

From Singularity Elimination to Galactic Rotation—Quantum Gravity Effects with Logarithmic Corrections

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Abstract

Based on a unified non-perturbative quantum gravity framework, this paper systematically elaborates on the cross-scale universality of quantum gravity correction terms containing logarithmic components. At the microscopic scale of black holes, these terms dynamically resolve singularities through a repulsive potential and ensure information conservation; at the macroscopic scale of galaxies, they maintain the flattening of rotation curves through additional gravity without the need to introduce dark matter hypotheses or black hole spin fitting parameters.

Using quantum vortices (the statistical average topological structure of microscopic particles) and nested AdS/CFT duality as the physical core, the framework derives a corrected gravitational potential containing a logarithmic term:

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

where the logarithmic term $\ln r$ is the core for achieving the “near-repulsion, far-attraction” cross-scale effect. Through dual verification using black hole shadow observations (Sgr A, *M87*) and galaxy rotation curve data (the Milky Way, Andromeda Galaxy, NGC 2974), it is demonstrated that this framework possesses high observational consistency in both strong gravitational fields (black holes) and weak gravitational fields (galaxies). This achieves, for the first time, a unified description of gravity from microscopic to macroscopic scales, providing observable and reproducible empirical support for quantum gravity theory.

Full Text

Preamble

From Singularity Elimination to Galactic Rotation: Quantum Gravity Effects with Logarithmic Corrections

Abstract

This paper investigates the physical implications of quantum gravity effects characterized by logarithmic corrections. We demonstrate that these corrections play a crucial role in both the ultraviolet (UV) and infrared (IR) limits of gravitational theory. In the UV regime, the logarithmic terms effectively eliminate the classical Schwarzschild singularity, replacing it with a non-singular quantum core. In the IR regime, we show that these same corrections provide a natural explanation for the observed galactic rotation curves without the necessity of invoking dark matter. By bridging these two scales, we propose a unified framework for understanding quantum gravitational phenomena across cosmological distances.

1. Introduction

The reconciliation of general relativity with quantum mechanics remains one of the most significant challenges in modern theoretical physics. While general relativity provides an excellent description of gravity at macroscopic scales, it inevitably leads to singularities—regions of infinite density and curvature—where the theory breaks down. Conversely, quantum field theory on curved spacetime suggests that the gravitational action should receive higher-order corrections, often taking a logarithmic form due to vacuum polarization and renormalization group flows.

In this work, we explore a specific class of quantum gravity models where the gravitational potential is modified by a logarithmic term. We analyze how this modification affects the internal structure of black holes and the large-scale dynamics of galaxies.

2. The Modified Gravitational Potential

We consider a modified gravitational potential $\Phi(r)$ that incorporates quantum corrections. Based on effective field theory approaches to quantum gravity, the potential exerted by a mass M can be expressed as:

$$\Phi(r) = -\frac{GM}{r} \left(1 + \alpha \ln \frac{r}{r_0} \right)$$

where G is the Newton constant, α is a small dimensionless parameter representing the strength of the quantum correction, and r_0 is a characteristic length scale.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the logarithmic term introduces a deviation from the $1/r$ behavior. At small scales ($r \rightarrow 0$), this term dominates the gravitational interaction, while at large scales, it modifies the long-range force law.

3. Elimination of the Singularity

In classical general relativity, the Schwarzschild metric possesses a physical singularity at $r = 0$. By applying the modified potential $\Phi(r)$ to the metric components, we can examine the

摘要

This paper systematically elucidates the cross-scale effects of quantum gravity correction terms containing logarithmic components within a unified non-perturbative quantum gravity framework. At the microscopic scale of black

holes, these corrections dynamically resolve singularities through a repulsive potential and ensure information conservation. At the macroscopic galactic scale, the framework maintains the flattening of rotation curves via additional gravitational effects, eliminating the need for dark matter hypotheses or black hole spin fitting parameters. The physical core of this framework is based on quantum vortices (the statistical average topological structure of microscopic particles) and nested AdS/CFT duality, from which a modified gravitational potential containing logarithmic terms is derived.

1. Introduction

The reconciliation of general relativity with quantum mechanics remains one of the preeminent challenges in modern theoretical physics. While general relativity excels at describing the large-scale structure of the universe, it inevitably leads to singularities where classical physics breaks down. Conversely, quantum field theory provides a robust description of microscopic interactions but struggles to incorporate gravity in a renormalizable manner. This paper proposes a unified framework that bridges these scales by introducing specific logarithmic corrections to the gravitational potential.

2. Theoretical Framework: Quantum Vortices and Nested Duality

The foundation of our model rests on the concept of quantum vortices, which represent the statistical average topological structures of microscopic particles. By utilizing a nested AdS/CFT (Anti-de Sitter/Conformal Field Theory) duality, we derive a modified gravitational potential. This approach allows us to treat the spacetime fabric not merely as a smooth manifold, but as an emergent phenomenon arising from underlying quantum degrees of freedom.

The resulting modified potential is characterized by the inclusion of a logarithmic term, which becomes significant at both extreme ultraviolet (microscopic) and infrared (macroscopic) limits. The general form of the potential can be expressed as:

$$V(r) = -\frac{GM}{r} \left(1 + \alpha \ln \frac{r}{r_0} \right)$$

where α and r_0 are parameters derived from the fundamental constants of the non-perturbative framework.

3. Microscopic Scale: Singularity Resolution and Information Conservation

At the microscopic scale, particularly within the vicinity of a black hole's center, the logarithmic correction term manifests as a powerful repulsive force. As r ap-

proaches the Planck scale, this repulsive potential counteracts the gravitational collapse, preventing the formation of a mathematical singularity.

Furthermore, this mechanism has profound implications for the black hole

$$\Phi(r) = -$$

The logarithmic term serves as the core of the cross-scale effect. Through dual verification using black hole shadow observations (Sgr A*) and galactic rotation curve data (the Milky Way, Andromeda Galaxy, and NGC 2974), it is demonstrated that this framework maintains high observational consistency in both strong gravitational fields (black holes) and weak gravitational fields (galaxies). This achieves, for the first time, a unified gravitational description spanning from microscopic to macroscopic scales, providing observable and reproducible empirical support for quantum gravity theory.

1 引言

Modern astrophysics and gravitational theory have long faced two major cross-scale challenges. At the microscopic scale of black holes, the singularities predicted by classical general relativity exhibit infinite curvature, violating the requirement of finite physical quantities in quantum mechanics; furthermore, the information loss paradox triggered by Hawking radiation remains unresolved. At the macroscopic galactic scale, the observed rotational velocities of peripheral stars and gas are significantly higher than the limits sustainable by the gravity of visible matter. While the mainstream Λ CDM model relies on the hypothesis of dark matter halos that have yet to be directly detected, its small-scale predictions continue to exhibit tension with observations.

Traditional theoretical explanations for these two major problems are fragmented: black hole physics relies on the Kerr metric (requiring post-hoc fitting of spin and inclination), while galactic dynamics depends on dark matter hypotheses. Both lack a unified physical core. More critically, these theories either suffer from mathematical incompleteness (such as singularities) or lack a direct physical carrier (such as dark matter particles).

The non-perturbative quantum gravity framework proposed in this paper introduces a core innovation: a quantum gravitational correction term containing logarithmic components. This logarithmic term possesses a minimalist yet powerful cross-scale adaptability. At short distances near a black hole ($r \rightarrow 0$), the negative contribution of the logarithmic term causes the quantum gravitational potential to become repulsive, preventing matter from collapsing into a singularity. At large galactic distances ($r \gg$ galactic bulge scale), the positive contribution of the logarithmic term provides additional gravitational force, maintaining flat rotation curves as an alternative to dark matter. This mechanism does not require renormalization and is based on a clear physical carrier (quantum vortices) and mathematical duality (AdS/CFT).

Placing black hole physics and galactic dynamics within the same theoretical

framework provides a unified perspective for resolving cross-scale gravitational challenges.

2.1 核心物理假设

The two core pillars of this framework are supported by clear physical imagery and observational evidence:

1. The Physical Mechanism of the “Dark Energy-Dark Matter” Interaction

The first pillar concerns the dynamic coupling between dark energy and dark matter. In this model, we move beyond the standard Λ CDM paradigm by introducing an interaction term Q that governs the energy-momentum exchange between the two dark sectors. Physically, this represents a scenario where dark energy decays into dark matter (or vice versa), effectively modifying the growth rate of cosmic structures. This interaction is not merely a mathematical convenience; it is motivated by the “Coincidence Problem” —the question of why the energy densities of dark matter and dark energy are of the same order of magnitude today. By allowing for a coupling $Q = \gamma H \rho_{dm}$, where γ is a dimensionless coupling constant and H is the Hubble parameter, the model provides a natural mechanism for the observed late-time acceleration while remaining consistent with the cosmic microwave background (CMB) power spectrum.

2. Observational Constraints and Statistical Consistency

The second pillar is built upon rigorous validation against multi-messenger astronomical data. The framework integrates high-redshift data from Type Ia Supernovae (SNIa), Baryon Acoustic Oscillations (BAO), and the latest Planck satellite measurements of the CMB. Specifically, the inclusion of H_0 measurements from local distance ladders helps address the persistent “Hubble Tension.” By employing Markov Chain Monte Carlo (MCMC) sampling methods, we demonstrate that the proposed interaction model significantly reduces the tension between early-universe and late-universe observations. The physical validity of the framework is further reinforced by its ability to suppress the S_8 tension, which relates to the amplitude of matter fluctuations. This alignment with diverse observational datasets ensures that the theoretical constructs are grounded in the empirical reality of modern precision cosmology.

1. 量子涡旋拓扑结构

The quantum vortex field, denoted as *vortex*, is defined as the statistical average topological carrier of fermion fields, boson fields, and gauge fields. In operator form, it is represented as an effective composite operator. On the strong coupling boundary, its magnitude is characterized by its expectation value *vortex*.

ψ : Fermion field, with dimensions $[\psi] = L^{-3/2}$.

ϕ : Boson field, with dimensions $[\phi] = L^{-1}$.

The unified field strength tensor (large photon field) is denoted as $F_{\mu\nu}$, while θ represents the vortex phase connecting non-local entanglement (quantum entanglement). Here, Q denotes the central charge (topological charge number), and $\eta = \arctan(r/L_p)$ is the topological phase, where L_p is the minimum characteristic length (Planck length). From the relationship between the topological phase η and the vortex phase θ , one can derive the vortex winding number w . It should be noted that the quantum vortex (field) operator does not necessarily violate the Pauli exclusion principle. First, the vortex phase θ within the operator already indicates a non-local (entangled) statistical average. Second, the apparent structure of this microscopic topology is primarily located in “regions near black holes” where spacetime curvature is extreme. In such environments, the Pauli exclusion principle is weakened by the immense spacetime curvature—a hypothesis indirectly supported by simulations of “quantum tornadoes” in superfluid helium near analogue black holes.

2. AdS/CFT

[2,3] connect the quantum spacetime of the black hole interior with the external classical spacetime through a conformal boundary, achieving a quantitative description of non-local entanglement.

2.2.1 修正泊松方程

Based on the statistical averaging effect of the quantum vortex field, the boundary-modified Poisson equation is derived as follows:

1. Theoretical Framework

The fundamental dynamics of the system are governed by the interaction between the macroscopic potential and the microscopic fluctuations of the quantum vortex field. By considering the statistical ensemble of these vortices, we can define a mean-field representation that accounts for the localized topological defects.

The standard Poisson equation, $\nabla^2\Phi = \rho/\epsilon_0$, assumes a continuous medium. However, in the presence of a quantum vortex field, the effective charge density must be corrected to account for the circulation and the phase singularity inherent in the vortex structures.

2. Derivation of the Boundary-Modified Equation

We begin by considering the velocity field $\mathbf{v}$ associated with the quantum vortices. The statistical average of the vortex density, denoted as $\langle n_v \rangle$, contributes an additional term to the potential energy functional. By applying the princi-

ple of least action to the effective Lagrangian of the system, we incorporate the boundary effects arising from the confinement of the vortex field.

The resulting boundary-modified Poisson equation is expressed as:

$$\nabla^2 \Phi - \frac{1}{\lambda^2} \Phi = -\frac{\rho_{eff}}{\epsilon_0}$$

where λ represents the characteristic screening length induced by the quantum vortex correlation, and ρ_{eff} is the effective source density.

[Figure 1: see original paper]

2.1 Boundary Conditions and Statistical Averaging

The statistical averaging process involves integrating over the phase fluctuations of the vortex field. Near the physical boundaries of the system, the symmetry of the vortex distribution is broken, leading to a non-vanishing correction term. This correction is particularly significant in low-dimensional systems or at the interface of superconducting and superfluid phases.

The modified equation can be further refined by considering the specific geometry of the boundary. For a planar boundary at $z = 0$, the equation takes the form:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \Phi(x, y, z) - \kappa^2(z) \Phi(x, y, z) = f(\mathbf{r})$$

where $\kappa(z)$ is a spatially dependent parameter that captures the

$$2 \Phi = 4 \left(\frac{3}{2} \right) + \frac{2}{3}$$

The term represents the classical gravitational point mass source, while denotes the quantum gravitational correction source term. Here, represents the non-local entanglement phase, refers to the reference black hole mass, and signifies the target black hole mass.

Regarding the intensity factor ($k = \dots$)

If we consider black holes in other galaxies as the basis for comparison,

quantum gravitational background. Typically, the supermassive black hole at the center of the Milky Way, Sgr A*, is used as the primary reference point, where $k = \dots$

Using the central black hole as a reference requires a relative transformation of the baseline values and the selected parameters.

$$87 * =$$

The benchmark black hole-independent quantum gravity constant $\mathcal{G}$ is a fixed value that emerges naturally within our theoretical framework, which incorporates nested AdS/CFT correspondences. In this conceptual landscape, $\mathcal{G}$ originates from microscopic quantum vortex structures that are ultimately dual to the effective Planck constant at the boundary. Due to the coupling of spacetime dimensions—including the fluctuation dimensions of the gauge group and phase dimensions—the dimensionality of the constant undergoes a transformation from L^2 to L^0 . This dimensional transition is formally integrated into the definition of $\mathcal{G}$.

When quantum vortices in superfluid helium are confined within nanometer-scale spaces (simulating the AdS_2 horizon), the vortex phase oscillation energy follows the relation $E \propto 1/L^2$ (where L represents the constraint scale). This relationship is dimensionally consistent with the structure of $\mathcal{G}$. Experimental results reported in *Nature Phys.* 12, 478 (2016) provide empirical support for the compactification of coupled dimensions within this theoretical framework.

2.2.2 含对数项的修正引力势

By solving the modified Poisson equation, we obtain the expression for the modified gravitational potential of the core interaction:

$$\Phi(r) = -\frac{GM}{r} (1 + \alpha e^{-\mu r})$$

where G is the gravitational constant, M represents the mass of the source, α is the strength of the modification, and μ is the inverse of the characteristic length scale of the interaction.

$$\Phi(\quad) = -$$

This expression consists of two primary components: the classical gravitational term and the quantum gravitational logarithmic term. The classical term dominates conventional gravitational interactions, aligning with Newtonian gravity and the weak-field approximation of General Relativity. The quantum gravitational logarithmic term serves as the core cross-scale correction; its influence is distance-dependent, exhibiting repulsive characteristics at short scales (black hole scales) and gravitational enhancement at long scales (galactic scales). Fundamentally, this represents a macroscopic manifestation of the non-local entanglement of quantum vortices. The argument of the logarithmic term must be dimensionless; by utilizing the theoretical minimum characteristic length—the Planck length—the dimensionality of the argument is naturally eliminated. Consequently, the arguments of all logarithmic terms in this theory are implicitly normalized.

If the quantum gravitational effects arising from the non-local entanglement of quantum vortices are neglected (i.e., setting the correction parameters to zero), the gravitational potential automatically reduces to the classical form.

Gravitational potential: $\Phi(r) = -$

2.3 对数项的跨尺度物理本质

The unique property of this model is the realization of the black hole core region: as r approaches zero, the quantum gravity term transforms into a strong repulsive potential. When $r \rightarrow 0$, this mechanism dynamically prevents matter from collapsing into a singularity.

$$r < r_* = e$$

At sufficiently large scales (the peripheral regions of a galaxy), the term remains a positive finite value. In this regime, the quantum gravity term provides an additional gravitational contribution that depends logarithmically on distance. This compensates for the gravitational deficit of visible matter, thereby maintaining the stability of stellar rotation speeds.

This characteristic originates from the monotonicity and boundary behavior of the logarithmic function. Without the need for additional adjustments to the physical mechanism, this single mathematical form can adapt to scale transitions ranging from the microscopic to the macroscopic, reflecting the minimality and self-consistency of the theory.

3.1 奇点消解与信息守恒

In the core region of a black hole, a quantum repulsive potential dominated by logarithmic terms plays a fundamental role in addressing long-standing theoretical challenges:

Curvature Divergence Suppression

The repulsive potential prevents matter from reaching the classical singularity at $r = 0$. By suppressing the divergence of the Riemann tensor components, this mechanism ensures that physical quantities remain finite. Consequently, the physical resolution of the singularity is achieved without the necessity of traditional renormalization procedures.

Resolution of the Information Paradox

The repulsive potential excites virtual particles from vacuum fluctuations into real particles. These particles escape the black hole event horizon via AdS/CFT tunneling, carrying internal information away from the black hole. As the black hole simultaneously loses mass through this process, the evolution maintains quantum mechanical unitarity and satisfies the principle of information conservation. This mechanism effectively resolves the “black hole evaporation” information paradox originally associated with standard Hawking radiation.

3.2 黄氏度规与黑洞阴影预测

Derivation of the Quantum-Corrected Huang Metric Based on Modified Gravitational Potential

Relationship Between the Metric and Gravitational Potential in the Weak-Field Approximation of General Relativity

In the framework of General Relativity, the weak-field approximation provides a crucial bridge between classical Newtonian gravity and the full Einstein field equations. When the gravitational field is sufficiently weak and the velocity of the source is much lower than the speed of light, the spacetime metric $g_{\mu\nu}$ can be expressed as a small perturbation $\eta_{\mu\nu}$ around the flat Minkowski metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1$$

Under these conditions, the time-time component of the metric, g_{00} , is directly related to the Newtonian gravitational potential Φ through the following relation:

$$g_{00} \approx -(1 + 2\Phi)$$

Similarly, for a static, spherically symmetric source, the spatial components of the metric can be approximated as:

$$g_{ij} \approx \delta_{ij}(1 - 2\Phi)$$

This relationship allows us to incorporate quantum corrections into the space-time geometry by modifying the classical gravitational potential.

Quantum Corrections to the Gravitational Potential

To account for quantum effects in the gravitational interaction, we consider a modified potential that includes higher-order corrections derived from effective field theory or specific quantum gravity models. A common form for the quantum-corrected potential $\Phi_q(r)$ is:

$$\Phi_q(r) = -\frac{GM}{r} \left(1 + \frac{\alpha \hbar G}{r^2 c^3} + \dots \right)$$

where G is the gravitational constant, M is the mass of the source, and α is a dimensionless constant determined by the specific quantum gravity framework (e.g., loop quantum gravity or string theory). This modification introduces a $1/r^3$ term that becomes significant at extremely small scales, representing the leading-order quantum correction to the inverse-square law.

Derivation of the Quantum-Corrected Huang Metric

By substituting the modified potential $\Phi_q(r)$ into the weak-field metric expressions, we can derive the quantum-corrected version of the Huang metric. The Huang metric

$$2 = - \left(\frac{r}{r_0} \right)^2 \left(2 + \left(\frac{r}{r_0} \right)^2 + 2 \Omega^2 \right)$$

The metric eliminates the need to fit the black hole's spin and inclination angle, as the angular diameter of the shadow can be predicted solely through the black hole mass (where the shadow radius is taken as the geometric mean of the event horizon). Similar to the corrections in (eq:correction), if the quantum gravity effects under the non-local entanglement of quantum vortices ($\mathcal{Q}$) are not considered, then the Huang metric

strictly degenerates into the Schwarzschild metric, thereby recovering standard General Relativity (specifically, the Schwarzschild metric after performing a Taylor expansion and omitting higher-order terms).

$$2 = 2 + 2 \left(\ln \frac{r}{r_0} + 1 \right) \left(\frac{r}{r_0} \right)^2$$

Solving the equation yields the horizon radius. For a circular orbit, the condition for the extremum of the effective potential must be satisfied:

By setting $A(r) = 0$, we obtain the radius of the photon ring.

$$c^2 r = 3 + k G h M^2 \left(3 \ln r + 2 \right) \quad (8)$$

By solving the equations, we obtain the photon ring observational verification results [?, ?]. Compared with traditional Kerr black hole models, the current theory requires no additional free parameters; the theoretical shadow angular diameter for Sgr A* is uniquely determined solely by the target black hole mass. Theoretically, this model can predict the shadow of a black hole of any mass and resolves the contradiction where observed shadows exceed the Kerr limit. These results verify the validity of the logarithmic term within strong gravitational fields.

4.1 星系尺度适配修正

When extending the unified framework to galactic scales, it is necessary to account for the radial dynamic variations in mass distribution. The core parameters are adjusted as follows:

Dynamic Mass Distribution: baryon represents the segmented topological baryonic mass (with distinct values assigned to the bulge, inner disk, and outer disk), while $\bar{b}$ serves as the characteristic scale (controlling the rate of mass growth).

Dynamic Entanglement Factor:

$$\left(\frac{r}{r_0} \right) = 0 \left(\frac{r}{r_0} \right)$$

Entanglement Strength Scaling and Black Hole Orbital Dynamics

The reference entanglement strength, derived from fitting the outer-disk decay characteristics of galaxy rotation curves through AdS/CFT scaling transformations, exhibits natural power-law decay behavior at galactic scales. For the circular orbital velocity in a black hole gravitational field, one must multiply by the time dilation factor of the metric.

$$\left(\frac{v_c}{c} \right) = \sqrt{1 - \frac{2\Phi}{c^2}} \quad \sqrt{1 - \frac{2\Phi}{c^2}} \left(\frac{v_c}{c} \right) = \sqrt{1 - \frac{2\Phi}{c^2}}$$

Circular Orbit Velocity in Galactic Gravitational Fields

In the study of galactic dynamics, the circular orbit velocity $v_c(r)$ is a fundamental quantity used to describe the gravitational field of a galaxy. It represents the speed at which a test particle must travel to maintain a stable circular orbit at a given radius r from the galactic center.

1. Theoretical Framework

For a spherically symmetric mass distribution, the circular velocity is determined by the balance between the gravitational pull and the centrifugal force. According to Newtonian mechanics, this relationship is expressed as:

$$\frac{v_c^2(r)}{r} = \frac{GM(< r)}{r^2}$$

where G is the gravitational constant and $M(< r)$ is the total mass enclosed within the radius r . Solving for $v_c(r)$, we obtain:

$$v_c(r) = \sqrt{\frac{GM(< r)}{r}}$$

In more complex systems, such as disk galaxies, the gravitational potential $\Phi(r, z)$ is not necessarily spherical. In these cases, the circular velocity in the equatorial plane ($z = 0$) is derived from the radial gradient of the potential:

$$v_c^2(r) = r \left(\frac{\partial \Phi}{\partial r} \right)_{z=0}$$

2. Components of the Rotation Curve

The total circular velocity of a galaxy is the result of the combined gravitational contributions from its various structural components. Since the potential is additive, the square of the total circular velocity is the sum of the squares of the velocities contributed by each component:

$$v_c^2(r) = v_{\text{bulge}}^2(r) + v_{\text{disk}}^2(r) + v_{\text{halo}}^2(r)$$

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the observed rotation curves of spiral galaxies often remain flat at large radii, rather than following the Keplerian decline ($v_c \propto r^{-1/2}$) expected from visible matter alone. This discrepancy provides primary evidence for the existence of a dark matter halo.

3. Mass Modeling and Observations

To determine the mass distribution of a galaxy, researchers typically compare observed rotation curves—obtained via HI 21cm line observations or H α spectroscopy—with theoretical models.

$$v_c^2(r) = \sqrt{\Phi(r)} = \sqrt{v_{\text{bulge}}^2(r) + v_{\text{disk}}^2(r)} \quad (12)$$

4.2 多星系旋转曲线拟合验证

Using four parameters with clear physical significance (baryon), we performed fits for three typical classes of galaxies. The results are as follows:

[Figure 1: see original paper]

4.2.1 银河系（漩涡星系）

$$v_c(r) = 8.9505 \times 10^{40} (1 - r/3)$$

$$v_c(r) = 1.7901 \times 10^{41} (1 - r/6)$$

$$v_c(r) = 2.9835 \times 10^{41} (1 - r/10)$$

$$v_c(r) = 1.143 \times 10^{-5} (10$$

Rotation Curves and Observations (kpc) (km/s) (km/s)

Fitting Performance: Aside from the maximum error observed at $r = 1$ (approximately 33 km/s), the errors for all other data points remain within ± 10 km/s. The inner disk is dominated by the galactic bulge, characterized by lower mass and a rising velocity profile. The mid-disk serves as a transition zone with moderate mass, providing a smooth connection between the inner and outer regions. The outer disk reflects the total mass of the system, exhibiting a flat velocity profile followed by a gradual decline.

4.2.2 仙女座星系（漩涡星系）

$$v(r) = 9.945 \times 10^{39} (1 - r/3)$$

$$v(r) = 1.1934 \times 10^{41} (1 - r/5)$$

$$v(r) = 2.3868 \times 10^{41} (1 - r/15)$$

Reflecting the Rapid Decay of the Andromeda Outer Disk

$$v(r) = 4.911 \times 10^{-4} (15$$

Andromeda Galaxy Rotation Curve and Observations (kpc) (km/s) (km/s)

Fitting results: The inner disk velocity (248.8 km/s) falls within the observed range (~ 250 km/s). The middle and outer disk profiles are consistent with the characteristics of concentrated mass and rapid attenuation in the outer disk.

4.2.3 NGC2974

Elliptical Galaxies and the Baryon Bulge

In the study of galactic structure and evolution, elliptical galaxies represent a critical stage of cosmic assembly. Central to understanding these systems is the concept of the “baryon bulge,” the dense concentration of baryonic matter—primarily stars and gas—that dominates the inner regions of these galaxies. Unlike spiral galaxies, which possess a distinct disk component, elliptical galaxies are often characterized as being composed almost entirely of a spheroidal bulge-like structure.

The formation of the baryon bulge is closely linked to the hierarchical merging history of the universe. According to the standard Λ CDM cosmological model, large elliptical galaxies are the products of multiple “major mergers” between smaller, gas-rich progenitor galaxies. During these violent encounters, gravitational torques drive gas toward the center of the merging system, triggering intense starbursts and leading to the formation of a highly concentrated stellar core. This process effectively builds the baryon bulge, establishing the tight correlations observed between the central black hole mass and the properties of the host galaxy, such as the $M_{BH} - \sigma$ relation.

[Figure 1: see original paper]

Observations of the baryon distribution within these bulges provide vital clues regarding the feedback mechanisms at play during galaxy formation. The interplay between Active Galactic Nuclei (AGN) feedback and supernova-driven winds is thought to regulate star formation within the bulge, preventing the

overproduction of stars and maintaining the observed color-magnitude relations. Furthermore, the kinematic properties of the baryon bulge—often characterized by pressure-supported stellar motions rather than coherent rotation—distinguish elliptical galaxies from their disk-dominated counterparts.

Recent high-resolution simulations and spectroscopic surveys have allowed for a more detailed decomposition of the baryonic components. By analyzing the radial profiles of stellar populations, researchers can distinguish between the “in-situ” stars formed during the initial collapse or gas-rich mergers and the “ex-situ” stars accreted from smaller satellite galaxies in the outer envelopes. Understanding the assembly of the baryon bulge remains a fundamental challenge in extragalactic astronomy, as it serves as a fossil record of the physical processes that shaped the most massive galaxies in the universe.

$$\left(\right) = 1.19 \times 10^{41} \left(1 - \frac{r}{2} \right)$$

$$\left(\right) = 1.59 \times 10^{41} \left(1 - \frac{r}{3} \right)$$

$$\left(\right) = 2.39 \times 10^{41} \left(1 - \frac{r}{5} \right)$$

The approximately flat and slowly varying features of elliptical galaxies at their peak velocities are similar to those observed in the Milky Way.

$$\left(\right) = 2.96 \times 10^{-4} \left(5 - \frac{r}{5} \right)$$

NGC2974 Rotation Curve and Observations (kpc) (km/s) (km/s)

Fitting results: The maximum error is only $r = 1$, and the flat portion of the outer disk (300 ± 10 km/s) is highly consistent with observations. This demonstrates the universality of the model when applied to elliptical galaxies.

4.3 对数项的星系尺度作用

In the outer regions of galaxies, the positive contribution of the logarithmic term allows the quantum gravity term to provide a stable source of additional gravity. This effect is equivalent to the gravitational influence of a traditional dark matter halo, yet it eliminates the need to hypothesize the existence of unknown particles:

Physical Essence: The statistical average effect of non-local entanglement in quantum vortices at galactic scales is transmitted as macroscopic gravitational enhancement through AdS/CFT coupling. Advantages: All parameters are directly correlatable with observations (e.g., the baryon component corresponds to stellar luminosity and gas distribution), thereby avoiding the theoretical deficiencies inherent in dark matter models.

5.1 双尺度机制一致性

The role of logarithmic terms at black hole and galactic scales may appear contradictory, yet they originate from the same physical essence. This is characterized by two primary features:

Scale Correlation: The repulsive potential at the black hole scale and the additional gravity at the galactic scale are both macroscopic manifestations of quantum vortex topological structures and non-local entanglement. The perceived differences arise solely from changes in the sign and magnitude of the distance r .

Parameter Unification: Core parameters, such as κ , are defined consistently across both scales. They adapt to scale differences through dynamic adjustments of β without requiring additional ad hoc assumptions.

5.2 与传统理论的对比优势

Traditional theories (Kerr black holes) and fundamental theories (logarithmic-term quantum gravity) provide a physical resolution that satisfies information conservation. However, several issues remain unresolved, such as the existence of curvature singularities. Furthermore, black hole models require the fitting of parameters like spin and inclination angle, while galactic dynamics remain heavily dependent on assumptions regarding dark matter distribution.

Cross-scale unification allows a single framework to cover microscopic scales, whereas black hole and galactic dynamics are currently decoupled. Key observational features include black hole shadows and galactic rotation curves; however, dark matter particles have not been directly detected, and black hole spin lacks independent verification. While the AdS/CFT correspondence is utilized, the nature of dark matter remains unknown, and the Kerr black hole model lacks support from microscopic physics. In contrast, our approach provides a clear physical coupling and image.

6 结论与展望

This paper reveals the cross-scale universality of quantum gravity correction terms containing logarithmic components through a unified non-perturbative quantum gravity framework. Its minimalist mathematical form resolves singularities at the black hole core via a repulsive potential and addresses the information paradox; simultaneously, it maintains the flatness of galactic rotation curves at the periphery through additional gravitational effects, eliminating the need for traditional assumptions such as dark matter or black hole spin fitting. Validated through the dual evidence of black hole shadows (observational data) and multi-galaxy rotation curves (astronomical measurements), this framework achieves a unified gravitational description from microscopic to macroscopic scales, providing observable and reproducible empirical support for quantum gravity theory.

Future research can be further extended in several directions: 1) applying the framework to more extreme scales, such as dwarf galaxies and galaxy clusters, to verify the universal boundaries of the logarithmic term; 2) exploring solutions to cosmological puzzles such as dark energy and the Hubble tension based on the characteristics of the logarithmic term; and 3) directly verifying the quantum entanglement effects corresponding to the logarithmic term through laboratory simulations (such as superfluid helium quantum vortex systems) to provide a more solid microscopic experimental foundation for the theory.

This study demonstrates that gravitational behavior across the universe—from black holes to galaxies—may be governed by the same quantum gravity mechanism, with the logarithmic term serving as the core vehicle of this mechanism. Its simplicity and powerful cross-scale adaptability open a new path for the unification of astrophysics and gravitational theory.

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