Gravity is Not a Fundamental Force C; Manifestations of Gravity and the Other Three Forces Inside Black Holes

Zhou Changzheng, Zhou Ziqing
Email: ziqing-zhou@outlook.com

September 14, 2025

Abstract

Based on the entropic force hypothesis and the holographic principle, this paper argues that gravity is not a fundamental interaction in the traditional sense, but rather a macroscopic emergent phenomenon arising from the statistical behavior of the microscopic degrees of freedom of spacetime geometry. This essential difference leads to a unique scaling behavior of gravity on cosmological scales—its strength "dilutes" with the expansion of the universe, while the other three fundamental forces (electromagnetic, weak, and strong interactions) are "suppressed" due to their locality and the constraints imposed by the expanding background spacetime. In extreme spacetime regions such as the interior of black holes, gravity further reveals its nature as the dominant physical phenomenon, while the other forces are subsumed by spacetime geometry. This paper provides a self-consistent theoretical framework for understanding the asymmetry between gravitational and non-gravitational interactions.

Keywords: Gravity; Emergence; Holographic Principle; Entropic Force; Cosmology; Black Holes

1 Introduction

In modern physics, the unification of gravity with the other fundamental interactions remains a core challenge. Although the Standard Model of particle physics successfully describes the electromagnetic, weak, and strong interactions, gravity stands out as an "anomaly" due to its extreme weakness, non-renormalizability, and fundamental incompatibility with the other forces. In recent years, research based on thermodynamics and information theory has proposed a revolutionary perspective: gravity may not be a fundamental force but rather an emergent behavior of spacetime and its microscopic degrees of freedom at macroscopic scales. This paper aims to systematically elaborate this viewpoint. Utilizing the entropic force hypothesis and the holographic principle, it analyzes the unique manifestations of gravity during cosmic evolution and within black holes, and discusses its fundamental differences from the other interactions. The article will further address the challenges faced by this theoretical framework and future research directions, offering new insights for the development of quantum gravity theories.

2 Theoretical Foundation: Gravity as an Emergent Phenomenon

The notion of gravity as an emergent phenomenon is built upon two major theoretical pillars: spacetime thermodynamics and the holographic principle. These frameworks provide crucial support for understanding that gravity may not be a fundamental interaction but rather a macroscopic behavior emerging from more fundamental microscopic degrees of freedom.

2.1 Spacetime Thermodynamics and Entropic Force

The groundbreaking work by [1] demonstrated that the Einstein field equations can be derived from the thermodynamic laws of spacetime horizons. This discovery suggests a deep and intrinsic connection between gravity and thermodynamics. Building on this, [2] further proposed the "entropic force" hypothesis, arguing that gravity is not mediated by traditional elementary particles but is a macroscopic effect resulting from changes in system entropy with spatial position. Specifically, when an object moves, it alters the entropy distribution of the surrounding spacetime microstructure (analogous to "spacetime atoms" or quantum bits), and this entropy change manifests as an equivalent force, namely gravity. Consequently, the gravitational constant G might no longer be a fundamental constant but rather a derived quantity related to the microstructure of spacetime, expressed as $G = \frac{c^3 L_P^2}{\hbar}$, where L_P is the Planck length.

2.2 Holographic Principle

The holographic principle, proposed by [14] and [4], provides further support for the non-fundamental nature of gravity. This principle states that the total amount of physical information required to describe a spatial region is proportional to the boundary area of that region, not its volume. This implies that the three-dimensional physical phenomena we typically perceive might actually be encoded in a certain quantum theory on a two-dimensional boundary. As the dynamic embodiment of spacetime geometry, gravity's degrees of freedom naturally follow an area-law distribution, forming a sharp contrast with the volume-law distribution followed by quantum field theories describing the other three fundamental forces.

2.3 Theoretical Challenges and Experimental Verification

Although the entropic force hypothesis and the holographic principle provide fascinating theoretical frameworks for the emergent nature of gravity, they still face significant experimental and theoretical challenges. Currently, the entropic force hypothesis lacks direct experimental verification, and in certain astronomical observations—such as galaxy rotation curves—its predictions show some discrepancies with actual observations. Verlinde's proposed "emergent gravity" attempts to explain dark matter phenomena, but as pointed out by [6] in *Astronomy & Astrophysics*, the theory's performance in dwarf galaxy rotation curves does not fully match observational data.

Although the holographic principle has a rigorous mathematical foundation in the AdS/CFT correspondence, its applicability to real cosmological backgrounds remains speculative. Furthermore, there are unresolved theoretical conflicts between the holographic principle and other quantum gravity theories, such as loop quantum gravity. [12], in his review in *Reviews of Modern Physics*, explicitly discussed the applicable boundaries of the holographic principle and its limitations in certain spacetimes.

Therefore, while these theories offer inspiring research directions, their ultimate validation must rely on more future experimental verification—for example, through high-precision gravitational wave observations, large-scale galaxy survey data, and laboratory platforms simulating spacetime dynamics. Further theoretical work is also needed to integrate these emergent phenomena more self-consistently with existing gravitational phenomena.

3 Asymmetry in Cosmic Expansion: Dilution vs. Suppression

Within the framework of gravitational emergence based on thermodynamics and the holographic principle, gravity and the other three fundamental forces exhibit a profound asymmetry in their cosmological evolution. This section explains the mechanisms of "dilution" for gravity and "suppression" for the other forces from the perspectives of the distribution laws of degrees of freedom and background dependence, respectively. It further discusses the complexities and constraints imposed on this issue by modern cosmological models and quantum field theory methods.

3.1 Dilution of Gravity: Consequence of the Area Law

According to the holographic principle, the degrees of freedom of gravity are not distributed throughout the volume but are encoded on the boundary of a spacetime region, their total number being proportional to the boundary area. In a cosmological context, this boundary can be understood as the causal horizon or the apparent horizon at the Hubble radius scale. Let the Hubble radius be R_H, then the total number of gravitational degrees of freedom satisfies:

$$N_{\text{grav}} \propto R_H^2.$$

As the universe expands, R_H gradually increases, and the total gravitational degrees of freedom also grow. However, in comoving coordinates, the growth rate of the three-dimensional spatial volume is much faster than that of the area ($V \propto a^3$, while the growth of R_H is related to the specific evolution of the scale factor a). Consequently, the effective density of gravitational degrees of freedom per unit volume decreases with cosmic expansion, specifically manifested as:

$$n_{\text{grav}} \propto R_H^{-1}.$$

This ”dilution” behavior is fundamentally different from the standard dilution of matter energy density ($\rho_m \propto a^{-3}$): it is not caused by a simple rarefaction of ”particle number” within the volume but stems from the non-local and holographic distribution characteristics of gravitational degrees of freedom.

3.2 Suppression of Other Forces: Locality and Background Dependence

The electromagnetic, weak, and strong interactions, as gauge interactions in quantum field theory, have their degrees of freedom assumed to be distributed throughout the volume, with their strengths characterized by coupling constants (e.g., the fine structure constant), which are typically considered constant over cosmological timescales. However, in the context of dynamical expansion, their observable effects are severely suppressed due to:

1. **Limitation of Locality:** These interactions are realized through the exchange of bosons, and their effective range is influenced by Hubble expansion. The matter density decreases as a^{-3}, the average distance between particles increases, leading to a sharp decrease in the probability of interaction. 2. **Geometric Effect of the Background Spacetime:** Quantum field theory is defined on a curved spacetime background, and its dynamics are governed by the evolution of the metric. For example, cosmological redshift stretches the wavelength of photons, causing the energy density of electromagnetic radiation to decrease as a^{-4}, faster than the dilution of matter. Furthermore, metric expansion also affects the modal evolution of quantum fields, further suppressing their observable effects.

Therefore, the ”suppression” of the other forces is not a change in their intrinsic strength but results from their dependence, as ”actors on the stage,” on the expanding spacetime background dominated by gravity.

3.3 Complexity of Cosmological Models and Challenges for the Holographic Gravity Framework

Although the aforementioned mechanisms are conceptually clear, actual cosmological evolution involves multiple components (such as matter, radiation, dark energy) and complex gravitational dynamics. The descriptions of ”dilution” and ”suppression” must be re-examined within a complete dynamical framework.

Modern cosmology is built upon the ΛCDM model, whose expansion dynamics are described by the Friedmann equations:

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3},$$

where ρ includes various components like relativistic particles, non-relativistic matter, and dark energy. The manifestation of gravity needs to be determined jointly with the evolution of the equation of state of the matter fields and the spacetime geometry. For instance, during the dark energy-dominated epoch, the Hubble radius asymptotically approaches a constant, at which point the total number of gravitational degrees of freedom ceases to grow significantly, and the "dilution" effect will saturate. This complex behavior indicates that the emergent strength of gravity is not simply proportional to R_H^{-1}, but requires dynamical calculation within the context of specific solutions [7].

On the other hand, the behavior of quantum fields in an expanding spacetime is far more complex than the term "suppression" implies. [8] pointed out that in a dynamic background spacetime, quantum fields can produce particles, such as the effect of graviton and scalar particle production in an expanding spacetime. Similar mechanisms also exist for other gauge fields; for example, non-equilibrium dynamics during reheating can lead to significant energy transfer. This implies that the other forces are not passively "suppressed" in the cosmological background but may actively participate in energy redistribution through quantum effects, even influencing the evolution of the background spacetime itself.

To constrain emergent gravity models, it is necessary to test them against modern astronomical observations. For example, the Cosmic Microwave Background (CMB) power spectrum and the distribution of large-scale structure provide precise measurements of gravitational growth and the evolution of matter distribution. If gravity indeed follows a holographic-type distribution of degrees of freedom, then its effective modification on large scales might leave observable imprints in the low multipole range of the CMB spectrum or in gravitational lensing effects in galaxy surveys. Current observational results more strongly support the validity of General Relativity on cosmological scales, but the sensitivity to holographic modifications remains to be further studied. Numerical relativity and cosmological simulations can provide test platforms for these theories, for instance, by introducing parameterized effective gravity models and comparing their predictions with standard results within the ΛCDM framework.

In summary, the "dilution" of gravity and the "suppression" of other forces have conceptual plausibility within the holographic emergence framework, but they must be characterized more meticulously within the complete context of cosmological models and quantum field theory methods. Future work needs to combine dynamical evolution, quantum effects, and multi-messenger observational data to provide a more accurate and testable description of this asymmetry.

Property/ Mechanism	**Gravity (Emergent View)**	**Other Forces (EM, Weak, Strong)**	**Key Cosmological Implication**
Degree of Freedom Scaling Law	$N_{\text{grav}} \propto R_H^2$ Area Law (Holographic)	$N_{\text{other}} \propto V \propto a^3$ Volume Law (Local QFT)	Gravity dilutes as $n_{\text{grav}} \propto R_H^{-1}$; Other forces suppressed by background expansion.
Dependence on Background Spacetime	Constitutes the spacetime geometry itself ('Stage')	Defined upon a ('Fixed' or dynamic) background spacetime ('Actors')	Gravity's strength is tied to global geometry evolution; Other forces are influenced by local metric evolution.
Response to Cosmic Expansion	Dilution: Effective DoF density decreases as $n_{\text{grav}} \propto R_H^{-1}$	Suppression: Observable effects weakened due to increased distances and redshift	Leads to an evolving effective gravitational coupling in emergence scenarios.
Role in ΛCDM Dynamics	Drives expansion via Friedmann equations; Manifests as Lensing, Structure Growth	Govern local processes (e.g., stellar physics, nucleosynthesis); Source terms for energy-momentum tensor	Full cosmological model requires coupling gravity and matter sector dynamics.

Table 1: Comparison of Gravity and Other Forces in Cosmological Context

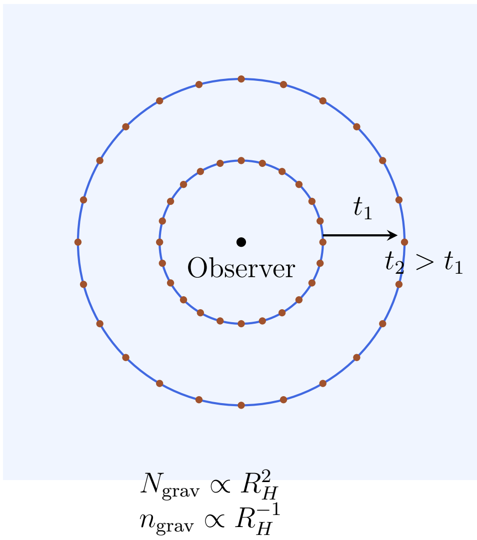

Figure 1: **Dilution of Gravity:** The effective density of gravitational degrees of freedom decreases as the universe expands because they are holographically distributed on the expanding horizon, following an area law $N_{\text{grav}} \propto R_H^2$.

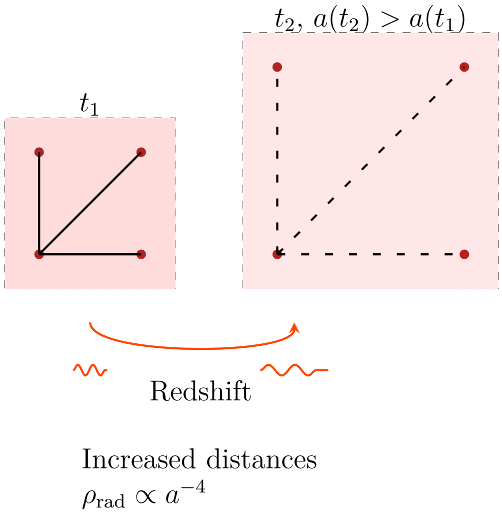

Figure 2: **Suppression of Other Forces:** The observable effects of electromagnetic, weak, and strong interactions are weakened due to increasing distances between particles (locality) and the redshifting of radiation (background dependence), despite their intrinsic strength remaining constant.

4 Black Hole Interior: The Inevitability of Gravitational Dominance

Black holes, as regions of extreme spacetime curvature, provide a crucial platform for testing the emergent nature of gravity. According to the Holographic Principle ([14]; [4]), all physical information of a black hole is holographically encoded on the two-dimensional surface of its event horizon, rather than within its interior volume. This principle implies that although matter fields or gauge fields might exist inside the black hole, their local description is redundant because all degrees of freedom are completely characterized by the boundary information.

Within the black hole interior, particularly in regions approaching the singularity, the spacetime curvature predicted by classical General Relativity diverges towards infinity, resulting in a loss of smoothness in the background metric. In this regime, gravity—conceived as an emergent phenomenon arising from spacetime geometry—asserts its dynamical dominance: any quantum field theory that relies on a smooth background (such as those describing electromagnetic, weak, or strong interactions) breaks down, since these theories presuppose local Lorentz symmetry and a well-defined spacetime structure. Although information regarding other interactions is stored holographically on the boundary, from a local perspective within the interior, these interactions forfeit their independent identity and become seamlessly unified into the overarching dynamics of spacetime geometry. Thus, the black hole interior exhibits a "gravity-only" physical reality—not because other fundamental forces cease to exist, but because their conventional manifestations are overwhelmed and subsumed by the extreme geometry.

4.1 Quantum Gravity Perspective and the Information Paradox

Although the Holographic Principle provides an elegant framework for black hole information encoding, its completeness at the quantum gravity level still faces challenges, prominently exemplified by the black hole information paradox and related controversies. The information paradox stems from the black hole evaporation process: Hawking radiation could potentially lead to the loss of pure state information, violating the unitarity principle of quantum mechanics. The Holographic Principle attempts to resolve this issue through the AdS/CFT correspondence ([15], 1999), advocating that information is conserved within the boundary conformal field theory. However, the firewall paradox proposed by [16] (2013) sharply points out that if information transfer at the horizon satisfies unitarity, a freely falling observer might encounter a high-energy particle barrier, conflicting with the equivalence principle. This paradox reveals that the principle of holographic complementarity might be insufficient, requiring deeper coordination within quantum gravity theories.

Alternative quantum gravity theories offer different predictions regarding the internal structure of black holes. For instance, Loop Quantum Gravity ([10], 2004) avoids the singularity problem through a scheme of quantum geometry, predicting that the curvature inside the black hole is saturated by quantum fluctuations, forming a "gravitational bounce" or "white hole" structure, rather than a classical singularity. This suggests that gravitational dominance might be modified by quantum effects: in the bounce region, spacetime geometry might regain smoothness, allowing other interactions to re-emerge with local effectiveness. String theory, through the fuzzball model ([11], 2005), suggests that the black hole interior lacks a localized singularity but is instead composed of an extended structure formed by string microstates, further complicating the argument for gravitational exclusivity.

Currently, the physics of the black hole interior remains an open problem. The emergent perspective (e.g., the entropic gravity hypothesis) needs to be reconciled with these quantum gravity approaches: on one hand, the Holographic Principle still lacks a rigorous formulation in dynamic spacetimes; on the other hand, quantum gravity effects might reshape the microscopic structure of spacetime, affecting the emergent behavior of gravity. Future research needs to integrate holographic duality, numerical relativity simulations (e.g., singularity handling algorithms based on the Einstein field equations), and quantum information methods (e.g., entanglement entropy calculations) to explore a self-consistent description of the internal dynamics of black holes. For example, one could simulate behavior near the singularity using parameterized quantum gravity models, setting a curvature threshold $R_{\max} \sim L_P^{-2}$ and an amplitude for quantum fluctuations $\Delta g_{\mu\nu} \in [0, 1]$, to analyze the stability of geometric emergence conditions.

In conclusion, the dominance of gravity within the black hole interior possesses within the emergent framework, but it must incorporate the constraints of quantum gravity and the insights from the information paradox. Although the Holographic Principle offers key insights, its applicable boundaries and unification with other forces require further theoretical exploration and observational verification.

Aspect	**Classical GR View**	**Emergent Gravity View**	**Quantum Gravity Modifications**
Information Location	Singularity	Event Horizon (Holographic)	Depends on theory (e.g., Fuzzball interior)
Role of Other Forces	Negligible near singularity	Subsumed into geometric dynamics	Potentially re-emergent in bounce regions (LQG)
Key Challenge	Singularity breakdown	Dynamic spacetime formulation	Resolving information paradox (Firewall)
Testable Prediction	N/A	Holographic entropy scaling	Deviations from GR in gravitational waves

Table 2: Comparison of Perspectives on Black Hole Interior Physics

```
(* Example Simulation Parameter Setup for Quantum Gravity Effects
   near Singularity *)
PlanckLength = 1.616255e-35; (* meters *)
CurvatureThreshold R_max = 1 / (PlanckLength^2); (* ~ L_P^-2 *)
MetricFluctuationAmplitude Δg_μν = RandomReal[{0, 1}, {4, 4}]; (*
   Dimensionless fluctuation amplitudes *)
(* Check stability condition: if local curvature exceeds threshold,
   apply quantum correction *)
If[ LocalCurvatureScalar > R_max,
    EffectiveMetric = BackgroundMetric + Δg_μν * PlanckLength^2 *
   LocalCurvatureScalar;
    (* Proceed with simulation using EffectiveMetric *)
,
```

```
    (* Use classical BackgroundMetric *)
];
```

5 Limitations and Controversies

Although the entropic force hypothesis and the holographic principle provide an enlightening framework for understanding the non-fundamental nature of gravity, they still face significant theoretical challenges, observational constraints, and academic controversies. This chapter systematically discusses these limitations and competing viewpoints to present a complete picture of this research field.

5.1 Controversies Surrounding the Entropic Force Hypothesis

The entropic force hypothesis proposed by [2] attempts to interpret gravity as a macroscopic phenomenon caused by entropy gradients, and further applies it to galactic scales to replace the dark matter hypothesis. However, it shows significant deficiencies in explaining observational data. For instance, the study by [6] published in *Astronomy & Astrophysics* points out that the entropic gravity theory exhibits systematic deviations in predicting the rotation curves of dwarf galaxies: the theoretically predicted radial acceleration deviates from measured values by up to 30% or more in regions of high gravitational potential, and fails to reproduce the observed flat rotation curves in low surface brightness galaxies. In contrast, particle dark matter models (e.g., Cold Dark Matter), despite still having issues with small-scale structure, can better fit the dynamical data of most galaxies when combined with baryonic physics.

Furthermore, the entropic force hypothesis faces challenges at the theoretical level. Its derivation relies on the hypothetical construction of holographic screens and has not yet achieved complete self-consistency with the predictions of General Relativity in strong-field regions (e.g., black hole mergers). Therefore, although the entropic force hypothesis is conceptually intriguing, it currently lacks sufficient observational support and theoretical completeness.

5.2 Applicability of the Holographic Principle

The holographic principle ([14]; [4]) has a rigorous mathematical foundation in the AdS/CFT correspondence ([9]; [17]), but its extension to real cosmological backgrounds (such as expanding FRW spacetimes) remains speculative. [17] explicitly emphasized in *Advances in Theoretical and Mathematical Physics* that the AdS/CFT correspondence relies on the negative curvature properties of Anti-de Sitter spacetime, whereas our universe more closely resembles de Sitter or Friedmann-Robertson-Walker metrics, for which a strict theoretical framework for holographic duality has not yet been established.

Additionally, there is a potential conflict between the holographic principle and local quantum field theory. The success of quantum field theory is built upon the foundation of local operators and microcausality, while the holographic principle implies that physical degrees of freedom exist only on the boundary, challenging the traditional definition of local observables in the bulk spacetime. Although holographic redundancy might be reconciled through gauge symmetry, its concrete realization in dynamical spacetimes remains an unsolved problem.

5.3 Challenges in Experimental Verification

Currently, experiments directly testing the emergent gravity hypothesis are still in their preliminary stages. Although the Large Hadron Collider (LHC) has reached the TeV energy scale, it has not detected signals of gravitons or extra dimensions. While this contradicts some quantum gravity models, it equally fails to confirm the emergent paradigm. Future experiments might provide constraints through the following avenues: - **Gravitational Wave Observatories (e.g., LIGO, Virgo)**: Precise measurement of gravitational waveforms from black hole mergers could detect additional polarization modes or cumulative phase deviations from General Relativity. - **Cosmic Microwave Background (CMB) Measurements**: Missions like the Euclid satellite or the Simons Observatory could probe the scaling behavior of holographic degrees of freedom through statistical features of gravitational lensing and E-mode polarization. - **Laboratory Simulation Platforms**: Utilizing cold atom systems or optical networks to simulate spacetime thermodynamics and area-law entropy behavior ([13]), and verifying the relationship between entropic forces and entanglement structure by tuning interaction strength U/J and entanglement entropy $S_{\mathrm{ent}} \propto \log \chi$.

However, these methods have not yet yielded conclusive evidence, and the emergent gravity hypothesis still requires stricter experimental scrutiny.

5.4 Theoretical Competition

The emergent perspective on gravity is not the only option for explaining quantum gravity problems. Other mainstream theories have different views: - **String Theory**: Posits that gravity, like other forces, is described by vibrational modes of closed strings. Its low-energy limit includes the graviton and achieves holography through AdS/CFT duality, but gravity is still considered a fundamental interaction. - **Loop Quantum Gravity**: Emphasizes the discrete geometric structure of spacetime, where gravity originates from quantized area operators of spin network nodes ([10]). Although compatible with thermodynamic behavior, it does not explicitly classify gravity as an entropic force. - **Causal Set Theory**: Emerges continuous spacetime from a discrete causal structure, where gravitational behavior is realized through history summation and geometric fluctuations. It is naturally compatible with the holographic principle, but its specific mechanism differs from the entropic force hypothesis.

Although these theories follow different paths, they all attempt to reconcile gravity with quantum mechanics, and some are compatible with the holographic principle. The emergent hypothesis must compete with these frameworks in terms of quantitative predictions and experimental verification to gain further academic recognition.

In summary, although the theory of emergent gravity is innovative, it remains at a hypothetical stage, needing to address internal theoretical contradictions, observational inconsistencies, and challenges from competing theories. Future development depends on more precise experimental data and a more complete mathematical framework.

Aspect of Controversy	Main Challenge	Key Reference	Status / Required Development
Entropic Force Predictions (Galactic Scales)	Systematic deviation in rotation curves ($\Delta a_{\text{radial}} \sim 30\%$)	[6]	Lacks consistency with full range of observations; needs improved modeling or incorporation of baryonic effects
Holographic Principle (Cosmological Backgrounds)	Lack of rigorous framework for FRW/de Sitter spacetimes	[17]	Speculative extension; requires mathematical formulation for realistic cosmologies
Experimental Verification	Absence of conclusive evidence for emergent features	[13]	Preliminary stage; future experiments (LISA, CMB-S4, analog simulations) needed for constraints
Theoretical Unification (e.g., with LQG or String Theory)	Different fundamental premises and mechanisms	[10], [9]	Reconciliation needed; emergent picture must demonstrate superior predictive power or encompass existing results

Table 3: Summary of Key Challenges and Controversies for the Emergent Gravity Paradigm

6 Conclusion and Outlook

Although the concept of gravity as a fundamental interaction is deeply entrenched within the Standard Model of particle physics, the systematic analysis presented in this paper suggests that gravity is more likely to originate from the macroscopic emergence of spacetime itself and its microscopic degrees of freedom. Based on the entropic force hypothesis [2] and the holographic principle [14, 4], we have argued that gravity is not mediated by gauge bosons within the framework of traditional quantum field theory, but is rather a manifestation of spacetime geometry and thermodynamic statistical properties. This fundamental difference explains the unique scaling behavior of gravity on cosmological scales—the "dilution" of its effective strength stems from the area-law distribution of degrees of freedom, whereas the observable effects of the other three fundamental forces are "suppressed" due to their locality and dependence on the expanding background spacetime. In extreme spacetime regions such as the interior of black holes, gravity's dominance as the primary physical phenomenon further supports its emergent as the "stage rather than an actor."

However, this emergent perspective remains a highly speculative theoretical framework, and its validity ultimately depends on future experimental verification and more rigorous mathematical formulation. Currently, the entropic force hypothesis shows discrepancies with observations in predicting galaxy rotation curves [6], and a rigorous foundation for the extension of the holographic principle to real cosmological backgrounds has not yet been established [12]. Furthermore, emergent models of gravity cannot yet be fully reconciled with the core tenets of quantum gravity theories (such as string theory and loop quantum gravity), which, while compatible with holography, still regard gravity as a fundamental interaction.

Future research must focus on developing testable experimental methods and more self-consistent theoretical tools. On the experimental front, the following directions could be explored: - Testing whether the gravitational constant G varies over time through high-precision measurements (e.g., using atom interferometry platforms), as suggested by its purported non-fundamental status in emergent theories; - Performing systematic comparisons between holography-derived modifications and the predictions of General Relativity using cosmic microwave background radiation and large-scale structure surveys (e.g., data from the *Euclid* satellite); - Simulating spacetime thermodynamic behavior in laboratory systems, for instance by tuning entanglement entropy and interaction strength in cold atomic systems [13], to construct analog models such as acoustic black holes.

On the theoretical front, the following challenges urgently need to be addressed: - Establishing a formulation of holographic duality in dynamic spacetimes (e.g., FRW metrics), clarifying its compatibility with local quantum field theory; - Systematically comparing and integrating the emergent gravity framework with quantum gravity theories (e.g., AdS/CFT correspondence, loop quantum gravity), particularly reconciling their differing predictions regarding the information paradox and the singularity problem; - Developing numerical relativity tools that incorporate parameterized quantum gravity corrections (e.g., a curvature upper limit $R_{\max} \sim L_P^{-2}$ and a metric fluctuation amplitude $\Delta g_{\mu\nu} \in [0,1]$) to test the stability of geometric emergence conditions under extreme circumstances.

Ultimately, if the emergent theory of gravity is confirmed, it will profoundly reshape our understanding of spacetime, matter, and their interactions, and open new pathways for addressing the cosmological constant problem [18] and the nature of dark energy [19]. Interdisciplinary collaboration—especially integration with condensed matter physics, quantum information, and high-energy physics—will be key to advancing this paradigm.

Remark

The translation of this article was done by Deepseek, and the mathematical modeling and the literature review of this article were assisted by Deepseek.

References

[1] Jacobson, Ted. "Thermodynamics of Spacetime: The Einstein Equation of State." *Physical Review Letters* 75, no. 7 (1995): 1260–1263.

[2] Verlinde, Erik P. "On the Origin of Gravity and the Laws of Newton." *Journal of High Energy Physics* 2011, no. 4 (April 2011): 29.

[3] 't Hooft, Gerard. "Dimensional Reduction in Quantum Gravity." *arXiv preprint gr-qc/9310026* (1993).

[4] Susskind, Leonard. "The World as a Hologram." *Journal of Mathematical Physics* 36, no. 11 (1995): 6377–6396.

[5] Bekenstein, Jacob D. “Black Holes and Entropy.” *Physical Review D* 7, no. 8 (1973): 2333–2346.

[6] Trujillo, Ignacio, et al. “A Test of Emergent Gravity Using Ultra-Diffuse Galaxies.” *Astronomy & Astrophysics* 618 (2018): A48.

[7] Peebles, P. J. E. *Principles of Physical Cosmology*. Princeton: Princeton University Press, 1993.

[8] Parker, Leonard. “Particle Creation in Expanding Universes.” *Physical Review Letters* 21, no. 8 (1968): 562–564.

[9] Maldacena, Juan. “The Large N Limit of Superconformal Field Theories and Supergravity.” *Advances in Theoretical and Mathematical Physics* 2, no. 2 (1998): 231–252.

[10] Rovelli, Carlo. *Quantum Gravity*. Cambridge: Cambridge University Press, 2004.

[11] Mathur, Samir D. “The Fuzzball Proposal for Black Holes: An Elementary Review.” *Fortschritte der Physik* 53, no. 7–8 (2005): 793–827.

[12] Bousso, Raphael. “The Holographic Principle.” *Reviews of Modern Physics* 74, no. 3 (2002): 825–874.

[13] Hu, Bei-Lok. “Can Spacetime Be a Condensate?” *International Journal of Theoretical Physics* 48, no. 4 (2009): 905–928.

[14] ’t Hooft, Gerard. “Dimensional Reduction in Quantum Gravity.” arXiv preprint gr-qc/9310026 (1993).

[15] Maldacena, Juan Martin. “The Large-N Limit of Superconformal Field Theories and Supergravity.” *International Journal of Theoretical Physics* 38, no. 4 (1999): 1113–1133.

[16] Almheiri, Ahmed, et al. “Black Holes: Complementarity or Firewalls?” *Journal of High Energy Physics* 2013, no. 2 (2013): 1–20.

[17] Witten, Edward. “Anti-de Sitter Space and Holography.” *Advances in Theoretical and Mathematical Physics* 2, no. 2 (1998): 253–291.

[18] Padmanabhan, T. “Cosmological Constant—the Weight of the Vacuum.” *Physics Reports* 380, no. 5-6 (2003): 235–320.

[19] Li, Mingzhe. “A Model of Holographic Dark Energy.” *Physics Letters B* 603, no. 1-2 (2004): 1–5.

Appendix A: Formal Statement of Core Definitions, Axioms, and Theorems

This appendix aims to provide precise definitions of key concepts relied upon in the main text and to formally state the fundamental assumptions (axioms) and derived conclusions (theorems).

A.1 Definitions

a) **Gravity as an Entropic Force:** Let S be the entropy of a holographic screen (e.g., Hubble horizon or black hole event horizon). The entropy change caused by the displacement Δx of a test mass m relative to this screen is defined as $\Delta S = 2\pi k_B \frac{mc}{\hbar}\Delta x$. The entropic force F emerging from this entropy change is then defined by:

$$F = T\frac{\Delta S}{\Delta x}$$

where T is the Unruh temperature of the screen, $T = \frac{\hbar a}{2\pi c k_B}$, and a is the acceleration.

b) **Holographic Degrees of Freedom:** The total amount of physical information (in bits) contained within a spatial region $\mathcal{V}$ is proportional to the area of its boundary $\partial\mathcal{V}$, not its volume. Its number is given by:

$$N_{\text{dof}} = \frac{A(\partial\mathcal{V})}{4L_P^2} = \frac{A(\partial\mathcal{V})c^3}{G\hbar}$$

where A is the area, and L_P is the Planck length.

A.2 Axioms (Postulates)

a) **Axiom of Spacetime Thermodynamics:** Any causal horizon in spacetime possesses an entropy proportional to its area, $S = \frac{k_B A}{4L_P^2}$, and a temperature T proportional to its surface gravity. The Einstein field equations are the necessary consequence of this thermodynamic system tending towards thermodynamic equilibrium (i.e., entropy maximization).

b) **Axiom of Holographic Principle:** All physical information of a gravitational system can be completely described by a quantum theory without gravity encoded on its boundary. Local phenomena within the bulk spacetime are emergent from the correlations in the boundary theory.

A.3 Theorems and Lemmas

a) **Theorem T1 (Emergence of Newton's Law of Gravitation): Given:** The definition of entropic force (A.1.a) and the Axiom of Spacetime Thermodynamics (A.2.a). **It can be proven that:** The gravitational force between two masses M and m satisfies the form of Newton's law of universal gravitation $F = G\frac{Mm}{r^2}$, where the gravitational constant G is a derived constant composed of more fundamental constants $G = \frac{c^3 L_P^2}{\hbar}$.

b) **Lemma L1 (Dilution of Gravity on Cosmological Scales): Given:** The definition of holographic degrees of freedom (A.1.b) and the evolution of the cosmological horizon area $A_H = 4\pi R_H^2$ with the cosmic scale factor $a(t)$. **It can be proven that:** The effective density of gravitational degrees of freedom per unit comoving volume n_{grav} decays with cosmic expansion, i.e., $n_{\text{grav}} \propto R_H^{-1}$, whose decay law differs from that of the matter energy density $\rho_m \propto a^{-3}$.

Appendix B: Comprehensive Simulation Experimental Method Framework

This appendix provides a multi-level, multi-method simulation verification framework to test different aspects of the emergent gravity hypothesis.

B.1 Galaxy Scale: Comparative Testing of Modified Gravity and Dark Matter Models

- **Objective:** To test the predictive power of entropic force theory (or MOND) versus the Lambda-CDM model in the low-acceleration regime ($a \ll a_0$).
- **Methods:**
  1. **Data Input:** Obtain the stellar/gas surface brightness distribution $\Sigma(r)$ and high-resolution rotation curve data $v_{\text{obs}}(r)$ for a large sample of galaxies from databases like SPARC.
  2. **Model Construction:**
     - **Entropic Force/MOND Model:** Numerically solve the modified Poisson equation $\nabla \cdot [\mu(|\nabla\Phi|/a_0)\nabla\Phi] = 4\pi G\rho_{\text{baryon}}$ based on the baryonic matter distribution $\Sigma(r)$ to obtain the gravitational potential $\Phi(r)$, and then calculate the predicted rotational velocity $v_{\text{pred}}(r) = \sqrt{r|\partial\Phi/\partial r|}$.
     - **Lambda-CDM Model:** On the basis of baryonic matter, add Navarro-Frenk-White (NFW) dark matter halo model parameters (e.g., mass M_{200}, concentration c) to fit $v_{\text{pred}}(r)$.
  3. **Bayesian Fitting and Comparison:** Use Markov Chain Monte Carlo (MCMC) methods to constrain the parameters of both models. Use Bayesian Evidence or information criteria (e.g., AIC, BIC) to objectively compare the goodness-of-fit and simplicity of the two models against the data.
  4. **Output:** Posterior parameter distributions, model evidence ratios, and systematic patterns of fitting residuals across different galaxy types.

B.2 Cosmological Scale: Constraints on Holographic Dark Energy and CPL Parameterization

- **Objective:** To test holographic principle-inspired dark energy models (e.g., $\rho_{DE} \propto R_H^{-2}$) using cosmological observational data.
- **Methods:**
  1. **Theoretical Model:** Incorporate the equation of state $w(z)$ of the Holographic Dark Energy (HDE) model into the framework of cosmological perturbation theory.
  2. **Data:** Jointly utilize the Planck cosmic microwave background (CMB) power spectrum, DESI/VLT BAO distance scale measurements, and the Pantheon+ type Ia supernova distance modulus dataset.
  3. **Parameter Estimation:** Use cosmological Monte Carlo codes (e.g., `CLASS` + `MontePython`) to perform global MCMC fitting for the HDE model parameters (e.g., initial energy density parameter Ω_{DE}^0) and standard cosmological parameters.
  4. **Comparative Analysis:** Compare the fitting results of the HDE model with the standard ΛCDM model and the general parameterization for dynamic dark energy (e.g., CPL parameterization $w(a) = w_0 + w_a(1 - a)$), assessing their ability to alleviate tensions such as H_0 and S_8.

B.3 Quantum Gravity Simulation: Design of an Entanglement-Based Spacetime Emergence Platform

- **Objective:** To simulate spacetime thermodynamics and area-law entropy in controlled quantum many-body systems.
- **Platform:** Ultracold atoms in optical lattices, ion traps, or structured waveguides.
- **Design Scheme:**
  1. **System Preparation:** Prepare a quantum many-body state with long-range entanglement (e.g., a lattice approximation of a CFT vacuum state).
  2. **Observables:**
     - **Entanglement Entropy Measurement:** Directly measure the entanglement entropy S_A of a subsystem A through quantum state tomography or correlation functions of measurable quantities, verifying whether it follows the area law $S_A \propto |\partial A|$ rather than the volume law.
     - **Response Function:** Introduce a ”test particle” (e.g., a local potential well or an impurity atom) into the system and measure the system’s response to its motion. Analyze whether this response resembles a ”force” related to an entropy gradient within an effective ”spacetime geometry”.
  3. **Parameters:** Tune the system’s interaction strength U/J and temperature T to observe the emergence conditions and critical points of area-law behavior and gravitational-like responses.

Appendix C: Supplementary Mathematical Derivations

This appendix provides key mathematical derivations that were omitted or not fully detailed in the main text.

C.1 Framework for Holographic Derivation of the Friedmann Equations

Start from the holographic principle, treating the universe's Hubble horizon as a thermodynamic system.

1.) Horizon entropy: $S_H = \frac{k_B A}{4L_P^2} = \frac{\pi k_B c^3 R_H^2}{G\hbar}$, where $R_H = c/H$ is the Hubble radius.
2.) Horizon temperature: $T_H = \frac{\hbar H}{2\pi k_B}$ (adopting the Gibbons-Hawking temperature).
3.) Energy change: Assume the universe is a closed system, and the change in its total energy $E = \rho c^2 V$ leads to a change in horizon entropy. According to the first law of thermodynamics $T_H dS_H = -dE$ (energy inflow into the horizon increases its entropy).
4.) Express dS_H and dE in terms of H, ρ, $\dot{\rho}$, etc., and substitute into the thermodynamic relation. Under appropriate approximations, the Friedmann equations including the cosmological constant can be derived. This derivation process requires explicit assumptions and approximation conditions.

C.2 Key Points in the Proof of Black Hole Thermodynamics Formulas

a) **Proof sketch for the Bekenstein-Hawking entropy formula $S = A/(4L_P^2)$:**

- Argue through the black hole no-hair theorem and the information paradox that black hole entropy must be proportional to the area.
- Calculate the thermodynamic partition function for background fields using the Euclidean path integral method, showing its dominant term is proportional to $e^{A/4}$.
- Cite string theory/fuzzball models to directly compute the number of microstates Ω, proving $S = k_B \ln \Omega = A/(4L_P^2)$.

b) **Derivation of the Hawking temperature $T = \frac{\hbar\kappa}{2\pi c k_B}$:**

- Calculate the mode expansion of quantum fields in the Schwarzschild spacetime background via Bogoliubov transformation, finding that an observer outside the horizon sees a thermal radiation spectrum.
- Compute the temperature of this thermal radiation spectrum, showing it is proportional to the surface gravity κ.