is precisely accounted for by the compression factor $k_{\dim}^{CFT_1} = 1\ [L]^{-10}[T]^7$. The factor $[L]^{-10}$ originates from the compactification of the 10-dimensional bulk space, while the factor $[T]^7$ ensures the conservation of fundamental scales (like the speed of light c) under this dimensional mapping. The numerical value of 1 is set by requiring the magnitude of the effective action at the CFT_1 boundary to be consistent with the standard quantum principles in the semi-classical limit.

Therefore, the effective Planck constant at the CFT_1 boundary becomes:

$$[h_{CFT_1}] = [h] \times [k_{\dim}^{CFT_1}] = ([M][L]^2[T]^{-1}) \times ([L]^{-10}[T]^7)$$
$$= [M][L]^{-8}[T]^6$$

This very unconventional dimension for an effective Planck constant finds a remarkable phenomenological analogy in confined quantum systems. For instance, in superfluid helium-4 confined to nano-scale geometries, experiments have observed that the effective Planck constant governing vortex dynamics scales inversely with a high power of the confinement scale d, approximately as $\hbar_{eff} \propto d^{-8}$ [6]. This scaling with d^{-8} is consistent with the $[L]^{-8}$ dimension in $[h_{CFT_1}]$, providing indirect empirical support for the physical plausibility of such dimensional compression in extreme gravitational environments.

The quantum gravitational constant G_h is then defined to absorb this dimensionally transmuted $[h_{CFT_1}]$, resulting in its final dimensions $[M]^{-2}[L]^3[T]^{-2}$. Therefore, the seemingly unusual dimensions of G_h are not arbitrary but are a natural signature of the ultimate holographic compression of quantum degrees of freedom at the deepest level near the black hole's core. The ultimate validation of this approach, as emphasized throughout this work, lies in its parameter-free, observational predictions.

$$\frac{kG_hM^2}{4\pi Gr^3} \qquad (8)$$

Quantum gravity mass source formed by the coupling of other forces (electromagnetic, strong, and weak forces);

$$k = \frac{M_{BH,ref}}{M_{BH,topo}} \quad (9)$$

Non-local entanglement factor. $M_{BH,ref}$: reference black hole mass for non-local entanglement, generally chosen as M_{SgrA*}(the current mass of the Galactic Center black hole). Any black hole can be chosen as the reference, but Planck's constant must change accordingly ($h_{other} = \frac{M_{SgrA*}}{M_{BH,ref}} \cdot h$) to reflect the relativity of non-local entanglement, which means the quantum gravitational constant also changes relatively ($G_h^{other} = \frac{M_{SgrA*}}{M_{BH,ref}} \cdot G_h$); $M_{BH,topo}$: The black hole mass that creates the main quantum gravitational (quantum spacetime curvature) background for the topological target of the calculation. Its non-local entanglement with $M_{BH,ref}$ reflects the relative strength; The definition of the winding number (W=8π), given by $W=\oint_C \nabla\theta \cdot dl$, serves as a quantized angular momentum characterization (corresponding to the topological angular momentum from the statistical average of microscopic particles). Meanwhile, $\partial_t \phi_{vortex}$ (temporal evolution of the vortex field) achieves dynamic correlation with the total angular momentum of the black hole, rendering the quantum vortex field a natural "carrier of quantized angular momentum." Its influence is naturally incorporated into the formula through the non-local entanglement factor k (determined by the ratio of the black hole mass to the reference black hole (e.g., Sgr A*)), thereby explaining the "spin-like spacetime correction effect" from a microscopic mechanism. In contrast, the Kerr spin (α) is a macroscopic fitting parameter within the classical spacetime framework ($0 \le \alpha \le 1$), which lacks a clear microscopic physical picture and must be inferred retroactively from observational data.

It follows that a black hole's angular momentum is not an isolated property, but rather a relative relationship established between black holes via quantum entanglement. This is analogous to the way properties of entangled particles are mutually defined in quantum mechanics—for instance, in the spin-entangled state of two electrons, $(|\uparrow\downarrow\rangle+|\downarrow\uparrow\rangle)/\sqrt{2}$, measuring one electron as "spin-up" immediately determines the other as "spin-down." Their "spin" attributes are defined through correlation.

Extending this logic to cosmic scales naturally reveals the intrinsic nature of black hole angular momentum—as captured by the ER=EPR conjecture, which posits that geometric "wormholes" are one and the same as quantum entanglement [7]. This implies that the quantum entanglement between two seemingly distant black holes can be geometrically understood as a wormhole connection, supporting the idea that entanglement between black holes can define their geometric attributes.

Given this mutually defined entanglement relationship between black holes, the quantum constant associated with the carrier of quantized angular momentum—the quantum vortex—namely, the Planck constant h, naturally exhibits different relative values under different quantum-gravitational backgrounds (i.e., different black hole gravitational fields). The concrete implementation to quantify this relative strength is embodied in the k-factor, which characterizes the mass ratio between black holes.We are fully aware that relativizing the Planck constant h once again pushes the boundaries of modern physics. Nevertheless, the guiding principle of our theoretical construction remains to test the plausibility of our hypotheses through the empirical accountability of their predictions—such as those concerning black hole shadows.

Furthermore, we note that the Planck constant h shares the same dimensional structure as angular momentum— $[M][L]^2[T]^{-1}$. Based on the concept of quantized angular momentum ($W=\oint_C \nabla\theta \cdot dl$), it is entirely reasonable to postulate a relationship between the black hole mass M and the Planck constant (representing quantized angular momentum, $\{mvr\}_{BH} \sim h_{BH}$) in its quantum-gravitational background:

$$M \propto \{mvr\}_{BH} \sim h_{BH}$$

(We reiterate that even this simple scaling relation must ultimately be validated by the empirical accountability of its predictions, such as those for black hole shadows.)

If we take the Galactic Center black hole (Sgr A*) as the reference, then:

$$M_{Sgr\,A*} \propto \{mvr\}_{Sgr\,A*} \sim h$$

and for any other black hole, it follows that:

$$kM_{BH,topo} = \frac{M_{Sgr\,A*}}{M_{BH,topo}} M_{BH,topo} = M_{Sgr\,A*} \propto \{mvr\}_{Sgr\,A*} \sim h$$

$$\Rightarrow M_{BH,topo} \propto \{mvr\}_{Sgr\,A*}/k \sim h/k$$

$$\Rightarrow M_{BH,topo} \propto \{mvr\}_{other} \sim h_{other}$$

This further supports the idea that, under the quantum-gravitational background formed by a different black hole's field, the corresponding Planck constant (h_{other}) must depend on the relative strength of the quantized angular momentum ($\{mvr\}_{other}$)—which is determined by the black hole mass ratio.

Solving this Poisson equation (spherically symmetric, $\Phi \to 0$ as $r \to \infty$) gives the total gravitational potential:

$$\Phi(r) = -\frac{GM}{r} - \frac{kG_hM^2(\ln r + 1)}{r} \qquad (10)$$

(Note: The argument of a logarithmic term must be dimensionless. By normalizing with the minimal characteristic length (ℓ) —effectively considering $\ln(r/\ell) = \ln(r/1) = \ln r$—the dimension of the logarithmic argument is naturally eliminated. That is, in all logarithmic expressions appearing in this theory, the radial coordinate r is implicitly normalized)

The logarithmic term $\ln r + 1$ becomes negative for $r < e^{-1}m(\approx 0.3679m)$, making $\Phi(r) > 0$ inside $r_* = e^{-1-G/(kG_hM)} \approx 8.792 \times 10^{-11}$ m ($\Phi(r_*) = 0$), generating a repulsive force that eliminates the singularity, which kicks virtual particles from vacuum fluctuations out of "particle-antiparticle" annihilation into excited particle states. Through the $AdS_2/CFT_1 \subseteq AdS_3/CFT_2 \subseteq AdS_4/CFT_3$ duality, the excited particle states undergo tunneling escape from the black hole via $CFT_1 \to AdS_2 \to CFT_2 \to AdS_3 \to CFT_3 \to AdS_4$, and finally become real particles outside the black hole.

For the first time, this makes the black hole consistent with the unitarity of quantum mechanics: tunneling particles carry away information with them as they escape. Concurrently, the black hole loses mass, thereby ensuring overall information conservation and resolving the long-standing black hole information paradox triggered by "Hawking radiation."

As evidenced by the above mechanism, this represents a proactive and preventive physical process. It operates before matter reaches the Planck scale (with $r_* \approx 8.792 \times 10^{-11}$ m $\gg l_p \approx 1.616 \times 10^{-35}$ m), thereby circumventing the need to directly confront the actual "infinity." This stands in contrast to many conventional approaches—such as string theory and loop quantum gravity—which often constitute retroactive interventions, attempting to perform mathematical "surgery" on a spacetime that has already diverged.

III. Huang Metric and Geodesic Analysis

A. Construction of the Huang Metric

Relationship between the metric and gravitational potential under the weak-field approximation of general relativity:

$$ds^2 = -A(r)c^2dt^2 + B(r)dr^2 + r^2d\Omega^2$$

$$A(r) \approx 1 + \frac{2\Phi(r)}{c^2}, \qquad B(r) \approx 1 - \frac{2\Phi(r)}{c^2}$$

Substituting $\Phi(r)$ gives the Huang metric $g_{\mu\nu}$:

$$ds^2 = -A(r)c^2dt^2 + B(r)dr^2 + r^2d\Omega^2 \qquad (11)$$

with

$$A(r) \approx 1 - \frac{2GM}{c^2r} - \frac{2kG_hM^2(\ln r + 1)}{c^2r} \qquad (12)$$

$$B(r) \approx 1 + \frac{2GM}{c^2 r} + \frac{2kG_h M^2(\ln r + 1)}{c^2 r} \quad (13)$$

The Schwarzschild radius remains unchanged:

$$r_s = \frac{2GM}{c^2}$$

Analyzing the Huang metric:

First, the critical radius for potential reversal: $r_* \approx 8.792\times10^{-11}\,m$ (where $\Phi(r_*)=0$) $\Rightarrow$ $A(r_*)=1$, $B(r_*)=1$. Thus, the metric at r_* is:

$$ds^2 = -c^2dt^2 + dr^2 + r_*^2 d\Omega^2$$

Since the order of magnitude of r_* is $\sim 10^{-11}$m, the terms dr^2 and $r_*^2 d\Omega^2$ are negligible compared to c^2dt^2 ($ds^2 \approx -c^2dt^2$). This is the standard one-dimensional flat metric, so r_* forms a natural CFT_1 boundary.

Second, from the condition $g_{tt}=0$ $\Rightarrow$ the horizon equation:

$$c^2 r = 2GM + 2kG_h M^2(\ln r + 1) \quad (14)$$

This equation yields two roots: the horizon r_h and $r_h^0 \approx 8.85\times10^{-11}$ m (a constant value). Both roots satisfy the relations: $A(r)\approx0$, $B(r)\approx2$ $\Rightarrow$ the metric at both r_h and r_h^0 is:

$$ds^2 \approx 2dr^2 + r^2 d\Omega^2$$

This is a conformally flat metric (after a variable substitution: $dl^2 \approx 2(d(\sqrt{2}\rho)^2 + \rho^2 d\Omega^2)$). Since the order of magnitude of r_h^0 is $\sim 10^{-11}$m, the term $2dr^2$ is negligible compared to $(r_h^0)^2 d\Omega^2$), forming a conformally two-dimensional flat metric ($ds^2 \approx (r_h^0)^2 d\Omega^2$). Therefore, r_h and r_h^0 similarly form two CFT boundaries: r_h^0 (CFT_2) and r_h (CFT_3). This constitutes a necessary condition for the nested duality $AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$ (i.e., the structure of the Huang metric naturally gives rise to three conformal boundaries: r_h, r_h^0, r_*).

Finally, the photon ring r_{ph} of the Huang metric: For photons ($ds^2 = 0$) on a circular orbit ($\dot{r} = 0$), satisfying the extremum of the effective potential $\frac{d}{dr}\left(\frac{r^2}{A(r)}\right) = 0$, yields the photon ring equation:

$$c^2 r = 3GM + kG_h M^2(3\ln r + 2) \quad (15)$$

This equation also admits two roots: the photon ring r_{ph} and the onset of the AdS_3 bulk $r_{ph}^0 \approx 1.23\times10^{-10}$ m (a constant value). If we regard r_{ph} as the onset of the AdS_4 bulk, then two bulk regions are formed, echoing the AdS_4 and AdS_3 bulks in the duality $AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$.

When k = 0, the Huang metric reduces to the Schwarzschild metric.

With the quantum-corrected Huang metric $g_{\mu\nu}$ and the new gravitational potential $\Phi(r)$ in hand, we proceed to derive the corresponding field equations with quantum corrections via general relativity.

First, based on the quantum correction term in the new gravitational potential, $\frac{kG_h M^2(\ln r+1)}{r}$, we posit that the modified field equation takes the form:

$$G_{\mu\nu} + \frac{kG_h M^2(\ln r + 1)}{r} g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad (16)$$

Next, by computing geometric quantities from the Huang metric:

1. Christoffel symbols

For the diagonal metric $g_{\mu\nu}=diag(-Ac^2, B, r^2, r^2\sin^2\theta)$, the non-vanishing Christoffel symbols are given by:

$$\Gamma^\lambda_{\mu\nu} = \frac{1}{2} g^{\lambda\sigma}(\partial_\mu g_{\sigma\nu} + \partial_\nu g_{\sigma\mu} - \partial_\sigma g_{\mu\nu})$$

2. Ricci tensor $R_{\mu\nu}$

$$R_{\mu\nu} = \partial_\lambda \Gamma^\lambda_{\mu\nu} - \partial_\nu \Gamma^\lambda_{\mu\lambda} + \Gamma^\lambda_{\sigma\lambda}\Gamma^\sigma_{\mu\nu} - \Gamma^\lambda_{\sigma\nu}\Gamma^\sigma_{\mu\lambda}$$

3. Scalar curvature R

$$R = g^{\mu\nu} R_{\mu\nu}$$

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4. Einstein tensor

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$$

Finally, comparing with the energy-momentum tensor $T_{\mu\nu}$ yields the Einstein - Huang field equation (where the quantum correction term requires division by c^2):

$$G_{\mu\nu} + \frac{kG_{\mathrm{h}}M^2(\ln r + 1)}{c^2 r} g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad (17)$$

Defining

$$\Lambda(r) = \frac{kG_{\mathrm{h}}M^2(\ln r + 1)}{c^2 r} \qquad (18)$$

the field equation simplifies to:

$$G_{\mu\nu} + \Lambda(r)\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad (19)$$

Foreground Curvature: the Einstein tensor $G_{\mu\nu}$ (classical spacetime curvature tensor) characterizes Newtonian gravity;

Background Curvature: $\Lambda(r)\, g_{\mu\nu}$ (quantum spacetime curvature tensor) characterizes quantum gravity formed by the coupling of other forces (electromagnetic, strong, and weak forces).

If we further define the Huang tensor as $H_{\mu\nu} = \Lambda(r) g_{\mu\nu}$, we can introduce the total curvature tensor $\hat{G}_{\mu\nu}$, allowing the Einstein - Huang field equation to be rewritten as:

$$\hat{G}_{\mu\nu} = G_{\mu\nu} + H_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad (20)$$

It is important to note that $\nabla^\mu H_{\mu\nu} \neq 0$ does not violate conservation in a generalized sense. When $\nabla^\mu G_{\mu\nu}=0$, the equation implies:

$$\nabla^\mu H_{\mu\nu} = \frac{8\pi G}{c^4} \nabla^\mu T_{\mu\nu} \qquad (21)$$

which indicates that quantum spacetime curvature fluctuations inside a black hole spontaneously generate an energy-momentum flow. That is, in the extreme environment within a black hole, virtual particle fluctuations can be excited into real particle excited states by the repulsive potential—which prevents singularity formation inside the critical radius $r<r_*\approx 8.792\times 10^{-11}$ m(where $\Phi(r)>0$)—thereby producing an energy-momentum flow. This extends the conservation law of general relativity.

This extension echoes the earlier description of "excited particle states carrying information tunneling out of the black hole"—the tunneling excited states are precisely generated by this energy-momentum flow. If we assume the absence of a black hole ($H_{\mu\nu}=0$), the Einstein - Huang field equation reduces to the standard Einstein field equation:

$$\hat{G}_{\mu\nu}=G_{\mu\nu}=\frac{8\pi G}{c^4} T_{\mu\nu}$$

The logic of this extension is consistent with the extension of Newtonian mechanics by general relativity: Newtonian mechanics was not overthrown by general relativity, but instead became its approximation under the conditions of "low speed and no consideration of spacetime curvature"; similarly, this theory does not overthrow general relativity, but makes general relativity the approximation of this theory under the conditions of "no consideration of black holes and quantum effects". The two constitute a hierarchical relationship rather than an opposing one.

Furthermore, from the field equation's $\Lambda(r) = \frac{kG_{\mathrm{h}}M^2(\ln r+1)}{c^2 r}$, we know: Within the black hole's central region, there exists an extremely small anti-de Sitter (AdS) spacetime region (since $\Lambda(r) < 0$ for $r < e^{-1}$ m). This becomes a key necessary condition for the nested AdS/CFT duality (the AdS_4 partial bulk corresponds to $r < r_*$, AdS_2 bulk to $r_* < r < r_h^0$, and the AdS_3 partial bulk to $r_{ph}^0 < r < e^{-1}$ m, all satisfying $\Lambda(r) < 0$).

Coupled with the three CFT boundaries formed by the Huang metric—the CFT_3 boundary at r_h, the CFT_2boundary at r_h^0, and the CFT_1 boundary at r_*—these together constitute the sufficient conditions for the nested duality $AdS_4/CFT_3 \supseteq AdS_3/CFT_2 \supseteq AdS_2/CFT_1$!

B. Geodesic Behavior

For null (lightlike) geodesics ($ds^2 = 0$) and timelike geodesics ($ds^2 = -c^2 d\tau^2$):

Singularity avoidance: As $r \to 0$, the effective potential $V \to +\infty$, forcing particles to rebound before reaching $r = 0$;

Finite crossing time: Unlike the Schwarzschild metric (divergent coordinate time t at r_h), the Huang metric has $B(r_h) = 2$, making $\int dr/\sqrt{A(r)}$ finite—particles cross the horizon in finite proper time τ and coordinate time t.

In addition, for null geodesics in the equatorial plane, the gravitational lensing deflection angle in the Huang metric is obtained:

$$\hat{\alpha}(b)=2\int_{r_0}^{\infty}\frac{dr}{r}\sqrt{\frac{B(r)}{A(r)}}\left[\left(\frac{r}{r_0}\right)^2\frac{A(r_0)}{A(r)}-1\right]^{-1/2}-\pi \quad (22)$$

1. In the strong field regime, as the closest distance approaches the photon sphere ($r_0 \to r_{ph}$), the deflection angle diverges. The additional logarithmic correction in A(r) causes the photon sphere radius to shift outward compared to the Schwarzschild metric; the divergence point appears earlier, "trapping" light earlier. Multiple diffracted orbits cannot form stable images. Therefore, the size of the black hole shadow and bright ring is mainly determined by the geometry of the Huang metric, rather than the superposition of numerous light deflections. In other words, the ring-shaped emission observed by the EHT is almost the true emission distribution of the black hole and its accretion disk, not an illusion formed by "bent and diffracted" light. That is, the critical impact parameter ($b_c = \frac{r_{ph}}{\sqrt{A(r_{ph})}}$) in the Huang metric no longer characterizes the black hole shadow radius.
2. In the weak field regime (weak deflection for $b \gg r_s$), expand A(r) and B(r) in the deflection angle integral to the 1/r order ($\frac{2GM}{c^2 r}, \frac{2kG_h M^2(\ln r+1)}{c^2 r} \ll 1$) and use the "thin lens" paraxial approximation:

$$\hat{\alpha}(b) \approx \frac{4GM}{c^2 b} + \frac{4kG_h M^2 \ln b}{c^2 b} \quad (23)$$

When $k = 0$, this reduces to gravitational lensing under standard general relativity ($\frac{4GM}{c^2 b}$).

IV. Observational Verification with EHT

The quantum term in the Huang metric, $\propto \frac{\ln r+1}{r}$, suggests that the logarithmic radius $\ln r$ is more natural than the linear coordinate r. We therefore perform the variable substitution $x=\ln r$, transforming the tunneling interval (r_h, r_{ph}) into $(\ln r_h, \ln r_{ph})$, i.e., (x_h, x_{ph}).

Analyzing the tunneling probability:

For a photon tunneling fromr_h to a visible radius r, the tunneling probability density under the WKB approximation is given by $P(x) \propto e^{-2S(x)}$, where the action is defined as:

$$S(x) \sim \int_{x_h}^{x}\sqrt{2m(V(x)-E)}\,\frac{dr}{dx}\,dx$$

From the total gravitational potential $\Phi(r)$, we identify that the potential barrier originates from the logarithmic term of the quantum gravitational potential:

$$V(x) \sim V_0 + a\frac{\ln r + 1}{r} = V_0 + a\frac{x+1}{e^x}$$

Within the tunneling region $r \in (r_h, r_{ph})$, we apply a linear approximation by expanding $\sqrt{V(x)\text{-}E}$ to first order, approximating it as a linear function over the interval (x_h, x_{ph}): $\sqrt{V(x) - E} \approx \alpha + \beta(x - x_c)$, where x_c is an intermediate point. Consequently, the action $S(x)$ becomes a quadratic function of x:

$$S(x) \approx S_0 + A(x - x_c) + B(x - x_c)^2,$$

which leads to:

$$P(x) \propto e^{-2S(x)} \sim e^{-2B(x-x_c)^2} \times (\text{a slowly varying factor})$$

This implies that within the tunneling region (r_h, r_{ph}), the tunneling probability follows a Gaussian distribution.

Thus, the process of decoupled photons tunneling into visibility within (r_h, r_{ph}) transforms into a problem of Brownian random equilibrium in logarithmic space over the interval (x_h, x_{ph}). In this scenario, the steady-state distribution of tunneling naturally localizes around the arithmetic mean of (x_h, x_{ph}):

$$x_{sh} \approx \frac{x_h + x_{ph}}{2} \quad \Rightarrow \quad \ln r_{sh} \approx \frac{\ln r_h + \ln r_{ph}}{2}$$

Therefore, the shadow radius—interpreted as the steady-state tunneling radius—is given by the geometric mean:

$$r_{sh} \approx \sqrt{r_h r_{ph}} \qquad (24)$$

(transforming back from the logarithmic variable $x = \ln r$ to the linear variable $r = e^x$)

The observed angular diameter is:

$$\theta_{sh} = 2r_{sh}/D \qquad (25)$$

(D = distance to the black hole)

Table 1. Comparison of theoretical predictions and EHT observations [8,9]: (Note: Per the theoretical definition, k denotes the mass ratio between the black hole providing the primary quantum gravitational background (target black hole) and the reference black hole (SgrA*), defined as $k = \frac{M_{SgrA*}}{M_{BH,topo}}$. It reflects the relative strength of non-local entanglement: the larger the black hole mass (e.g., M87*), the smaller the k value, corresponding to weaker entanglement).

Black Hole	M ($M_\odot$)	k	θ_{sh} (μas)	EHT Measured (μas)	Matching Error
Sgr A*	4.3×10^6	1	53.3	51.8 ± 2.3	Within range
M87*	6.5×10^9	6.61×10^{-4}	46.2	42 ± 3	1.4σ
M31*	1.4×10^8	3.07×10^{-2}	20.37	To be measured	—
IC1459	2.51×10^9	1.71×10^{-3}	10.14	To be measured	—

V. limitations of Traditional Models

1. Kerr Black Hole Contradiction: M87*'s observed shadow ($\sim 5.5r_s$) exceeds the maximum-spin Kerr upper limit ($4.8r_s \sim 5.2r_s$), and the Kerr model relies on an unrealistic equatorial view (actual M87* view: 17° polar inclination);
2. Light Diffraction Misconception: Traditional models attribute the EHT bright ring to multiple light diffractions, but 2021 EHT polarization data [10] show M87*'s jet base aligns with the ring center—consistent with the Huang metric's prediction of "true emission from the accretion disk" (no multiple diffractions).

Characteristics	Our Theory	Standard Kerr Black Hole Model [11]
Singularity Problem	Resolved.Quantum gravity generates a repulsive potential when $r < 8.792 \times 10^{-11}$m , dynamically preventing any matter from reaching the singularity and satisfying information	Unresolved.The Kerr model contains an intrinsic ring singularity, which reflects the incompleteness of classical general relativity and fails to satisfy information conservation
Theoretical Inputs	Black hole mass M, distance D	Black hole mass M, distance D
Additional Degrees of Freedom	None	Requires fitting of two key additional parameters:1. Dimensionless spin a $(0 \leq a \leq 1)$ 2.Observation inclination i
Predictability	Strong	None (requires observational fitting of α, i)

VI. Conclusions and Outlook

Our framework eliminates black hole singularities non-perturbatively using quantum vortices, unifies dark matter interpretation (quantum vortex density), and provides parameter-free black hole shadow predictions. EHT observations of Sgr A* and M87* validate the theory, resolving contradictions of classical models. Future extensions to Andromeda's M31* ($\theta_{sh} = 20.37\mu$as) and IC1459 ($\theta_{sh} = 10.14\mu$as) will further test the paradigm.

Procedure for Predicting Black Hole Shadow Size:

1. Input the target black hole mass: $M_{BH,topo}$;

2. Calculate the relative strength factor of non-local entanglement: $k = \frac{M_{SgrA*}}{M_{BH,topo}}$;

3. Solve the system of equations to obtain the horizon radius (r_h) and photon sphere radius (r_{ph}), where $M = M_{BH,topo}$:

$$\begin{cases} c^2 r = 2GM + 2kG_h M^2(\ln r + 1) & (solve\ for\ r_h) \\ c^2 r = 3GM + kG_h M^2(3\ln r + 2) & (solve\ for\ r_{ph}) \end{cases}$$

4. Predict the black hole shadow radius:

$r_{sh} \approx \sqrt{r_h r_{ph}}$;

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5. Calculate the shadow angular diameter: $\theta_{sh} \approx \frac{2r_{sh}}{D}$ (where D is the distance to the target black hole);
6. Validate the theoretical result against EHT observational data.

Just as EHT data is publicly available, the core calculations of our theory are also transparent and reproducible.

Notably, two aspects will be elaborated one by one in detail in subsequent studies: first, how the interior of a black hole generates unique quantum gravitational effects through new physical mechanisms such as the release of extreme quantum gravitational potential and winding number transitions—specifically, ultra-high circularly polarized radiation accompanied by polarization flips (with a polarization degree exceeding 90%, a phenomenon incompatible with the traditional magnetar model where ultra-high circular polarization and polarization flips cannot coexist), and the observed repeating fast radio burst (FRB) 20201124A is a typical example; second, the breakthroughs of this theory in naturally explaining many long-standing physical puzzles, including galaxy rotation curves (related to dark matter), the nature and dynamic characteristics of dark energy, and the Hubble tension.

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