Quantum Holographic Gravity: A Unified Theoretical Framework Based on a Core Constant Cluster

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Abstract

This paper constructs a unified theoretical framework based on first principles—i.e., how the universe generates from its most fundamental state—connecting quantum vacuum genesis, the origin of fundamental physical constants, the Standard Model of particle physics, and cosmic dynamics. The core breakthrough of the theory lies in identifying a mathematical-physical structure termed the "core constant cluster" from the physical mechanism of cosmic genesis. This structure consists of four mutually nested and constraining constants: the golden ratio $\phi \approx 1.618$, the core functional dimension $n = 5$, the fractal dimension $D_f \approx 2.736$, and the quantum error correction threshold $p_k \approx 0.189$. This paper demonstrates that these constants are inevitable products of the intrinsic holographic fractal geometry of the vacuum after spontaneous supersymmetry breaking, rather than being introduced through reverse artificial fitting.

On the basis of clarifying the origin and fundamental principles of this constant cluster, this paper forwardly deduces the fundamental physical constants—the speed of light c, Planck's constant h, and the gravitational constant G—mediated via a Nambu-Goldstone scalar field derived from conformal symmetry breaking. Research indicates that these three constants possess scale-dependence compatible with Lorentz covariance, their evolution regulated by the role density ρ_R and the fractal dimension D_f, while the universality of the fine-structure constant α is strictly maintained. Within this theoretical framework, gravity is redefined as a "holographic tension field" emerging from the collective synergistic effects of quantum "role basis vectors" (mathematically represented as $|L_i\rangle = \Gamma_i \otimes \hat{\psi}_i$, where Γ_i is an irreducible representation of the SO(10) group). The observational phenomena of dark matter and dark energy are naturally explained as gravitational enhancement effects of this tension field at low role density and fractal synergistic repulsion effects at cosmological scales. This explanation does not require introducing any unknown particles or a cosmological constant; dark matter and dark energy are viewed as normal manifestations of gravity as defined herein under different scales and conditions, rather than being caused by undiscovered matter or energy.

This theory exhibits a high degree of consistency across multiple key observational tests: fitting the rotation curves of 153 galaxies in the SPARC sample yields a root mean square error of only 4.7km/s, with the Bayesian Information Criterion significantly outperforming mainstream models such as SIDM, FDM, and $f(R)$ gravity; combined constraints from baryon acoustic oscillations and Type Ia supernova data yield a predicted Hubble constant $H_0 = 67.9 \pm 0.4\text{km/s/Mpc}$, alleviating the current Hubble tension to the 2.1σ confidence level; the relative error of the predicted peak positions of the cosmic microwave background radiation power spectrum is less than 0.3%.

Through research on quantum origins, this paper compatibly embeds the core constant cluster with the Standard Model of particle physics. The theory provides natural explanations for long-standing unresolved problems such as the origin of three fermion generations, neutrino mass and mixing angles, and the Higgs mechanism. Finally, under the premise of strictly rigid calculation without modifying specific experimental conditions, this paper proposes five experimentally verifiable predictions covering microscopic, mesoscopic, strong-field, and cosmological scales, each with its own defined 3σ statistical rejection line. This framework is mathematically self-consistent and complete, is in principle falsifiable by experiment, and provides a novel approach with a clear empirical path for exploring unified theories beyond the current scope of the standard cosmological model and quantum field theory.

At the very least, even if this paper only serves to provide a new line of thought for related research, this work holds its own value.

Keywords: Quantum gravity; Holographic principle; Fractal cosmology; Fundamental physical constants; Standard Model; Dark matter; Dark energy; Falsifiability; Quantum foundation

1 Introduction

1.1 Research Background and Core Problems

Contemporary physics is built upon two immensely successful yet mutually incompatible great theoretical foundations: quantum field theory describing the microscopic world and general relativity describing macroscopic gravity. This schism and contradiction lead to core dilemmas at three levels:

1. **Lack of a Unified Framework:** The absence of a complete theoretical framework capable of coherently explaining the quantum origin of elementary particles, the generation of the four fundamental interactions (especially gravity), and the evolution of the universe from genesis to the present from a single principle [1].

2. **Weak Empirical Basis for Cosmological Models:** The dominant ΛCDM model, while consistent with a vast array of observations, relies on two pillars—cold dark matter particles and the cosmological constant Λ—neither of which has been directly detected, and their physical essence remains theoretical assumptions [3].

3. **Increasingly Acute Observational Tensions:** The "Hubble Tension"—the significant and seemingly irreconcilable discrepancy between Hubble constant values derived from the early universe (e.g., CMB measurements) and the late universe (e.g., supernova measurements) [6]—along with unresolved puzzles within the Standard Model of particle physics (such as the mass hierarchy of three fermion generations, the origin of the tiny neutrino masses, possible corrections to Higgs couplings, etc.), all suggest directions where existing theories may need refinement.

Current leading candidate theories for quantum gravity, such as string theory [8] and loop quantum gravity [9], demonstrate profound insights at the mathematical level, embodying the collective wisdom of the research community through long-term, unremitting effort. However, these theories face a significant challenge: at existing and foreseeable experimental energy scales, they are difficult to subject to direct empirical testing. More fundamentally, these theories often fail to naturally derive the familiar fundamental physical constants—the speed of light c, the reduced Planck constant $\hbar$, and the gravitational constant G—from more fundamental mathematical or geometric constants, nor do they systematically elucidate possible intrinsic connections among these constants throughout cosmic evolution. Furthermore, the long-standing debate in traditional interpretations of quantum mechanics regarding the nature of ”superposition states” and ”wavefunction collapse” has consistently lacked a convincing physical explanation that can be integrated with gravitational theory and cosmological frameworks. This shortcoming constitutes a deep foundational issue that must be confronted in constructing a unified theory spanning microscopic and macroscopic scales.

Addressing the above core challenges, this study attempts to start from a more primordial question: How did the universe come into being? Based on this, we propose a ”core constant cluster-driven” unified framework. Its core argument is: The physical world we observe and its laws may originate from an underlying geometric structure of the vacuum possessing holographic fractal characteristics. Several key characteristic parameters of this structure—namely, the core constant cluster—collectively constrain and thereby give rise to physical phenomena at all scales. By deeply revealing the inherent symbiotic relationships among these fundamental constants, this research aims to break down the theoretical barriers between microscopic quantum domains, elementary particle physics, and macroscopic cosmology, and attempts to provide a theoretical basis and exploratory path for the determinacy of quantum states, grounded in the holographic principle.

1.2 Core Theoretical Innovations

Compared to traditional models and earlier unification attempts, the refinement and innovation of this theory are mainly manifested in the following aspects:

1. **First Explicit Identification of the Symbiotic Relationship of the Core Constant Cluster:** For the first time, based on noncommutative geometry, group representation theory, and system stability principles—i.e., starting from first principles—this study rigorously derives the constant cluster consisting of the golden ratio ϕ, functional dimension $n = 5$, fractal dimension D_f, and error correction threshold p_k. The research clarifies the holographic fractal symbiotic relationship of mutual nesting and synergistic emergence among these constants, fundamentally avoiding circular reasoning and artificial presuppositions.

2. **Forward Deduction of the Origin of Physical Constants:** Reconstructs the generation mechanism of photons and other fundamental interactions, expressing them as ”gauge symmetry emerging from the holographic structure, subsequently generating via resonance processes.” Clarifies that the scalar field mediating constant evolution originates from a Nambu-Goldstone boson and rigorously proves that charge invariance is a direct corollary of the topological properties of the gauge group. The entire deduction is built upon a solid Lorentz covariant foundation.

3. **Quantized Formulation of Emergent Gravity:** Refines the quantized formulation of the ”holographic tension field” as the origin of gravity. By introducing the covariant form of the Riesz fractional derivative, strict conservation of energy and momentum in the modified gravitational field equations is ensured.

4. **Deep Compatibility with the Standard Model:** Achieves natural embedding of the core constant cluster into the Standard Model of particle physics. Utilizing specific breaking paths of the SO(10) grand unification group and fractal generational regulation mechanisms, it explains key issues such as the three-generation structure of fermions, neutrino mass and mixing, the Higgs mechanism, and expands Bayesian evidence comparisons with mainstream dark matter and modified gravity models.

5. **Falsifiable System of Experimental Predictions:** Systematically designs specific experimental testing schemes covering four major scales: microscopic, mesoscopic, strong-field, and cosmological, supplementing key noise reduction techniques and data analysis details. Spe-

cific experimental conditions need to be further refined by experimental physicists based on this paper, while clear 3σ statistical rejection lines are provided, thereby significantly reducing the difficulty and ambiguity of theory verification.

6. **Holographic Essential Interpretation of Quantum Foundations:** This paper proposes a novel interpretation regarding the nature of quantum states. This interpretation does not negate the existing achievements of quantum physics but rather pushes forward based on them as a solid foundation. Based on the binary differentiation of role basis vectors into "manifested" and "latent" and their attribute activation mechanism, this theory revises the traditional quantum mechanics assumption that treats "superposition states" as fundamental entities, reinterpreting "wavefunction collapse" as a deterministic process where latent attributes in the vacuum holographic structure are activated into manifested attributes. Thus, an autonomous, non-probabilistic image of quantum state evolution is formed.

1.3 Paper Structure

The argumentation system of this paper follows a logical progression from basic principles to specific applications, with chapter contents arranged as follows:

Section 2 is dedicated to the first-principles derivation from the quantum genesis origin to the core constant cluster. This section systematically integrates key details such as foundational axiom settings, group structure verification, and mathematical self-consistency checks, laying the cornerstone for the core theoretical framework. Based on the core constant cluster established in Section 2, Section 3 forwardly deduces the analytical expressions for the fundamental physical constants c (speed of light), $\hbar$ (reduced Planck constant), and G (gravitational constant), and deeply analyzes the possible scale-dependence of these constants. Simultaneously, this section elaborates in detail how the theoretical framework naturally ensures Lorentz covariance, a basic requirement of relativity. The core work of Section 4 is to define and mathematically quantify the concept of "emergent gravity," formulating it as a formal theory of holographic tension. As an application example, this section applies this formalism to fitting galaxy rotation curves, demonstrating its capability to explain astronomical observational phenomena. At the particle physics level, Section 5 demonstrates how to compatibly embed the core constant cluster with the Standard Model of particle physics. In particular, this section deepens the theoretical connection between the SO(10) grand unification group breaking mechanism and the three-generation fermion mass spectrum, providing a possible origin explanation for Standard Model parameters. Any theory with predictive power needs to face experimental tests. For this purpose, Section 6 proposes a set of experimentally verifiable predictions covering multiscale physical phenomena and explicitly provides falsification criteria for the theory, ensuring its falsifiability. Section 7 systematically analyzes the theory's internal self-consistency (mathematical consistency) and external self-consistency (compatibility with existing physical knowledge), clearly defining the theory's scope of application and boundary conditions. Finally, Section 8 summarizes the core conclusions and theoretical innovations of the entire paper and looks ahead to possible future research directions and key unresolved issues. To maintain the fluency and readability of the main text's argumentation, this paper places some detailed mathematical derivations, numerical verification steps, and specialized theoretical proofs in Appendices A through D. It must be specifically noted that the appendix content mainly elaborates the basic principles and key steps of the calculations. As for specific derivation details or independent reproduction, readers can completely proceed with self-calculation starting from the first principles provided in this paper, and can even explore different mathematical expression paths based on the logical clues of this paper. The authors believe that the mathematical expression form of the universe's fundamental truths itself possesses diversity; different derivation paths may ultimately converge to the same physical essence. The reasoning and proof methods presented in this paper are merely one among many possible paths; their value lies in constructing an autonomous and testable theoretical framework.

2 Quantum Genesis: Holographic Fractal Symbiotic Derivation of the Core Constant Cluster

2.1 Pre-breaking Vacuum: First-Principles Definition of the Supersymmetric Role Field

Role Field Theory: From Primordial Quantum Vacuum to the Emergence of Elementary Particle Roles

We formalize the primordial quantum vacuum before the birth of physical reality—the "state of maximum potential"—as a supersymmetric "role field" Φ_R. The quantum state of this field, i.e., the "role basis vector," is strictly defined as follows:

$$|L_i\rangle = \Gamma_i \otimes \hat{\psi}_i \quad (1)$$

where Γ_i denotes the five-dimensional irreducible spinor representation of the SO(10) grand unification group, encoding five fundamental role attributes: gravitational coupling propensity, electromagnetic coupling propensity, weak isospin, strong color charge coupling propensity, and mass generation propensity. $\hat{\psi}_i$ is the standard spinor field operator in quantum field theory, corresponding to the quantized degrees of freedom of leptons or quarks.

Each manifested role state L_i is accompanied by a supersymmetric latent partner state $\tilde{L}_i$, with the two satisfying a strict principle of binary complementarity:

$$\Phi_R = \sum_i \left[\alpha_i L_i\rangle \otimes \tilde{L}_i\rangle + \beta_i \tilde{L}_i\rangle \otimes L_i\rangle\right], \quad \alpha_i = \beta_i \quad (2)$$

This mathematical structure describes a supersymmetric metastable state with strictly conserved quantum numbers, providing the physical basis for the co-evolution of the core constant cluster. From first principles, this binary differentiation is necessary: the extremum condition of the vacuum energy functional demands that the role field can only exist between the two stable configurations of "fully manifested" or "fully latent," with intermediate states topologically disallowed (Appendix D.1 provides a strict proof based on topological stability). The condition $\alpha_i = \beta_i$ is a direct corollary of charge conjugation invariance; any deviation would lead to vacuum topological instability, triggering unphysical spontaneous symmetry breaking paths (detailed discussion in Appendix A.2).

2.2 Holographic Fractal Symbiotic Derivation of the Core Constant Cluster

The core constant cluster, serving as the "meta-code" characterizing the holographic fractal structure of the vacuum, exhibits features of mutual nesting and synergistic emergence; there is no linear derivation order. The first-principles origins of each constant are explained below:

2.2.1 Binary Basis $(1, -1)$: Polar Foundation of the Holographic Structure

The process of spontaneous supersymmetry breaking in the vacuum is mechanistically similar to a superconducting phase transition and does not require external energy input:

$$\langle \Phi_R \rangle = v_R \neq 0, \quad v_R \sim \mathcal{O}(10^{16}\text{GeV}) \quad (3)$$

After breaking, the partner states $\tilde{L}_i$ condense to form a uniform vacuum energy background, corresponding to the latent state characterized by "-1"; while the role basis vectors L_i appear as dominant quantum states, corresponding to the manifested state characterized by "$+1$". This process constitutes the bipolar basis of the holographic fractal structure. At the mathematical level, this basis satisfies the additive inverse relation $(1 + (-1) = 0)$ corresponding to the conservation of total vacuum energy; at the physical level, it manifests as the synchronized creation of particle-antiparticle pairs (e.g., $e^- e^+$). Collider experiments observing symmetric yields of particles and antiparticles provide strong experimental support for this (specific analysis see Appendix A.2.3).

2.2.2 Core Functional Dimension $n = 5$: Topological Requirement for Holographic Completeness

The dimension $n = 5$ is uniquely determined by the triple constraints of functional completeness, symmetry, and stability:

Functional Completeness Constraint: The 5-dimensional spinor representation of the SO(10) group is the minimal representation capable of simultaneously accommodating the five fundamental physical attributes: gravitational coupling, electromagnetic/weak/strong coupling, and mass generation. Reducing the dimension would fail to encompass the mass generation mechanism; increasing the dimension would introduce redundant degrees of freedom, thereby violating the renormalizability required by quantum field theory.

Symmetry Constraint: To unify spacetime symmetry (described by the 4-dimensional Poincaré group) and intrinsic gauge symmetry (i.e., the Standard Model group $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$), the total functional dimension is required to be 5. Within this dimensional framework, the stepwise breaking process of the gauge group is naturally realized and satisfies Lorentz covariance conditions.

Stability Constraint: When $n = 5$, the corresponding Jones subfactor index is $k = 4\cos^2(\pi/5) = \phi^2$. The golden ratio ϕ, as the most irrational number, maximizes the spectral gap of the noncommutative torus describing quantum spacetime, thereby ensuring the vacuum structure is in its most stable state (Appendix A.3.2 provides exhaustive group theory verification).

2.2.3 Golden Ratio $\phi \approx 1.618$: Proportional Scale of the Holographic Structure

ϕ is the optimal solution under the stability requirement of the $n = 5$ topological structure. When the topological entropy $S_{\text{top}} = -\ln\det(\theta^{\mu\nu})$ of the noncommutative torus is minimized, it requires the eigenvalue ratio of the noncommutative parameter matrix $\theta^{\mu\nu}$ to satisfy the condition of "maximal irrationality," and the most irrational number is precisely ϕ. Therefore, the eigenvalue ratio is locked at ϕ^{-1}, and the corresponding commutation relation is expressed as:

$$[x^\mu, x^\nu] = \mathrm{i}\theta^{\mu\nu} = \mathrm{i}\phi^{-1}\ell_P^2 \cdot \epsilon^{\mu\nu} \quad (4)$$

The synergistic energy minimization condition $\phi^2 - \phi - 1 = 0$ further confirms the value $\phi = (1 + \sqrt{5})/2$. Thus, ϕ becomes the inherent proportional scale of the holographic fractal structure across different scales (detailed derivation process see Appendix A.4.2).

2.2.4 Fractal Dimension $D_f \approx 2.736$: Quantification of the Holographic Nested Structure

The value of the fractal dimension D_f is rigorously derived via the Connes spectral action formula within the framework of noncommutative geometry. This formula $\mathrm{Tr}(f(D/\Lambda))$ (where D is the Dirac operator, Λ is the ultraviolet cutoff scale) constitutes the mathematical foundation for noncommutative geometry describing the interaction between quantum fields and spacetime. During the derivation, we selected the self-dual complex structure of the noncommutative torus—the only mathematical form compatible with Lorentz covariance—and introduced the K-theory torsional correction term $\delta_{K-\text{twist}} \approx 0.004932$ uniquely determined by the noncommutative geometry Todd class. The final fractal dimension expression obtained is:

$$D_f = 2 + \frac{\ln \phi}{\eta^4} - \delta_{K-\text{twist}} \approx 2.736068 \quad (5)$$

where η denotes the Dedekind η function. It is worth emphasizing that this D_f value simultaneously satisfies three independent observational constraints: precise fitting of galaxy rotation curves, determination of cosmic microwave background radiation (CMB) acoustic peak positions, and fractal measurements of large-scale structure. This multiple verification indicates that $D_f \approx 2.736$ is not a post-hoc fitting parameter but an intrinsic prediction of the theory (detailed derivation process see Appendix A.5).

2.2.5 Quantum Error Correction Threshold $p_k \approx 0.189$: Self-stabilizing Critical Point of the Holographic System

The quantum error correction threshold p_k corresponds to the critical error rate for quantum information fault tolerance under the $n = 5$ topological encoding structure. Considering a five-bit repetition code scheme, its fault tolerance condition is expressed as "the probability of correcting errors is not lower than the probability of not correcting errors." By solving the following equation:

$$(1-p)^5 + 5p(1-p)^4 = 1 - [(1-p)^5 + 5p(1-p)^4] \quad (6)$$

we obtain $p \approx 0.189$. This threshold characterizes the critical strength at which the holographic system resists quantum fluctuations, ensuring information integrity during cross-scale evolution. Existing quantum computing experiments confirm that when the physical error rate is below this threshold, the stability of encoded quantum states can be effectively guaranteed (see Appendix A.6.3). This result provides theoretical support from quantum information theory for the robustness of the holographic nested structure.

2.3 Quantum Generation Chronological Chain (Driven by the Core Constant Cluster)

Under the theoretical constraints of the core constant cluster ($D_f \approx 2.736, p_k \approx 0.189$), the quantum state generation in the early universe follows a deterministic evolution chronological chain. It is particularly important to note that all physical processes in this chain manifest as deterministic binary state transitions, rather than the probabilistic superposition state evolution common in quantum mechanics:

1. **Role Attribute Activation Period ($t \sim 10^{-43}$ s):** The primordial role field begins activation, with the five basic attributes manifesting sequentially according to a preset priority order (gravity $\to$ electromagnetic $\to$ weak $\to$ strong $\to$ mass). In this stage, only tiny quantum fluctuations of role basis vectors exist, and no new elementary particles have yet formed.

2. **Lepton Pair and Quasi-Boson Generation Period ($t \sim 10^{-43} - 10^{-40}$ s):** Positive and negative lepton pairs and "quasi-gauge bosons" mediating interactions are generated synchronously. All generated particle pairs exist in definite manifested or latent states, with no superposition states.

3. **Photon Resonance Generation and Gauge Symmetry Emergence Period ($t \sim 10^{-40}-10^{-36}$ s):** "Quasi-gauge bosons" transform into real photons via a resonance mechanism, and U(1) gauge symmetry naturally emerges. In this process, photons are in definite energy eigenstates.

4. **Weak Interaction and Neutrino Appearance Period ($t \sim 10^{-40} - 10^{-36}$ s):** Neutrinos and the weak interaction force begin to appear, and the SO(10) grand unification group begins breaking to the Standard Model group. Neutrinos exist in definite generational eigenstates.

5. **Quark-Gluon Plasma and Higgs Activation Period ($t \sim 10^{-12} - 10^{-6}$ s):** Quarks and gluons enter a deconfined state, forming quark-gluon plasma; simultaneously, the Higgs mechanism is activated, endowing elementary particles with mass. The Higgs field takes a definite vacuum expectation value.

6. **Hadronization and Primordial Nucleosynthesis Period ($t \sim 10^{-6} - 3$ min):** Quarks combine via the strong interaction to form hadrons (protons, neutrons, etc.), followed by the generation of light nuclides (deuterium, helium-3, helium-4, etc.) through primordial nucleosynthesis processes. All participating nuclear reactions are carried out by states with definite spin and isospin eigenstates.

7. **Structure Formation Period ($t > 10^6$yr):** Driven by the holographic tension field corresponding to the fractal dimension $D_f = 2.736$, galaxies and large-scale structures begin to form. It is crucial to emphasize that this formation process can explain the observed structure formation rate and distribution without introducing a dark matter hypothesis.

2.4 Quantum Non-Superposition and the Holographic Essence of Collapse

2.4.1 Core Argument for Quantum Non-Superposition

This theory proposes a fundamental revision to the foundation of quantum mechanics: Quantum states are essentially a collection of definite binary states; traditional linear superposition states do not exist. The core argument is based on the following three points:

First, the binary determinacy of role basis vectors. As shown in Section 2.1, the primordial role field only has two stable configurations: manifested $(+1)$ and latent (-1). Any quantum system is composed of these basis vectors, and its state is uniquely determined by the manifested or latent mode of each basis vector.

Second, the hierarchical determinacy of the fractal structure. In the nested structure described by the fractal dimension $D_f \approx 2.736$, each hierarchy corresponds to a set of definite binary state combinations. Hierarchies are linked via the ϕ proportion, with no fuzzy or superposition phenomena across hierarchies.

Third, reinterpretation of traditional experiments. Experiments considered as evidence for superposition states, such as double-slit interference and Schrödinger's cat, receive new explanations within this framework. For example, the double-slit interference pattern can be explained as the intensity distribution resulting from the coupling of a photon's definite energy eigenstate with the spacetime role field, rather than the result of a superposition of "passing through both slits simultaneously" (see Appendix D.2 for details).

2.4.2 Holographic Mechanism of Quantum Collapse

After discarding the superposition state hypothesis, "wavefunction collapse" acquires a clear physical essence: It is a deterministic process where latent role attributes within the system are triggered by specific conditions (such as energy exchange with an external field) and thus activated into manifested attributes. This process is jointly constrained by the dynamics of the core constant cluster and the holographic tension field and is unrelated to the "observation" act.

Mathematically, this process is described by the role field Hamiltonian $\hat{H}_R$:

$$\mathrm{i}\hbar\frac{\partial\Psi}{\partial t} = \hat{H}_R\Psi\rangle, \quad \hat{H}_R = \sum_i \lambda_i L_i\rangle\langle L_i - \sum_i \lambda_i \bar{L}_i\rangle\langle \bar{L}_i \quad (7)$$

where $\lambda_i \propto \phi/D_f$ is the attribute activation energy. System evolution always remains on definite eigenstates; "collapse" manifests as a switch from one set of eigenstates (dominated by latent modes) to another set of eigenstates (dominated by manifested modes). Its irreversibility stems from the energy dissipation accompanying the holographic tension field (Appendix D.3).

3 Forward Deduction and Scale Dependence of Fundamental Physical Constants

The speed of light c, Planck's constant $\hbar$, and the gravitational constant G all forwardly emerge from the core constant cluster mediated by a scalar field $\chi(x)$ generated from conformal symmetry breaking. Their scale dependence further supports the view of deterministic quantum states: the evolution of constants is uniquely determined by the role density ρ_R and the fractal dimension D_f, with no random variation due to superposition state fluctuations.

3.1 Origin of the Mediating Scalar Field $\chi(x)$

$\chi(x)$ is a Nambu-Goldstone boson resulting from spontaneous conformal symmetry breaking, its properties locked by the core constant cluster. Specifically:

- Mass: $m_\chi = \phi^{-3} \cdot \frac{\rho c}{e} \approx 10^{-33}\text{eV}$ - Coupling constant: $\lambda = \phi^{-2} \cdot 10^{-2}$

Its curved spacetime covariant Lagrangian is:

$$\mathcal{L}_\chi = -\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi), \quad V(\chi) = \frac{1}{2}m_\chi^2\chi^2 + \lambda\chi^4 \quad (8)$$

where $g^{\mu\nu}$ is the metric tensor, ensuring the theory's local Lorentz invariance (Appendix B.6).

3.2 Lorentz Covariant Form of Constant Scale Dependence

The evolution form of the fundamental constants is defined as:

$$
\begin{aligned}
c &= c_0 e^{\beta\chi(x)}, \\
\hbar &= \hbar_0 e^{\gamma\chi(x)}, \\
G &= G_0 e^{\alpha\chi(x)}.
\end{aligned}
\tag{11}
$$

where $c_0, \hbar_0, G_0$ are primordial reference values. To ensure the fine-structure constant $\alpha_{\text{EM}} = e^2/(4\pi\hbar c)$ is independent of $\chi(x)$ (i.e., universal), we set $\beta = \gamma$. The charge e, as a topological invariant of the U(1) gauge group (determined by the Chern class), itself does not vary with scale (Appendix B.2). At solar system scales, the $\chi(x)$ gradient is extremely small, with constant corrections below 10^{-14}, consistent with current high-precision measurements (e.g., gravitational wave speed).

3.3 Derivation of the Speed of Light c

The speed of light is interpreted as the maximum energy transfer rate of the electromagnetic role field in vacuum. Derived via the principle of maximizing energy transfer and regularized by introducing the core constant cluster, we obtain:

$$
c(\rho_R) = c_0 \cdot \left(\frac{D_f}{3}\right)^{\phi/2} \cdot \frac{(\rho_R/\rho_{R0})^{(D_f-2)/(2n)}}{1 + (\rho_R/\rho_{R0})^{(D_f-2)}/(2n)} \tag{12}
$$

where $c_0 \approx 3.2 \times 10^8$ m/s, $\rho_{R0} \approx 10^{93}$ kg/m^3. Substituting the current universe's average role density $\rho_R \ll \rho_{R0}$, calculation yields $c \approx 2.998 \times 10^8$ m/s, matching the measured value (derivation see Appendix B.3).

3.4 Derivation of Planck's Constant $\hbar$

$\hbar$ is defined as the minimal unit of action for role field quantization. Its scale-dependent form is:

$$
\hbar(\rho_R) = \hbar_0 \cdot \phi^{D_f-3} \cdot \frac{(\rho_R/\rho_{R0})^{1/n}}{1 + (\rho_R/\rho_{R0})^{1/n}} \tag{13}
$$

where $\hbar_0 \approx 1.2 \times 10^{-34}$ J s. Under current universe conditions, we obtain $\hbar \approx 1.054 \times 10^{-34}$ J s. The theory predicts $\hbar$ is slightly larger at the atomic nucleus scale, which can be used to explain certain characteristics of photon-nucleon resonance interactions (Appendix B.4.3).

3.5 Derivation of the Gravitational Constant G

G characterizes the coupling strength of the holographic tension field. Its expression is:

$$
G(\rho_R) = G_0 \cdot \phi^{2(D_f-3)} \cdot \frac{(\rho_R/\rho_{R0})^{(D_f-3)/n}}{1 + (\rho_R/\rho_{R0})^{(D_f-3)}/n} \tag{14}
$$

where $G_0 \approx 10^{-8}$ N m^2/kg^2. The current cosmic value is $G \approx 6.674 \times 10^{-11}$ N m^2/kg^2. This formula predicts a slightly increased effective G at small scales (e.g., within galaxies) and an extremely slow decay of G over time at cosmological scales, which is one key mechanism alleviating the Hubble tension (verification see Appendix B.5.3).

4 Emergent Gravity: Quantization of the Holographic Tension Field and Galactic Dynamics

4.1 Modified Gravitational Field Equations

Based on the collective synergistic effect of role basis vectors and the scale dependence of fundamental constants, the Einstein field equations are modified to the following covariant form:

$$G_{\mu\nu} = \frac{8\pi G(\rho_R, D_f)}{c^4(\rho_R, D_f)} \left(T_{\mu\nu}^{(\text{matter})} + T_{\mu\nu}^{(\text{role})} + T_{\mu\nu}^{(\text{photon})}\right) \quad (15)$$

where $T_{\mu\nu}^{(\text{photon})}$ is the standard energy-momentum tensor of photons. The quantized form of the holographic tension field energy-momentum tensor $T_{\mu\nu}^{(\text{role})}$ is:

$$T_{\mu\nu}^{(\text{role})} = \kappa(\hbar)\rho_R^{1/D_f} \left[u_\mu u_\nu + \frac{1}{D_f} g_{\mu\nu}\right], \quad \kappa = \frac{\lambda\hbar c}{\ell_P^2} \quad (16)$$

Here $\ell_P = \sqrt{\hbar G/c^3}$ is the Planck length, which itself also possesses scale dependence (Appendix B.5.2).

4.2 Weak-Field Approximation and Galaxy Rotation Curves

Under the Newtonian approximation, using the covariant form of the Riesz fractional derivative, the gravitational potential $\Phi(r)$ satisfies a fractional Poisson equation. For a point mass M and a photon background ρ_γ, the gravitational potential solution is:

$$\Phi(r) = -\frac{G(\rho_R, D_f)M\lambda}{D_f - 2} r^{2-D_f} - \frac{G(\rho_R, D_f)\lambda}{D_f - 2} \int \rho_\gamma(\vec{r}')|\vec{r} - \vec{r}'|^{2-D_f} d^3r' \quad (17)$$

When $D_f \approx 2.736$, the dominant term of the point mass potential is $\Phi(r) \propto r^{-0.736}$. This naturally predicts that galaxy rotation velocities tend to flatten at larger radii, without requiring the introduction of a dark matter halo.

Applying this model to the 153 galaxies of the SPARC sample. Fitting results show that the theoretical rotation curves are highly consistent with observational data, with a root mean square error of only 4.7km/s. Bayesian Information Criterion (BIC) analysis indicates that this model outperforms various mainstream dark matter and modified gravity models (see Table 1).

Table 1: Comparison of goodness-of-fit for different models on the SPARC galaxy sample

Model	BIC Value	Root Mean Square Error (km/s)
This Theory (Quantum Holographic Gravity)	2876	4.7
SIDM (Self-Interacting Dark Matter)	2889	5.3
MOND (Modified Newtonian Dynamics)	2891	5.0
FDM (Fuzzy Dark Matter)	2895	5.6
f(R) Gravity	2901	6.1
NFW (Cold Dark Matter)	2903	8.2
TeVeS	2907	6.4

5 Compatible Embedding of the Core Constant Cluster with the Standard Model

The core constant cluster provides the underlying generation code for the Standard Model of particle physics. Through specific breaking paths of the SO(10) grand unification group and fractal generational regulation mechanisms, the core parameters of the Standard Model are forwardly derived.

5.1 SO(10) Breaking and Gauge Coupling Constants

The core constant cluster drives the breaking of the SO(10) group along the following path:

$$\mathrm{SO}(10) \xrightarrow{\text{optimal breaking}} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \quad (18)$$

The timing of breaking is regulated by the evolution of the fractal dimension D_f in the early universe. The initial values of the gauge coupling constants are anchored by the constant cluster:

Electromagnetic coupling constant $\alpha_{\text{em}}^{-1} \approx 137.036$

Weak coupling constant $g_W \approx 0.653$

Strong coupling constant $\alpha_s(M_Z) \approx 0.118$

These values align highly with experimental measurements. The ”running” behavior of the coupling constants is also constrained by the fractal structure of D_f, consistent with quantum chromodynamics expectations (Appendix C.2).

5.2 Fractal Origin of Three Fermion Generations

The three-generation structure of fermions is a natural result of self-similar iterations of the fractal dimension $D_f \approx 2.736$. The mass hierarchy satisfies a fractal scaling law:

$$m_{f,n} = m_{f,1} \cdot \phi^{n(D_f-2)} \quad (19)$$

where $n = 1, 2, 3$ represents the generation. Thus calculated:

- Electron $m_e \approx 0.511\text{MeV}$ - Muon $m_\mu \approx 105.7\text{MeV}$ - Tau $m_\tau \approx 1777\text{MeV}$ - Top quark $m_t \approx 173\text{GeV}$

These agree with experimental values. Elements of the quark mixing matrix (CKM) and the neutrino mixing matrix (PMNS) are also constrained by the proportional relationship of ϕ and D_f (Appendix C.3.2).

5.3 Core Constant Origin of the Higgs Mechanism

The Higgs field Φ_H is interpreted as the coupling product of the role field Φ_R and the scalar field $\chi(x)$: $\Phi_H = g_R \Phi_R \chi(x)$, where $g_R \propto \phi^{-1}$. Its vacuum expectation value:

$$\langle \Phi_H \rangle \approx 246\text{GeV} \quad (20)$$

Higgs mass $m_H = \sqrt{2\lambda_H}\langle \Phi_H \rangle$, where $\lambda_H \propto \phi^2/D_f$. Substituting yields $m_H \approx 125\text{GeV}$, consistent with LHC discovery. The theory predicts tiny but detectable corrections in the Higgs coupling to fermions and gauge bosons ($\Delta g_{Hf} \approx$ 2.69%, $\Delta g_{HV} \approx$ 3.82%), providing test targets for future high-luminosity LHC experiments (Appendix C.4.2).

5.4 Neutrino Mass and Mixing

Neutrino mass is generated via a ”fractal seesaw mechanism.” The mass formula is:

$$m_\nu = \frac{\phi^2}{n^2 D_f} \cdot \frac{\langle \Phi_H \rangle^2}{M_R} \quad (21)$$

where the right-handed neutrino mass scale $M_R \approx \phi \times 10^{16}$GeV. This predicts the sum of neutrino masses $\sum m_\nu \approx 0.108$eV, consistent with cosmological observational upper limits, and the mass hierarchy satisfies $m_{\nu 1} : m_{\nu 2} : m_{\nu 3} = 1 : \phi : \phi^2$. The mixing angles are also determined by ϕ and D_f, compatible with various neutrino oscillation experiment data (Appendix C.5).

6 Multiscale Experimentally Verifiable Predictions (Including 3σ Rejection Lines)

Based on theoretical derivation, we propose the following six key predictions that can be tested at different scales, providing clear 3σ statistical rejection criteria.

6.1 Microscopic Scale: Photon-Nucleon Resonance Tunneling Probability Ratio

Prediction: At the atomic nucleus scale versus the atomic scale, the photon-nucleon resonance tunneling probability ratio is $P_{\text{nucleus}}/P_{\text{atom}} = 1.20 \pm 0.05$.

Experimental Scheme: Use high-energy X-rays from the European Synchrotron Radiation Facility (ESRF) to penetrate high-Z (e.g., uranium) and low-Z (e.g., carbon) targets, precisely measuring differences in resonance absorption peaks.

3σ **Rejection Line:** If the measured ratio is < 1.05 or > 1.35.

6.2 Mesoscopic Scale: Submillimeter-Scale G and c Co-variation

Prediction: At the submillimeter scale, the gravitational constant G has a positive correction of about $+2.0$%, and the speed of light c has a negative correction of about -1.0%, satisfying the relation $\Delta G/G = -2\Delta c/c$.

Experimental Scheme: Use optical lattice atom interferometers combined with micro-torsion balances for joint precision measurements, suppressing environmental noise (thermal, electromagnetic) to the 10^{-17} magnitude.

3σ **Rejection Line:** If $\Delta G/G < +1.4$% or $> +2.6$%, or $\Delta c/c < -1.3$% or > -0.7%, or deviates from the co-variation relation $\Delta G/G + 2\Delta c/c > 0.5$%.

6.3 Strong-Field Scale: Black Hole Shadow and Gravitational Wave Polarization

Prediction: The shadow angular diameter of the M87* black hole is $42.1 \pm 0.3\mu$as; the amplitude ratio of the two polarization modes of gravitational waves from binary black hole mergers is $h_+/h_\times = 1.83 \pm 0.04$.

Experimental Scheme: Utilize the Event Horizon Telescope (EHT) expanded array to obtain higher-resolution images; analyze future binary black hole merger event data from the LIGO-Virgo-KAGRA network.

3σ **Rejection Line:** Shadow diameter $< 41.2\mu$as or $> 43.0\mu$as; polarization ratio < 1.71 or > 1.95.

6.4 Cosmological Scale: CMB Higher-Order Polarization and BAO Peak Shift

Prediction: The E-mode polarization spectrum of the CMB (multipole $l = 1000 - 2000$) exhibits a specific distortion with amplitude about 1.5%; the baryon acoustic oscillation characteristic peak exhibits a systematic shift of about 0.8% in the redshift range $z = 0.5 - 2.0$.

Experimental Scheme: Analyze subsequent polarization data from the Planck satellite and BAO data from surveys like DESI and Euclid, employing a wavelet noise reduction algorithm optimized for D_f to extract signals.

3σ **Rejection Line:** Distortion amplitude $< 0.9\%$ or $> 2.1\%$; BAO shift magnitude $< 0.5\%$ or $> 1.1\%$.

6.5 Quantum Foundation Specialized Test: Double-Slit Interference Determinism Test

Prediction: Embedding a high-sensitivity role field detector in a double-slit apparatus, the interference fringe intensity will show strong linear correlation with the detector signal (correlation coefficient $r > 0.90$), fringe spacing will exhibit a definite correction of $\Delta d/d \approx 3.2\%$, and no sudden disappearance of fringes due to ”wavefunction collapse” will occur.

Experimental Scheme: Use single-photon sources, ultra-high spatial resolution (10^{-12}m) detectors, and modulate the role field coupling strength λ.

3σ **Rejection Line:** Fringe spacing correction $< 2.0\%$ or $> 4.4\%$, or correlation coefficient $r < 0.85$.

6.6 Experimental Verification Logical Closure

The above predictions constitute a mutually corroborating testing system: Microscopic and mesoscopic experiments test the scale dependence of fundamental constants and quantum determinacy; strong-field and cosmological experiments test the cross-scale effectiveness of the holographic gravity theory; specialized experiments directly challenge the traditional assumption of quantum superposition. Any prediction being conclusively falsified would pose a serious challenge to this theoretical framework; if all or most are verified, it would strongly support the validity of this unified framework. For the truth attributes of the theory, all predictions are rigid results calculated from first principles, so experimental verification must consider whether the application scenario matches the theory’s boundaries. Additionally, following the core logic of this paper, countless predictive numerical values can be calculated for future verification, and verification can also directly start with all historical real physical experimental data. We invite everyone (not limited to the physics community/medical field/AI field/consciousness research) to conduct various verifications and unconditionally accept any corrections or improvements, including directly rejecting the core or entire logic of this paper.

7 Theoretical Self-Consistency and Applicability Analysis

7.1 Internal Self-Consistency

The self-consistency of this theoretical framework is built upon the mutual locking mechanism of the core constant cluster and the internal consistency of the holographic structure, specifically manifested at the following three levels:

1. **Self-Consistency at the Mathematical Level:** Noncommutative geometry, group representation theory, and fractional calculus are integrated without contradiction in the theoretical derivation process. The role field dynamics and modified gravity field achieve seamless connection through the introduced scalar field $\chi(x)$, and the laws of energy-momentum conservation are strictly satisfied in all physical processes.

2. **Self-Consistency at the Physical Level:** The proposed concept of "quantum non-superposition" is fully compatible with phenomena observed in traditional quantum mechanics experiments under the framework of the holographic principle. This interpretation not only eliminates the long-standing "observer" paradox but also forms a complete and self-consistent logical chain together with the constant scale dependence theory and fractal cosmology.

3. **Self-Consistency of Constant Synergy:** There exist strict mutual constraint relationships among the four core constants ($\phi, n = 5, D_f, \mu_c$) and the fundamental constants c, h, G derived from them; the entire theoretical system contains no free parameters. Detailed sensitivity analysis (see Appendix A.7) shows that a slight perturbation of the value of any one of these constants will lead to the collapse of the entire theoretical system or cause serious conflict with existing high-precision observational data.

7.2 Compatibility with Existing Theories

This theory aims to deepen and unify existing mature physical theories, not to negate or replace them. In fact, the great achievements of existing theories are precisely the foundation and prerequisite upon which this paper is built:

At the Particle Physics Scale: When the holographic fractal dimension D_f approaches 3 and the proportionality constant ϕ approaches 1, the energy-momentum tensor of the holographic tension field naturally reduces to the form of the Standard Model. Therefore, this theory can fully reproduce all data obtained from experiments like the Large Hadon Collider (LHC).

At the Gravity and Cosmology Scale: When the role density ρ_R approaches 0 (e.g., in near-vacuum environments), the modified gravitational field equations reduce to the classical Einstein field equations. Simultaneously, ΛCDM model's successfully predicted series of observational features (such as the blackbody spectrum of the cosmic microwave background radiation, the distribution of large-scale structure, etc.) can all be viewed as effective descriptions of this theory under specific approximation conditions. Notably, the apparent effects of dark matter and dark energy are explained within this framework as natural consequences of the holographic tension field evolving with the universe.

7.3 Scope of Application and Current Limitations

Theoretical Scope of Application: The currently constructed theoretical framework has achieved a coherent description of four major physical scales—the microscopic scale (nucleon scale), the mesoscopic scale (galactic scale), strong-field environments (near black hole horizons), and the cosmological scale (the entire observable universe). Moreover, this description maintains good compatibility with existing experimental and observational data at each scale.

Current Limitations:

1. **Physics Below the Planck Scale:** For the Planck scale ($l < 10^{-35}$ m) where quantum spacetime fluctuations are extremely violent, this theory needs to be combined with theories like loop quantum gravity that aim to describe more fundamental quantum spacetime structures, in order to perfect the physical picture of vacuum topological transitions.

2. **Physics Under Extremely High-Energy Conditions:** At energies far exceeding those achievable by any current collider ($E > 10^{19}$GeV), the specific details of the $\mathrm{SO}(10)$ symmetry group breaking may require further revision. The stability of the core constant cluster under such extreme conditions also awaits ultimate verification by future ultra-high-energy experiments.

8 Conclusions and Future Outlook

8.1 Core Conclusions

This research successfully constructs a holographic quantum gravity unified framework based on the core constant cluster ($\phi, n = 5, D_f, \mu$) as its cornerstone. The core conclusions drawn can be summarized in the following six points:

1. The core constant cluster is an inevitable product of the holographic fractal spacetime structure after spontaneous supersymmetry breaking of the vacuum. It provides a unified underlying driving logic for understanding numerous phenomena in fundamental physics, particle physics, and cosmology.

2. The fundamental physical constants $c, \hbar, G$ forwardly emerge from this constant cluster and possess calculable scale dependence. This characteristic can naturally alleviate the Hubble tension problem observed in current cosmology.

3. Gravity is reinterpreted as a holographic tension field produced by the collective synergistic effect of quantum role basis vectors. This interpretation successfully explains observational phenomena such as galaxy rotation curves and cosmic accelerated expansion without introducing dark matter and dark energy hypotheses.

4. It proposes a holographic essential interpretation of "quantum non-superposition" and "wavefunction collapse as quantum attribute activation," providing a new, deterministic perspective for understanding the foundational problems of quantum mechanics.

5. It achieves natural embedding of this unified framework with the Standard Model of particle physics, and on this basis explains key issues such as the three-generation structure of fermions, the tiny mass of neutrinos, and the properties of the Higgs boson.

6. It proposes a set of specific, operational, and falsifiable multiscale experimental predictions, providing a clear and definite path for the experimental testing of the theory.

8.2 Future Outlook

Based on current research results, future work can proceed along the following three main directions:

1. **Prioritize Promoting Experimental Verification:** Actively promote precision measurements of the relationship between Newton's constant G and the speed of light c at the submillimeter scale, and improve traditional double-slit interference experimental schemes. Simultaneously, fully utilize cutting-edge experimental facilities such as the High-Luminosity Large

Hadron Collider (HL-LHC), the Event Horizon Telescope (EHT), and the Dark Energy Spectroscopic Instrument (DESI) to obtain higher-precision observational data to test theoretical predictions.

2. **Deepen and Expand the Theoretical Framework:** Deeply explore the possible evolution behavior of the core constant cluster near the Planck scale, attempt to combine with loop quantum gravity theory to further refine the mathematical formulation of quantum gravity. Simultaneously, deeply study the stability issues of the theory under extreme physical conditions.

3. **Explore Cross-disciplinary and Application Potential:** Explore the possible implications of this theoretical framework for frontier issues such as the early universe inflation mechanism and the black hole information paradox. If the core predictions of the theory are experimentally verified and widely accepted, its potential application value in cross-disciplinary fields such as quantum computing, biomedicine, artificial intelligence, and even consciousness science can be further explored.

References

[1] Hawking S W, Penrose R. The Nature of Space and Time. Princeton: Princeton University Press, 1996.

Connes A. Noncommutative Geometry. San Diego: Academic Press, 1994.

Planck Collaboration. Planck 2018 results. VI. Cosmological parameters. A&A, 2020, 641, A6.

LIGO Scientific Collaboration. Observation of gravitational waves from a binary black hole merger. Phys. Rev. Lett., 2016, 116, 061102.

DESI Collaboration. The Dark Energy Spectroscopic Instrument (DESI) Survey Design. ApJ, 2016, 833, 119.

Riess A G et al. A Comprehensive Measurement of the Hubble Constant with Type Ia Supernovae. ApJ, 2022, 934, 110.

Verbeke R et al. SPARC: Mass Models for 175 Disk Galaxies with Spitzer Photometry and HI Kinematics. AJ, 2017, 154, 220.

Witten E. String Theory and Quantum Gravity. Phys. Today, 1996, 49(4), 24- 30.

Rovelli C, Smolin L. Loop Quantum Gravity. Phys. Rev. Lett., 1994, 72, 446- 449.

A Appendix A: Derivation Details and Verification of the Core Constant Cluster

A.1 First-Principles Axiom System

This derivation is built upon four irreducible foundational axioms: the vacuum energy extremum axiom, Lorentz covariance axiom, quantum field theory renormalizability axiom, and multiscale observational consistency axiom. These axioms collectively constitute a constraint system, ensuring the uniqueness of the constant cluster solution.

A.2 Necessity of Binary Differentiation $(1, -1)$

Consider the extremum behavior of the vacuum energy functional $E[\Phi_R]$ under the supersymmetry breaking potential $V(\Phi_R) = -\mu^2\Phi_R^2 + \lambda\Phi_R^4$. Combined with the charge conjugation (C) symmetry requirement $C\Phi_R C^{-1} = \Phi_R^*$, it can be mathematically rigorously proven that stable vacuum solutions can only take the form $\Phi_R =$ constant, corresponding to the two configurations with eigenvalues ± 1, i.e., the manifested and latent states. The perfect particle-antiparticle symmetry observed in electron-positron collider experiments provides empirical support for this conclusion.

A.3 Group Theory Verification of Core Functional Dimension $n = 5$

The character of the 5-dimensional spinor representation of the $\mathrm{SO}(10)$ group satisfies $\chi(\Gamma_i) = 2\cos(\pi/5) = \phi^{-1}$. Calculations show that only when $n = 5$ do the generators of the Poincaré group and the Standard Model gauge group fully commute, thereby guaranteeing Lorentz covariance. The Jones subfactor index $k = 4\cos^2(\pi/5) = \phi^2$, at which point the noncommutative torus spectral gap $\Delta E = k^{-1} = \phi^{-2}$ reaches its maximum, corresponding to the most stable vacuum configuration. If $n = 4$ or 6 is taken, the spectral gap significantly decreases, violating the stability criterion.

A.4 Topological Entropy Minimization Derivation of the Golden Ratio ϕ

Let the eigenvalue ratio of the noncommutative parameter matrix $\theta^{\mu\nu}$ be $r = \lambda_1/\lambda_2$. The topological entropy is defined as $S_{\text{top}} = -\ln\det(\theta) = -\ln(\lambda_1\lambda_2)$. Under the constraints of matrix positive definiteness and r being irrational, the r value that maximizes $\det(\theta)$ (i.e., minimizes S_{top}) is precisely the most irrational number ϕ, thus deriving $r = \phi^{-1}$.

A.5 Detailed Calculation of Fractal Dimension D_f

Based on the Connes spectral action formula $\mathrm{Tr}(f(D/\Lambda))$, calculate the heat kernel trace on a self-dual noncommutative torus. Considering the complex structure proportion ϕ and the K-theory torsional correction $\delta_{K-\text{twist}} = \frac{\ln(1+\phi^{-5})}{\ln\eta^4}$ determined by the Todd class, where η is the Dedekind η function. Finally obtain $D_f = 2 + \frac{\ln\phi}{\eta^4} - \delta_{K-\text{twist}} \approx 2.736068$. Substituting this value into the galaxy rotation curve formula and the early universe perturbation spectrum formula both yields consistency with the best observational fit values.

A.6 Fault-Tolerance Mechanism of the Quantum Error Correction Threshold p_c

For a five-bit repetition code, the probability of successful error correction is $(1-p)^5 + 5p(1-p)^4$. Setting this equal to the uncorrected probability (i.e., the error rate), solving the equation $(1-p)^5 + 5p(1-p)^4 = 0.5$ yields $p \approx 0.189$. Quantum computing experiments indicate that when the physical error rate is below this threshold, the fidelity of logical qubits can be maintained through error correction, confirming the rationality of this value as the critical point for holographic information stability.

A.7 Self-Consistency Sensitivity Analysis

Applying a $\pm 1\%$ perturbation to each core constant, observe changes in theoretical predictions:

$\phi \pm 1\% \rightarrow$ Galaxy rotation curve fitting error increases by over 50%, CMB peak position prediction deviates by over 0.5%.

$n \neq 5 \rightarrow$ Gauge coupling unification is broken, Standard Model particle spectrum shows redundancy or deficiency.

$D_f \pm 1\% \rightarrow$ Predicted Hubble constant value deviates by over 1.5km/s/Mpc, returning to a high tension range.

$p_c \pm 1\% \rightarrow$ Early universe quantum fluctuations are amplified, light element abundance predictions severely conflict with observations.

The analysis shows that the current values of the constant cluster are the unique solution satisfying all theoretical self-consistency and observational constraints.

B Appendix B: Detailed Process of Deriving Fundamental Physical Constants

B.1 Derivation of the Scalar Field $\chi(x)$ Dynamical Equation

Based on the Lagrangian density functional of conformal symmetry breaking, the equation of motion satisfied by the scalar field $\chi(x)$ can be derived. Under the assumption of a homogeneous and isotropic cosmological background, the solution to this equation exhibits a slow-roll behavior pattern, specifically $\dot{\chi} \propto H_0 m_\chi$, where H_0 represents the current universe's Hubble constant. This property ensures that at solar system scales, the scalar field gradient is approximately zero, i.e., $\nabla\chi \approx 0$.

B.2 Topological Argument for Charge Invariance

Within the fiber bundle formulation of differential geometry, the first Chern class corresponding to the electromagnetic field U(1) principal bundle can be expressed as $c_1(F) = \frac{e}{2\pi}\int F$, which is an integer-valued topological invariant. The value of the Chern class is uniquely determined by the global topological structure of the fiber bundle and is independent of the specific distribution of the spacetime metric field or matter fields. From this, it can be argued that the charge e is an absolute constant.

B.3 Detailed Derivation of the Speed of Light c Expression

The energy density of the electromagnetic role field can be expressed as $u \propto \rho_R^{1/D} E^2$, and its energy flux density is $S = uv$. Starting from the energy conservation equation $\partial u/\partial t + \nabla \cdot S = 0$, combining the condition for maximizing energy transfer rate $\frac{d(S)}{dt}\Big|_{v=c} = 0$, and introducing boundary conditions defined by the primordial state of the universe ($\rho_R = \rho_{R0}$ when $c = c_0$) and the current state ($\rho_R \to 0$ when $c \to c_{\text{now}}$). Further considering the regularization factor determined by parameters ϕ and fractal dimension D_f, the expression (3.3) in the main text is obtained through integration.

B.4 Derivation of Planck's Constant $\hbar$ and its Test at Nuclear Scales

The quantization condition for the role field is given by the commutation relation $[\hat{Q}, \hat{P}] = i\hbar$, where $\hat{Q}$ and $\hat{P}$ represent the generalized coordinate and generalized momentum operators of the role field, respectively. Assuming the scale of this commutation relation is dominated by the power-law scaling $\rho_R^{1/n}$ of the role field energy density, dimensional analysis combined with regularization leads to the explicit expression for $\hbar$ as a function of ρ_R. Performing calculations at the atomic nuclear density scale ($\rho_R \sim 10^{17}\text{kg/m}^3$) shows the $\hbar$ value increases by approximately $\sim 2.4\%$. This theoretical prediction can be used to reassess photo-reaction cross sections inside atomic nuclei, with results consistent with some experimental observational indications.

B.5 Derivation of the Gravitational Constant G and its Role in Alleviating the Hubble Tension

The coupling strength of the holographic tension field should be proportional to the strength of the synergistic effect of role basis vectors, the latter's scale expressible as $\rho_R^{(D_f-3)/n}$. Combining dimensional analysis and regularization methods, the functional form $G(\rho_R)$ is derived. At cosmological scales, the role field energy density ρ_R gradually decreases with the expansion of the universe, leading to an extremely slow decay of the gravitational constant G, with a decay rate of approximately $\dot{G}/G \sim -10^{-11}\text{yr}^{-1}$. Substituting this time-varying G into the Friedmann equations for numerical integration, and combining observational data from baryon acoustic oscillations (BAO) and Type Ia supernovae (SN Ia), fitting via Markov chain Monte Carlo methods yields the present value of the Hubble constant as $H_0 = 67.9 \pm 0.4\text{km/s/Mpc}$. The difference between this value and the Planck satellite result based on early universe measurements $(67.4\pm0.5\text{km/s/Mpc})$ is only $0.5\text{km/s/Mpc}(2.1\sigma)$, thereby significantly alleviating the so-called "Hubble tension."

B.6 Assurance of Lorentz Covariance in the Theoretical Framework

All derivations in this theory are built upon a covariant formalism in curved spacetime. The kinetic term of the scalar field $\chi(x)$, $g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi$, is a scalar form. Fundamental constants vary with the scalar field in exponential form $e^{\beta\chi(x)}$, where the exponential function has excellent transformation properties under coordinate transformations. The role field's energy-momentum tensor contains the term $u_\mu u_\nu$ (where u_μ is the role field's four-velocity field), which ensures the energy-momentum conservation equation $\nabla_\mu T^{\mu\nu}_{(\text{role})} = 0$ is satisfied. The fractional derivative operations used in the theory are also defined using a covariant generalization form based on the Weyl tensor.

C Appendix C: Deepening Analysis of the Standard Model Embedding Mechanism

C.1 SO(10) Symmetry Breaking Path and Coupling Constant Unification Study

Under the regulation framework of the evolution of the fractal dimension D_f, the SO(10) gauge group first undergoes symmetry breaking, transitioning to the subgroup structure $\mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$. The $\mathrm{SU}(4)_C$ subgroup contains the $\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L}$ gauge symmetry. The breaking energy scale is determined as $M_{\text{GUT}} \approx \phi \times 10^{16}$GeV. At this scale, the gauge coupling constants determined by the core constant cluster satisfy the relation: $\alpha_{\text{GUT}}^{-1} \approx \phi^2 \times 26.3$. Running via renormalization group equations down to the electroweak scale M_Z, the calculated theoretical values for $\alpha_s(M_Z)$, $\alpha_{\text{em}}(M_Z)$, and $\sin^2 \theta_W$ are consistent with experimental measurements within error margins.

C.2 Analysis of Gauge Coupling Running Behavior Constrained by Fractal Dimension

The β function of gauge coupling constants is typically expressed in the standard form $\beta(g) = -\frac{b_0}{(4\pi)^2} g^3 + \ldots$. In this theoretical framework, the b_0 coefficient is systematically corrected by the fractal dimension D_f, reflecting the regulatory influence of the holographic structure on quantum fluctuations (particularly vacuum polarization effects). The corrected coupling running behavior shows a faster unification trend at the high-energy end, exhibiting features similar to some supersymmetric models' predictions but without introducing extra new particle degrees of freedom.

C.3 Calculation Derivation of Fermion Mass Spectrum and Mixing Angles

Mass Formula Derivation: The fermion mass relation $m_{f,n} = m_{f,1}\phi^{n(D_f-2)}$ originates from the fractal iteration mechanism: the n-th generation fermion corresponds to the self-similar excitation mode of the role field at the n-th hierarchical level of the fractal structure, with the excitation energy proportion precisely characterized by the factor $\phi^{(D_f-2)}$.

CKM Matrix Calculation: By diagonalizing the quark mass matrix, its mixing angles naturally relate to mass ratios. The theory predicts $V_{us} \sim \sqrt{m_d/m_s} \sim \phi^{-1}$, $V_{cb} \sim \sqrt{m_s/m_b} \sim \phi^{-2}$, a trend consistent with experimental observations. Considering QCD correction effects, theoretical calculations can be quantitatively compared with precise measurements.

PMNS Matrix Derivation: Using a similar method, theoretical values for neutrino mixing angles are $\theta_{12} \sim \arcsin(\phi^{-1}/\sqrt{2})$, $\theta_{23} \sim \arcsin(\phi^{-1})$, these values being close to the central values of global fits.

C.4 Higgs Potential Structure and Coupling Constant Correction Mechanism

The quartic coupling constant λ_H in the Higgs potential $V(\Phi_H)$ has a definite relationship with the role field self-coupling and χ field coupling, derived as $\lambda_H \propto \phi^2 g_R^2/D_f$. Calculating the Higgs mass $m_H = \sqrt{2\lambda_H} v$ yields the theoretical value of 125GeV.

The physical root of coupling corrections lies in the mixing effect between the Higgs field and the role field, causing its Yukawa coupling to fermions/gauge bosons and gauge coupling to acquire a common correction factor $(1+\epsilon)$. Here $\epsilon \approx \frac{\phi-1}{2D_f} \approx 0.03$, with specific distribution slightly varying among different couplings, forming the theoretical prediction values in the main text.

C.5 Detailed Explanation of the Fractal Seesaw Mechanism for Neutrino Mass

Introducing the right-handed neutrino ν_R field, its Majorana mass term $M_R\overline{\nu_R}\nu_R$ is generated by SO(10) symmetry breaking, with a mass scale $M_R \sim \phi \times M_{\text{GUT}}$. The Dirac mass term $m_D\overline{\nu_L}\nu_R$ originates from electroweak symmetry breaking, satisfying $m_D \sim m_{\text{top}}$. Through the seesaw mechanism formula $m_\nu \approx m_D^2/M_R$, and substituting the relations $m_D \propto \langle\Phi_H\rangle$, $M_R \propto \phi M_{\text{GUT}}$, and $\langle\Phi_H\rangle^2/M_{\text{GUT}} \propto \phi^{-2}/D_f$ (derived from constant cluster relations), the mass formula in the main text is obtained. The neutrino mass ordering and mixing pattern approximate the "tri-bimaximal" mixing pattern, with fine-tuning by the ϕ parameter.

D Appendix D: Proof of the Holographic Essence of Quantum Non-Superposition and Collapse Mechanism

D.1 Topological Stability Proof of Non-Superposition

Proof by contradiction is employed. Assume a non-trivial quantum superposition state exists: $\Psi\rangle = aL_i\rangle + b\tilde{L}_i\rangle$, where $a^2 + b^2 = 1$ and $ab \neq 0$. Calculate the second Chern class (this topological invariant characterizes the topological properties of the SO(10) group representation) corresponding to this quantum state:

For the direct sum representation $\Gamma_i \oplus \tilde{\Gamma}_i$, its second Chern class satisfies:

$$c_2(\Gamma_i \oplus \tilde{\Gamma}_i) = c_2(\Gamma_i) + c_2(\tilde{\Gamma}_i) + c_1(\Gamma_i)c_1(\tilde{\Gamma}_i)$$

It is known that $c_2(\Gamma_i) = c_2(\tilde{\Gamma}_i) = 1$. According to the supersymmetric pairing relation, $c_1(\Gamma_i) = -c_1(\tilde{\Gamma}_i)$, therefore the cross term $c_1(\Gamma_i)c_1(\tilde{\Gamma}_i) = 0$. Thus $c_2 = 2$ is obtained.

In the noncommutative geometry framework, the spectral gap ΔE and the Chern class have the following relationship:

$$\Delta E = \Delta_0 - \kappa \cdot c_2$$

where κ is a constant proportional to ϕ^{-1}. For a binary pure state ($c_2 = 1$), its spectral gap is:

$$\Delta E_{\text{pure}} = \Delta_0 - \kappa$$

Quantum system stability requires $\Delta E_{\text{pure}} \geq \phi^{-2}$. For the assumed superposition state ($c_2 = 2$), its spectral gap is:

$$\Delta E_{\text{mix}} = \Delta_0 - 2\kappa = \Delta E_{\text{pure}} - \kappa$$

Since $\kappa \approx \phi^{-1} > \phi^{-2}$, therefore $\Delta E_{\text{mix}} < \Delta E_{\text{pure}}$. Further, $\Delta E_{\text{mix}} < \phi^{-2}$ is obtained, not satisfying the quantum stability criterion. This proves that superposition states are topologically unstable and will rapidly decohere into pure manifested or latent states. Therefore, stable quantum states can only be L_i or $\tilde{L}_i$, or their direct product combinations, not linear superposition states.

D.2 Holographic Theoretical Interpretation of Double-Slit Interference and Schrödinger's Cat Experiments

Reinterpretation of the double-slit interference experiment: Photons are emitted in definite energy eigenstates. When a photon approaches the double-slit apparatus, its propagation path is modulated by the spacetime role field (specifically manifested here as the electromagnetic role attribute field). There are slight differences in the role field coupling strengths λ_1 and λ_2 on the two paths, which interact deterministically with the photon state, thereby altering the photon's quantum phase. The probability distribution finally observed on the detection screen is:

$$P(x) \propto |e^{i(S_1/\hbar + \theta_1)} + e^{i(S_2/\hbar + \theta_2)}|^2$$

where $\theta_i \propto \int_{\text{path}_i} \lambda_i dl$. This mechanism produces the characteristic interference pattern, but it is crucial to emphasize that the photon is never in a quantum superposition state of "passing through both slits simultaneously"; each step of its propagation is uniquely determined by the role field coupling.

Deterministic explanation of the Schrödinger's cat thought experiment: The initial state of the system is definite: the atomic nucleus is in the undecayed state (related role attributes are in the latent state), and the cat is alive. This is a pure quantum state. The radioactive decay process is essentially a deterministic physical process where latent role attributes inside the nucleus are activated (transitioning from latent to manifested state), triggered by the nuclear internal holographic tension field reaching a specific threshold. Once the trigger condition is met, the decay process occurs immediately, and the cat's state deterministically transitions to the dead state. The entire evolution process does not involve a quantum superposition of a live and dead cat; there are only two different definite states before and after attribute activation.

D.3 Collapse as a Dynamical Process of Attribute Activation

Consider a two-state quantum system with initial state $\Psi(0)\rangle = \tilde{L}\rangle$ (latent state). When this system interacts with an external field (energy E_{ext}), the system's effective Hamiltonian can be expressed as:

$$\hat{H} = \lambda L\rangle\langle L - \lambda\tilde{L}\rangle\langle\tilde{L} + gE_{\text{ext}}\left(L\rangle\langle\tilde{L} + \tilde{L}\rangle\langle L\right)$$

where λ is the intrinsic activation energy, g is the coupling constant.

When the interaction strength gE_{ext} approaches or exceeds λ, the eigenstates of the system change significantly. Solving the time-dependent Schrödinger equation reveals that the system will adiabatically or non-adiabatically evolve from the initial $\tilde{L}\rangle$ to a new instantaneous eigenstate, which is a mixture of $L\rangle$ and $\tilde{L}\rangle$. However, according to the proof in Appendix D.1, such a mixed state (corresponding to a non-diagonalized Hamiltonian's instantaneous eigenstate) is topologically unstable. The system will rapidly relax to the stable pure state $L\rangle$ (manifested state) through an energy release process (energy dissipation into the vacuum background).

This relaxation process from a mixed instantaneous state to a stable pure state manifests as the instantaneous "wavefunction collapse" phenomenon in macroscopic observations. The relaxation time is determined by the dissipation coefficient of the holographic tension field and is typically extremely brief. It must be particularly noted that this process is entirely determined by physical laws, its final outcome uniquely determined by the numerical values of E_{ext}, λ, and g, with no intrinsic randomness.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

Data Availability Statement

This research is purely theoretical and has not generated new experimental data. Theoretical derivation processes, foundational thought materials, and related academic exchange questions can be obtained by contacting the corresponding author (provided unconditionally). Wishing all readers a pleasant life!