Resolution of Non-renormalizable Singularities and Verification of Black Hole Shadows

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Abstract

This paper proposes a novel non-perturbative quantum gravity framework based on quantum topological structures. By introducing "quantum vortices" to characterize the topological order of statistical averages of microscopic particles and embedding AdS/CFT holographic duality, it eliminates black hole singularities without requiring renormalization. Theoretical derivations demonstrate that the gravitational potential generated by the quantum vortex field forms a repulsive barrier within a critical radius, dynamically prohibiting matter from reaching the singularity (r=0) and completely avoiding curvature divergence. The constructed Huang metric (Schwarzschild metric with quantum gravity corrections) can predict the angular diameter of black hole shadows without free parameters, eliminating the need for post-observational fitting of Kerr black hole spin.

Observational verification demonstrates that: the theoretical shadow angular diameter of Sgr A* is 53.3 as, showing excellent agreement with EHT measurements (51.8$\pm 2.3\mu as); thetheoreticalshadowangulardiameterofM87* is46.2\mu as, fallingwithinthereasonableerrorrangeofEHTmeasurements(42\pm$3 as). This fundamentally resolves the intrinsic contradiction of the Kerr black hole model in interpreting the M87* shadow (where the theoretical viewing angle at maximum black hole spin does not match the actual viewing angle).

This theory, for the first time, achieves a unified quantum gravity explanation of singularity elimination, information conservation, and black hole shadows, providing the first testable quantum gravity framework for exploring the quantum structure of spacetime.

Full Text

Preamble

Non-Renormalized Singularity Resolution and Black Hole Shadow Verification

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Abstract

We propose a non-perturbative quantum gravity framework that resolves black hole singularities without renormalization by utilizing quantum vortices—statistical average topological structures of microscopic particles—embedded within the AdS/CFT holographic duality. This constitutes a singularity resolution mechanism based on physical processes rather than mathematical techniques. The quantum vortex field generates a repulsive potential within a critical radius $r^* \approx 8.792 \times 10^{-11}$ m, dynamically preventing matter from reaching $r = 0$ and thereby avoiding curvature divergence. The derived Huang metric (a Schwarzschild metric with quantum corrections) predicts the angular diameter of black hole shadows without free parameters, eliminating the need for post-observational fitting of Kerr black hole spin. Observational validation demonstrates: the theoretical shadow for Sagittarius A* (Sgr A*) is* $53.3\,\mu as$ *(Event Horizon Telescope (EHT) observed value:* $51.8 \pm 2.3\,\mu as$*), and for M87* is $46.2\,\mu$as (EHT observed value: $42 \pm 3\,\mu$as), resolving contradictions inherent to Kerr models. This framework unifies singularity elimination, information conservation, and shadow prediction, providing a testable quantum gravity paradigm.

I. Introduction

The "singularity problem" has long impeded 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 study adopts a fundamentally different path from conventional perturbative methods or purely mathematical constructions, prioritizing the development of a physical framework that can be directly integrated with key astronomical observations. The core innovation introduces "quantum vortices" as a unified microscopic carrier with a clear physical picture, embedded within AdS/CFT duality to achieve non-locality. The primary objective is to demonstrate that this framework simultaneously resolves the singularity problem and enables free-parameter predictions of black hole shadows (without requiring observational adjustment of black hole spin). The consistency between theoretical predictions and Event Horizon Telescope (EHT) observations provides compelling preliminary support for this physical picture.

The Event Horizon Telescope imaging of Sagittarius A* (Sgr A*) and M87* has revealed discrepancies between Kerr black hole predictions and observational results (for example, M87*' s shadow exceeds the Kerr upper limit). To address these issues, we introduce quantum vortices—quantum topologies arising from the statistical average of fermions, bosons, and gauge fields (with non-local entanglement)—which naturally constitute a "unified field" after statistical averaging of all fields. Embedding this "unified field" within AdS/CFT duality non-perturbatively generates an internal repulsive potential that "dissolves" singularities at their source and enables free-parameter black hole shadow predictions.

II. Theoretical Framework

A. Quantum Vortices and AdS/CFT Duality

Quantum vortices are defined as statistical average quantum topological structures of microscopic particles, with the operator:

$$\mathcal{O}_{\text{vortex}}(x,y) \sim \sqrt{\psi\psi}\,\phi\,\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}\,e^{iW\theta(x,y)} \tag{1}$$

(The "quantum tornado" observed in superfluid helium experiments [1], which detected vortex lattice structures, provides preliminary support for this topological structure' s existence.)

The quantum vortex field operator is:

$$\Phi_{\text{vortex}}(x,y) = \mathcal{O}_{\text{vortex}}(x,y)\int d^{4y}\sqrt{-g(y)}K(x,y) = \sqrt{\psi\psi}\,\phi\,\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}\,e^{iW\theta(x,y)}\int d^{4y}\sqrt{-g(y)}\frac{e^{iW\theta(x,y)}}{(|x-y|^2+\ell^2)^2} \tag{2}$$

where: - $\psi\psi$: fermion field, $[\psi\psi] = L^{-3}$ - 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 (macro-photon field), $[\mathcal{A}_{\mu\nu}] = L^{-2}$ - $e^{iW\theta(x,y)}$: vortex phase (connecting non-local entanglement) - $\theta(x,y) \sim \arctan\left(\frac{y_2-x_2}{y_1-x_1}\right)$: topological phase - $W = \oint_{\mathcal{C}} \nabla\theta \cdot dl$: vortex winding number - $K(x,y) = \frac{e^{iW\theta(x,y)}}{(|x-y|^2+\ell^2)^2}$: non-local kernel function, with ℓ as the minimal characteristic length (Planck length)

We employ nested AdS/CFT duality ($AdS_4/CFT_3 \supseteq AdS_3/CFT_2$ [2,3]): the AdS_4 bulk spacetime outside the black hole undergoes dimensional reduction to its internal CFT_3 boundary (and CFT_2 boundary), where quantum vortices generate discrete mass density. This nested AdS/CFT duality ($AdS_4/CFT_3 \supseteq AdS_3/CFT_2$) builds upon the core holographic correspondence of standard AdS/CFT, which establishes equivalence between gravitational theories in AdS bulk and conformal field theories on the boundary [2,3]. Standard AdS/CFT demonstrates that strongly coupled CFTs on the boundary can be equivalently described by weakly coupled gravity in the AdS bulk [2], and this core logic persists in our nested structure. We extend the single-level duality to a hierarchical structure based solely on spacetime property transitions (classical outside the black hole, quantum inside) and quantum vortex distribution, consistent with AdS/CFT' s flexible adaptation to different spacetime scenarios [3].

B. Modified Poisson Equation

In standard flat spacetime, the d' Alembertian for a scalar field is $\partial_t^2 - \nabla^2\phi$. Inside the black hole, spacetime is spacelike ($g_{tt} > 0$), and time undergoes extreme dilation near the horizon (internal timelike radial coordinate $r_t \to \infty$), approximating flat spacetime. Using AdS/CFT duality, we reduce dimensions from the AdS_4 bulk to the three-dimensional CFT_3 boundary, i.e., the black hole exterior spacetime is dual to its interior ($\mathrm{AdS}_4/\mathrm{CFT}_3$). The quantum vortex field then satisfies a quantized d' Alembertian (replacing scalar field ϕ with quantum vortex field ϕ_{vortex}):

$$\Box\phi_{\text{vortex}} = c^2\partial_t^2\phi_{\text{vortex}} - \nabla^2\phi_{\text{vortex}}$$

where k is the non-local entanglement relative strength factor (reflecting the relativity of Planck' s constant under entanglement). Treating the quantum vortex field ϕ_{vortex} as a free scalar field:

$$\Box\phi_{\text{vortex}} = 0 \Rightarrow \nabla^2\phi_{\text{vortex}} = c^2\partial_t^2\phi_{\text{vortex}}$$

The CFT_3 boundary experiences extreme timelike radial expansion ($r_t \to \infty$), making microscopic structure dynamics approximate flat supersymmetry. By definition, $\phi_{\text{vortex}} = \langle\phi_{\text{micro}}\rangle_{\text{stat}}$, where ϕ_{micro} is the topological field of individual microscopic particles (e.g., local phase field of vortex lines) and $\langle\rangle_{\text{stat}}$ represents discrete statistical averaging over many particles. While individual particle topological fields satisfy linear dynamics (e.g., free field equation $\partial_t^2\phi_{\text{micro}} = \nabla^2\phi_{\text{micro}}$), topological entanglement between particles generates non-linear coupling.

When performing statistical averaging over these microscopic fields, cross-term expectations transform into macroscopic field non-linearities: $\langle\partial_t^2\phi_{\text{micro}}\rangle_{\text{stat}} = \langle\nabla^2\phi_{\text{micro}}\rangle_{\text{stat}} + \langle\lambda\phi_{\text{micro}}\partial_t\phi_{\text{micro}}\rangle_{\text{stat}}$, where λ is a coupling constant. For "high-density vortex systems" (regions with extreme quantum vortex density inside black holes), statistical averaging of cross-terms dominates linear terms, yielding $\partial_t^2\phi_{\text{vortex}} \approx \lambda\langle\phi_{\text{micro}}\partial_t\phi_{\text{micro}}\rangle_{\text{stat}} \sim \lambda\phi_{\text{vortex}}\partial_t\phi_{\text{vortex}}$. Assuming the vortex field' s temporal evolution exhibits "self-similarity" (i.e., $\phi_{\text{vortex}} \sim \partial_t\phi_{\text{vortex}}$, where the topological structure' s time variation rate is comparable to its own intensity), this simplifies (setting $\lambda \sim a^2$) to $\partial_t^2\phi_{\text{vortex}} \sim \lambda(\partial_t\phi_{\text{vortex}})^2 \sim a^2(\partial_t\phi_{\text{vortex}})^2$ (analogous to turbulence' s "Reynolds stress" statistical averaging logic: linear molecular motion accumulates into macroscopic fluid non-linear stress via collisions ($\langle u_i u_j\rangle \sim \partial_i U_j$); here, linear evolution of microscopic topological fields accumulates into macroscopic vortex field non-linear time derivatives through non-local entanglement).

Thus:

$$\nabla^2\phi_{\text{vortex}} \approx c^2(a \cdot \partial_t\phi_{\text{vortex}})^2$$

Substituting black hole mass M and applying self-similarity further yields:

$$\partial_t \phi_{\text{vortex}} = \frac{8\pi GM}{4\pi t}$$

where 8π is the vortex winding number (winding phase W), with $W = 8\pi$ derived from the AdS/CFT conformal dimension formula $\Delta_{\text{vortex}} \sim \frac{W^2}{C}$. The conformal dimension $\Delta_{\text{vortex}} \approx 2$ (characterizing phase oscillation dimensions) and central charge $C \approx 8$ (the number of statistical generators on the CFT_3 boundary: 4 fermions (weak hypercharge + left/right/z-component $\Rightarrow 1{+}3 = 4$) and 4 bosons (hypercolor (color precursor) + transverse/longitudinal/circular polarization $\Rightarrow 1 + 3 = 4$), giving $C = 4 + 4 = 8$, satisfying black hole interior CFT_3 boundary symmetry: $U(2)_F \times U(2)_B$, where $U(2)_F = U(1)_Y \times SU(2)_L$ represents electroweak symmetry (fermionic properties from Standard Model symmetry $U(1)_Y \times SU(2)_L \times SU(3)_c$) and $U(2)_B = U(1)_C \times SU(2)_P$ represents color-precursor symmetry (bosonic properties). This reasonable modeling enables singularity dissolution through physical mechanisms at the source, with ultimate correctness determined by observational data (e.g., black hole shadows).

With the vortex winding number ($W = 8\pi$), we obtain $a \approx \frac{kGM}{4\pi}$, representing the phase density of non-local entanglement coupling on the CFT_3 boundary (coupling coefficient per winding phase, requiring normalization). The quantum vortex field satisfies:

$$\nabla^2 \phi_{\text{vortex}} \approx c^2 (a \cdot \partial_t \phi_{\text{vortex}})^2 = \frac{k\hbar c^2 G^2 M^2}{64\pi^2 t^2}$$

(If following the Standard Model strictly, hypercolor should correspond to fermions (quarks), but considering symmetry, assigning it to bosons (gluons) is more reasonable ($C = 4{+}4$), i.e., treating color analogously to the Higgs mechanism for mass generation, acquired through gluon-quark interactions (analogous to Yukawa coupling), naturally explaining observed color confinement.)

From the quantum vortex operator ($\mathcal{O}_{\text{vortex}}(x, y) \sim \sqrt{\psi\psi}\, \phi\, \mathcal{A}_{\mu\nu} \mathcal{A}^{\mu\nu} e^{iW\theta(x,y)}$), we see the quantum vortex field is essentially a scalar field coupled from other interactions (excluding classical gravity), physically possessing properties of other forces. For instance, the "Yukawa potential" representing strong force remains statistically reliable when the system satisfies $\alpha m \sqrt{\langle r^2 \rangle} \ll 1$ (i.e., at "extremely short distances"), through Taylor expansion [4,5]: $\langle e^{-\alpha m r} \rangle \approx \langle 1{+}\ln(1{-}\alpha m r) \rangle = 1 - \alpha m \langle r \rangle - (\alpha m)^2 \langle r^2 \rangle + \cdots$. At statistically averaged "extremely short distances," the Yukawa potential exhibits "logarithmic dependence" ($\ln(1 - \alpha m r)$), which naturally possesses "sign reversal" characteristics (force direction reversal). Extending this to the quantum vortex field ϕ_{vortex} can generate a quantum repulsive barrier competing with classical gravity at these distances, achieving non-perturbative "singularity removal" (rather than "smoothing" or "erasing" singularities). The divergent behavior of Riemann tensor component ${R_{trt}}^r$ near singularities (${R_{trt}}^r \propto r^{-3}$) naturally provides the source term for this logarithmic-dependent quantum effect. Through the spacelike nature of black hole interior time ($g_{tt} > 0$), we can approximate by replacing t^{-2} with r^{-3} to construct a "logarithmic-dependent" quantum gravity potential (generated by quantum vortex field ϕ_{vortex}) that counteracts classical gravitational potential and "removes" singularities:

$$\frac{k\hbar c^2 G^2 M^2}{64\pi^2 t^2} \approx \nabla^2 \phi_{\text{vortex}} \approx \frac{k\hbar c^2 G^2 M^2}{64\pi^2 r^3}$$

This replacement implies that classical general relativity' s own divergent behavior near singularities (Riemann tensor component ${R_{trt}}^r \propto r^{-3}$) simultaneously provides an intrinsic source term ($\frac{k\hbar c^2 G^2 M^2}{64\pi^2 r^3}$) that prevents curvature divergence. Integrating this source term (solving Poisson' s equation) naturally generates a logarithmic term that repels classical gravitational collapse toward singularities. In other words, spacetime spontaneously responds to the ${R_{trt}}^r \propto r^{-3}$ divergence, producing a finite observable result (such as black hole shadows) in a non-perturbative manner, thereby naturally and physically shielding the "singularity" without introducing exotic entity assumptions (like 11-dimensional "strings" in string theory or "discretized spacetime" in loop quantum gravity).

Substituting the new density $\nabla^2 \phi_{\text{vortex}}$ into Poisson' s equation yields the modified Poisson equation for CFT boundary spacetime inside black holes:

$$\nabla^2 \Phi = 4\pi G \left(M\delta^3(r) + \frac{k\hbar c^2 G^2 M^2}{64\pi^2 r^3} \right) = 4\pi G M \delta^3(r) + \frac{k G_h M^2}{r^3} \tag{3}$$

where Φ is the gravitational potential, k is the non-local entanglement relative strength factor, $\delta^3(r)$ is the three-dimensional Dirac delta function, $M\delta^3(r)$ is the point mass source term, and $\frac{kG_h M^2}{r^3}$ is the quantum gravity mass source term.

We define the quantum gravity constant:

$$G_h \equiv \frac{\hbar c^2 G^3}{64\pi^2} \tag{4}$$

with dimensions $[G_h] = \mathrm{kg}^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-2}$. The dimensional peculiarity of $[\hbar_{\text{CFT2}}] = \mathrm{kg}\cdot\mathrm{m}^{-8}\,\mathrm{s}^6$ arises from spacetime compression in the nested duality ($\mathrm{AdS}_4/\mathrm{CFT}_3 \supseteq \mathrm{AdS}_3/\mathrm{CFT}_2$). Due to the spacetime compression factor $k_{\text{dim}}^{\text{CFT}_2} = 1\,\mathrm{m}^{-10}\,\mathrm{s}^7$ (nested duality makes $\hbar \to \hbar_{\text{CFT2}}$ value-invariant), the 10-dimensional coupled spacetime of AdS_4 (4 fluctuation dimensions + 6 phase dimensions from gauge group $(U(1)_Y \times SU(2)_L \times SU(3)_c)$ complex phase space coupling: $1 + 2 + 3 = 6$) compresses into the 7-dimensional coupled timelike dimensions of CFT_2 (1 fluctuation dimension + 6 phase dimensions), yielding $[\hbar_{\mathrm{CFT2}}] = (\mathrm{kg} \cdot \mathrm{m}^2\,\mathrm{s}^{-1}) \cdot (\mathrm{m}^{-10}\,\mathrm{s}^7) = \mathrm{kg} \cdot \mathrm{m}^{-8}\,\mathrm{s}^6$ (when quantum vortices in superfluid helium are confined to nanoscale spaces (simulating spacetime compression), their vortex phase oscillation energy $E \propto \hbar_{\mathrm{eff}}\omega$ satisfies $\hbar_{\mathrm{eff}} \propto d^{-8}$ (d: confinement scale), consistent with the dimension m^{-8} (Nature Phys. 12, 478, 2016) [6], indirectly validating spacetime compression rationality).

After defining quantum gravity constant G_h, $[\hbar_{\mathrm{CFT2}}]$ is absorbed into $[G_h]$, yielding $G_h \approx 3.52245 \times 10^{-49}\,\mathrm{kg}^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-2}$.

We acknowledge that dimensional reconstruction of fundamental constants (like $\hbar$) is a profound proposition. However, a scientific theory' s validity must ultimately be judged by its predictive power. As demonstrated below, this framework' s precise predictions of black hole shadows without any post-hoc fitting parameters provides strong preliminary support for this unconventional approach.

The non-local entanglement relative strength factor (characterizing Planck constant relativity under non-local entanglement) is:

$$k \equiv \frac{M_{\mathrm{BH,ref}}}{M_{\mathrm{BH,topo}}} \tag{5}$$

where $M_{\mathrm{BH,ref}}$ is the non-local entanglement reference black hole mass, typically chosen as $M_{\mathrm{SgrA*}}$ (the current Galactic Center black hole mass). Any black hole can be selected as reference, with Planck' s constant changing accordingly ($\hbar_{\mathrm{other}} = \frac{M_{\mathrm{SgrA*}}}{M_{\mathrm{BH,ref}}} \cdot \hbar$), reflecting non-local entanglement relativity and implying that the quantum gravity constant also changes relatively ($G_h^{\mathrm{other}} = \frac{M_{\mathrm{SgrA*}}}{M_{\mathrm{BH,ref}}} \cdot G_h$). $M_{\mathrm{BH,topo}}$ is the black hole mass creating the primary quantum gravity (quantum spacetime curvature) background for calculation, with non-local entanglement manifesting relative strength against $M_{\mathrm{BH,ref}}$. The winding number definition ($W = 8\pi$ from $W = \oint_{\mathcal{C}} \nabla\theta \cdot dl$) quantizes angular momentum (corresponding to topological angular momentum from microscopic particle statistics), while $\partial_t \phi_{\mathrm{vortex}}$ (vortex field time evolution) dynamically correlates with the black hole' s total angular momentum, making the quantum vortex field ϕ_{vortex} a natural "quantized angular momentum carrier." Its effects incorporate naturally through the non-local entanglement factor k (determined by black hole mass ratio relative to a reference like Sgr A*), microscopically explaining "spin-like spacetime correction effects" (Kerr spin (α) is a macroscopic fitting parameter in classical spacetime frameworks ($0 \leq \alpha \leq 1$) lacking clear microscopic physical pictures and requiring observational data for inference).

Thus, black hole angular momentum is not an isolated property but a relative relationship established through quantum entanglement between black holes. This parallels quantum mechanics, where entangled particle properties are mutually defined (e.g., two-electron spin entanglement $(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$ means measuring one electron' s spin as "up" necessarily yields "down" for the other—

their "spin" properties are relationally defined). Elevating this logic to cosmic scales naturally constitutes the intrinsic nature of black hole angular momentum —the ER=EPR conjecture, where geometric "wormholes" and quantum entanglement are identical [7]. This implies that quantum entanglement between two distant black holes can be viewed as a "wormhole" connection in spacetime geometry, supporting that inter-blackhole entanglement defines their geometric properties. With this mutual definition of black hole entanglement relationships, the quantum constant related to black hole quantized angular momentum carriers (quantum vortices)—Planck' s constant $\hbar$—exhibits different relative values across different quantum gravity backgrounds (different black hole gravitational fields). The specific implementation measuring this relative strength is the k factor characterizing black hole mass ratios. We recognize that relativizing Planck' s constant $\hbar$ again touches the frontier of modern physics, but our theoretical construction remains validated by whether predictions (e.g., black hole shadows) match observations.

Moreover, we note that Planck' s constant' s dimensions $[M][L]^2[T]^{-1}$ match angular momentum dimensions. Based on the quantized angular momentum concept ($W = \oint_{\mathcal{C}} \nabla\theta \cdot dl$), we can reasonably hypothesize a relationship between black hole mass (M) and Planck' s constant in that black hole' s quantum gravity background (quantized angular momentum) ($\{mvr\}_{\mathrm{BH}} \sim \{\hbar\}_{\mathrm{BH}}$): $M \propto \{mvr\}_{\mathrm{BH}} \sim \{\hbar\}_{\mathrm{BH}}$ (we reiterate that this simple scaling relationship remains validated by theoretical predictions matching observations).

Using the Galactic Center black hole (Sgr A*) as reference: $M_{\mathrm{SgrA*}} \propto \{mvr\}_{\mathrm{SgrA*}} \sim \hbar$. For other black holes:

$$kM_{\mathrm{BH,topo}} = \frac{M_{\mathrm{SgrA*}}}{M_{\mathrm{BH,topo}}} M_{\mathrm{BH,topo}} = M_{\mathrm{SgrA*}} \propto \{mvr\}_{\mathrm{SgrA*}} \sim \hbar$$

$$\Rightarrow M_{\mathrm{BH,topo}} \propto \frac{\{mvr\}_{\mathrm{SgrA*}}}{k} \sim \frac{\hbar}{k}$$

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

This corroborates that in quantum gravity backgrounds formed by other black holes' gravitational fields, Planck' s constant values ($\hbar_{\mathrm{other}}$) must vary with the relative strength of "quantized angular momentum ($\{mvr\}_{\mathrm{other}}$)" —the black hole mass ratio.

Solving the modified Poisson equation:

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

yields the gravitational potential:

$$\Phi(r) = \Phi_1 + \Phi_2 = -\frac{GM}{r} - \frac{kG_h M^2(\ln r + 1)}{r} \tag{7}$$

The classical gravity source term $4\pi GM\delta^3(r)$ corresponds to Newtonian potential $-GM/r$, while the quantum gravity source term $\frac{kG_h M^2}{r^3}$ corresponds to quantum gravity potential $-\frac{kG_h M^2(\ln r+1)}{r}$. Note: The logarithmic term' s argument (r) must be dimensionless; we can normalize Planck length to 1 m, making $(\ln(r/1) = \ln r)$ naturally dimensionless. Thus, all logarithmic term arguments (r) in this theory implicitly contain normalization.

Analyzing Potential Behavior

In the quantum gravity potential $(\Phi_2 \propto (\ln r + 1)/r)$, the logarithmic term $\ln r$ becomes negative starting from $r < 1$. This behavior causes the quantum gravity potential (Φ_2) to begin repelling the Newtonian potential (Φ_1) until, below a critical radius $(r^* = e^{kG_h M} = e^{G_h M_{\mathrm{SgrA^*}}} \approx 8.792 \times 10^{-11}\,\mathrm{m}, \Phi(r^*) = 0)$, $|\Phi_2| > |\Phi_1|$ makes the total potential $\Phi(r) > 0$, naturally preventing curvature divergence and eliminating the singularity (non-perturbatively and without renormalization). Moreover, in the region $r < r^*$, the total potential $\Phi(r) > 0$ generates repulsive forces that kick vacuum fluctuation virtual particles out of "particle-antiparticle" annihilation into excited particle states. Through the $\mathrm{AdS}_4/\mathrm{CFT}_3 \supseteq \mathrm{AdS}_3/\mathrm{CFT}_2$ duality, these excited particle states tunnel and escape the black hole via $\mathrm{AdS}_4 \to \mathrm{CFT}_2 \to \mathrm{AdS}_3 \to \mathrm{CFT}_3 \to \mathrm{AdS}_4$, finally becoming real particles outside the black hole (e.g., through electroweak symmetry breaking), consistent with quantum mechanical unitarity. Tunneling particles carry black hole information outward, ensuring information conservation and naturally resolving the "black hole information paradox."

III. Huang Metric

The relationship between metric and gravitational potential in general relativity' s weak-field approximation is:

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

with:

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

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

$$ds^2 = -A(r)c^2dt^2 + B(r)dr^2 + r^2 d\Omega^2 \tag{10}$$

$$A(r) \approx 1 + \frac{2kG_h M^2(\ln r + 1)}{c^2 r}, \quad B(r) \approx 1 - \frac{2kG_h M^2(\ln r + 1)}{c^2 r} \tag{11}$$

Key differences and physical implications between the Huang metric (Schwarzschild metric with quantum corrections) and the Schwarzschild metric:

- **Schwarzschild**: $B = 1/A \Rightarrow \sqrt{B/A} = 1/A$, so coordinate time t diverges at the horizon.
- **Huang metric**: $B(r_h) = 2 \Rightarrow \sqrt{B/A} \sim 1/\sqrt{A}$, making $\int dt$ finite, so coordinate time t remains finite.

This means: the horizon is de-singularized (g_{rr} regular), and external static time t no longer presents the horizon as an "infinite-time boundary." Particles' escapability at the horizon means black holes grow primarily through mergers rather than accretion, naturally explaining observed low accretion rates—celestial debris tidally disrupted by black hole gravity only forms accretion disks.

With the quantum-corrected Huang metric $g_{\mu\nu}$ and new gravitational potential $\Phi(r)$, generalized relativity calculations yield quantum-corrected field equations. First, based on the quantum correction term in the new gravitational potential ($\frac{kG_h M^2(\ln r+1)}{r}$), we postulate the quantum-corrected field equation form:

$$G_{\mu\nu} + \frac{kG_h M^2(\ln r + 1)}{r} g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{13}$$

Then, through Huang metric calculation:

1. Christoffel Symbols

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

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

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

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

3. Ricci Scalar R

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

4. Einstein Tensor $G_{\mu\nu}$

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

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

$$G_{\mu\nu} + \Lambda(r)g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{14}$$

where:

$$\Lambda(r) = \frac{kG_h M^2(\ln r + 1)}{c^2 r} \tag{15}$$

The field equation becomes:

$$G_{\mu\nu} + \Lambda(r)g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{16}$$

Foreground curvature: Einstein tensor $G_{\mu\nu}$ (classical spacetime curvature) characterizes Newtonian gravity. Background curvature: $\Lambda(r)g_{\mu\nu}$ (quantum spacetime curvature) characterizes quantum gravity coupled from other interactions (electromagnetic, strong, weak). Defining the Huang tensor ($H_{\mu\nu} = \Lambda(r)g_{\mu\nu}$) allows defining total curvature tensor $\hat{G}_{\mu\nu}$, further simplifying the Einstein-Huang field equation to:

$$\hat{G}_{\mu\nu} = G_{\mu\nu} + H_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{17}$$

Note that $\nabla_\mu \hat{G}^{\mu\nu} \neq 0$ does not violate general conservation because when $\nabla_\mu G^{\mu\nu} = 0$, the field equation yields $\nabla_\mu H^{\mu\nu} = \frac{8\pi G}{c^4}\nabla_\mu T^{\mu\nu}$, meaning quantum spacetime curvature fluctuations inside black holes spontaneously generate energy-momentum flow. In extreme black hole interiors, virtual particle fluctuations can be excited into real particle excited states by the repulsive potential ($\Phi(r) > 0$) within the critical radius ($r < 8.792 \times 10^{-11}$ m) that prevents singularity formation, thereby extending general relativity' s conservation laws. This extension echoes the earlier "excited particle states tunneling out of black holes with information" —tunneling particles are precisely generated by this energy-momentum flow. If we assume no black hole ($H_{\mu\nu} = 0$), the Einstein-Huang field equation reduces to the standard Einstein field equation: $\hat{G}_{\mu\nu} = G_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$. This extension logic mirrors general relativity' s extension of Newtonian mechanics: Newtonian mechanics wasn' t overturned but became the low-speed, non-spacetime-curvature limit; similarly, this theory doesn' t overturn general relativity but makes it the limit of our theory when "black holes and quantum effects are ignored ($H_{\mu\nu} = 0$)," establishing a hierarchical relationship rather than opposition.

Additionally, for equatorial null geodesics, defining impact parameter $b \equiv Lc/E$, the closest approach r_0 satisfies $b^2 = \frac{A(r_0)}{B(r_0)} r_0^2$, yielding the gravitational lensing deflection angle under the Huang metric:

$$\hat{\alpha}(b) = 2 \int_{r_0}^{\infty} \frac{dr}{r\sqrt{\frac{A(r)}{B(r)}\frac{r^2}{b^2} - 1}} - \pi \tag{18}$$

a) Strong-field regime: As the closest approach approaches the photon ring $r_0 \to r_{ph}$, divergence occurs. The extra logarithmic correction in $A(r)$ causes the photon ring radius to shift outward compared to Schwarzschild and divergence to appear earlier, trapping light sooner. Consequently, any light attempting to graze near the horizon undergoes extreme deflection and cannot contribute to a "clear imaging" light path—multiple diffraction orbits cannot form stable images. Therefore, black hole shadow and bright ring sizes are primarily determined by the Huang metric' s geometry rather than by 叠加 of numerous light ray deflections. In other words, the light paths forming images near black holes originate from the stable luminous ring at the shadow edge (accretion disk/plasma emission), not from complex multiple diffractions. The ring observed by EHT is almost the true luminous distribution of the black hole and accretion disk, not an illusion "patched together" by bent and diffracted light. Thus, the critical impact parameter ($b_c = \sqrt{A(r_{ph})}$) no longer characterizes the black hole shadow radius.

b) Weak-field regime: For weak deflection with $b \gg r_s$, expanding $A(r), B(r)$ to $1/r$ order ($\frac{2kG_h M^2(\ln r+1)}{c^2 r} \ll 1$) and applying the "thin lens" paraxial approximation:

$$\hat{\alpha}(b) \approx \frac{4kG_h M^2}{c^2 b}(\ln b + 1 - \ln 2) \approx \frac{4kG_h M^2}{c^2 b}\ln b \tag{19}$$

When $k = 0$, this reduces to standard general relativistic gravitational lensing.

IV. Black Hole Shadow Calculation and Observational Validation

- **Schwarzschild radius unchanged**: $r_s = 2GM/c^2$
- **Huang metric horizon** r_h: From $g_{tt} = 0$, the horizon equation is:

$$c^2 r = 2GM + 2kG_h M^2(\ln r + 1) \tag{20}$$

This equation has two roots: horizon r_h and CFT_2 boundary $r_{\mathrm{CFT}} \approx 8.85 \times 10^{-11}\,\mathrm{m}$ (constant), satisfying $r \to r_h^- \Rightarrow g_{tt} \to 0^+$ and $r \to r_{\mathrm{CFT}}^- \Rightarrow g_{tt} \to 0^-$. The condition $g_{tt} \to 0$ causes time dilation ($t \to \infty$) near both r_h and r_{CFT}, approximating flat spacetime when approaching these locations (black hole interior time is spacelike ($g_{tt} > 0$): $t \to \infty \Rightarrow r_t$ (timelike radial) $\to \infty$), naturally forming two CFT boundaries: CFT_3 boundary r_h (horizon) and CFT_2 boundary $r_{\mathrm{CFT}}(\approx 8.85 \times 10^{-11}\,\mathrm{m})$. This constitutes a necessary condition for nested duality ($AdS_4/CFT_3 \supseteq AdS_3/CFT_2$).

For $r < r_{\mathrm{CFT}} \approx 8.85 \times 10^{-11}\,\mathrm{m}$, $\Lambda(r) < 0$ creates an extremely small AdS_4 anti-de Sitter spacetime at the black hole center, providing the second necessary condition for AdS/CFT duality. Combined with the two approximately flat spacetime boundaries formed by the Huang metric ($g_{tt} \to 0^+$ at r_h^- forming CFT_3 boundary and $g_{tt} \to 0^-$ at r_{CFT}^- forming CFT_2 boundary), these together constitute the sufficient and necessary conditions for $AdS_4/CFT_3 \supseteq AdS_3/CFT_2$ duality!

- **Huang metric photon ring** r_{ph}: For photons with $ds^2 = 0$ and circular orbits $\dot{r} = 0$, satisfying effective potential $V_{\mathrm{eff}}(r_{ph}) = 0$, the photon ring equation is:

$$c^2 r = 3GM + kG_h M^2(3\ln r + 2) \tag{21}$$

This equation also has two roots: photon ring r_{ph} and AdS_3 bulk onset $r_{\mathrm{AdS}} \approx 1.23 \times 10^{-10}\,\mathrm{m}$ (constant). Interpreting r_{ph} as the AdS_4 bulk onset also forms two bulk boundaries, echoing the $AdS_4/CFT_3 \supseteq AdS_3/CFT_2$ duality.

The Huang metric’ s quantum term $\propto \ln r + 1$ suggests that under non-local entanglement, logarithmic radius $\ln r$ is more natural than linear coordinate r. Performing variable substitution $x = \ln r$, the (r_h, r_{ph}) tunneling interval becomes $(\ln r_h, \ln r_{ph})$ (i.e., (x_h, x_{ph})).

Analyzing Tunneling Probability

For photons tunneling from r_h to visible r, the WKB approximation gives tunneling probability density $P(x) \propto e^{-2S(x)}$ (where action $S(x) \sim \int \sqrt{2m(V(x)-E)}dx$). From total gravitational potential $\Phi(r)$, the potential barrier arises from the quantum gravity potential’ s logarithmic term: $V(x) \sim V_0 + a(\ln r + 1)/r = V_0 + ae^{-x}$. In the tunneling interval $r \in (r_h, r_{ph})$, linear approximation expands $\sqrt{V(x)-E}$ to first order, approximating it as a linear function in (x_h, x_{ph}): $\sqrt{V(x)-E} \approx \alpha + \beta(x - x_c)$, where x_c is an intermediate point. Thus, action $S(x)$ becomes a quadratic function of x: $S(x) \approx S_0 + A(x - x_c) + B(x - x_c)^2$, giving $P(x) \propto e^{-2S(x)} \sim e^{-2B(x-x_c)^2} \times$ (slowly varying factor). This means tunneling probability follows a Gaussian distribution in the (r_h, r_{ph}) interval. The decoupled tunneling of photons in (r_h, r_{ph}) becomes Brownian random walk in logarithmic space

(x_h, x_{ph}). In this case, the tunneling steady-state naturally distributes at the arithmetic mean: $x_{sh} \approx (x_h + x_{ph})/2 \Rightarrow \ln r_{sh} \approx (\ln r_h + \ln r_{ph})/2$.

- **Therefore, shadow radius (tunneling steady-state radius) takes geometric mean**:

$$r_{sh} \approx \sqrt{r_h r_{ph}} \tag{22}$$

(returning from logarithmic variable $x = \ln r$ to linear variable $r = e^x$)

- **Observed shadow angular diameter**:

$$\theta_{sh} = \frac{2r_{sh}}{D} \tag{23}$$

where D is distance.

Black Hole Shadow Angular Diameter Calculation and EHT Observation Comparison [8,9]

Black Hole	$M(M_\odot)$	k	Theoretical $\theta_{sh}(\mu\text{as})$	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	Within range
IC1459	2.51×10^9	1.71×10^{-3}	3.07	To be measured	–

V. Inadequacy of Traditional Mechanisms for Explaining EHT Shadows

Contradiction A: Kerr black hole spin explanations for shadows show that M87' *s observed shadow angular diameter implies an actual shadow diameter* ($5.5r_s$) *slightly exceeding the maximum-spin Kerr black hole prediction* 上限 ($4.8r_s$-$5.2r_s$, *specifically* $5.2r_s$). *This* 上限 *depends on equatorial horizon observation, but the actual observed horizon angle (M87* jet-horizon inclination of 17°) is not equatorial but polar, so Kerr black hole shadows should bias toward $4.8r_s$, creating significant theory-observation tension (worsening with increasing black hole mass, i.e., Kerr shadows become increasingly smaller than observed). Subsequent RQCBH (rotating quantum-corrected black hole) and GCKBH (generalized uncertainty principle-corrected) models explaining M87*' s actual shadow diameter both rely on free parameters: $\alpha \sim 0.1$ and $\epsilon \sim 0.4$ to fit observed shadows.

The Huang metric's free-parameter black hole shadow calculation (requiring only black hole mass M and mass ratio k relative to Sgr A*) means any black hole shadow can be calculated without prior EHT observation—EHT observations serve only as validation.

Contradiction B: Traditional views hold that light deflection near black holes creates false imaging through multiple diffractions (like a "funhouse mirror"). If EHT' s bright ring resulted from light deflection, the jet base should deviate from the ring center (since jets emit along the rotation axis). However, 2021 EHT polarization data revealed M87' s jet base precisely passes through the bright ring' s geometric center [10], directly contradicting traditional multiple-diffraction scenarios.

Gravitational lensing deflection angle analysis under the new metric (Huang metric) shows that strong fields near black holes do not produce false imaging through multiple diffractions (since the photon ring shifts outward compared to Schwarzschild, trapping light earlier). Instead, true luminous distributions (including accretion disk/plasma emission) are observed, naturally explaining 2023 EHT jet observations. Genuine gravitational lensing light deflection occurs in weak fields far from black holes.

This Theory vs. Kerr Black Hole Model [11]

The Kerr black hole model has resolved certain issues, but when $r < 8.792 \times 10^{-11}$ m, quantum gravity generates a repulsive potential barrier that dynamically prevents any matter from reaching the singularity while satisfying information conservation. In contrast, the Kerr model retains intrinsic ring singularities, remains incomplete within classical general relativity, and cannot satisfy information conservation. The Huang metric requires only black hole mass M and distance D, with no additional degrees of freedom, whereas Kerr models require observational fitting of two key extra parameters: dimensionless spin α ($0 \leq \alpha \leq 1$) and observation inclination angle i. The Huang metric provides free-parameter predictions (requiring only black hole mass M and mass ratio k), while Kerr models lack predictive power (requiring observational fitting of α, i). For the two black holes observed by EHT, quantum-corrected Huang metric calculations match observations almost perfectly without post-hoc spin fitting (especially resolving M87* 's maximum-spin equatorial horizon angle vs. actual polar horizon angle contradiction). This proves that introducing quantum vortices' statistical average quantum topological structure eliminates singularities non-perturbatively without renormalization, consistent with actual EHT observations!

Predicting Arbitrary Black Hole Shadow Sizes

1. **Input black hole mass** $M_{\mathrm{BH,topo}}$
2. **Calculate non-local entanglement relative strength factor**: $k = \frac{M_{\mathrm{BH,ref}}}{M_{\mathrm{BH,topo}}}$ (taking $M_{\mathrm{BH,ref}} = M_{\mathrm{SgrA*}}$)

3. **Solve equation system** ($M = M_{\text{BH,topo}}$):

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

4. **Calculate shadow radius**: $r_{sh} = \sqrt{r_h r_{ph}}$
5. **Calculate angular diameter**: $\theta_{sh} = 2r_{sh}/D$
6. **Compare with EHT observations**

Like EHT observational data, these calculations are public and reproducible.

Notably, unique quantum gravity effects produced by new physical mechanisms inside black holes—such as extreme quantum gravity potential energy release, winding number transitions, and accompanying polarization-flipping super-circular polarization radiation (polarization degree exceeding 90%, a phenomenon contradictory to traditional stellar models where super-circular polarization and polarization flipping cannot coexist), with the observed repeating radio burst FRB20201124A as a typical example—along with this theory' s breakthroughs in naturally explaining long-standing physical puzzles including galaxy rotation curves (dark matter-related), dark energy nature and dynamics, and Hubble tension, will be elaborated in subsequent studies.

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Note: Figure translations are in progress. See original paper for figures.