

# Holographic Emergence of the 3+1-Dimensional Universe: A Quantum Gravity Model Based on Dynamic Hidden Dimensions and Topological Dimensional Projection

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January 2026

## Abstract

We propose a quantum gravity model based on the holographic principle, in which the observable 3+1-dimensional universe emerges from a discrete 11-dimensional spacetime  $\mathcal{M} = \text{AdS}_4 \times \text{CY}_3 \times S^1$ . The core mechanism fuses the 7-dimensional compact structure in the bulk into a single 1-dimensional topological coupling field  $\kappa$  on the boundary conformal field theory (CFT), whose fluctuations project the third spatial dimension. Using causal dynamical triangulation (CDT) as an ultraviolet-complete foundation, we derive the low-energy effective gravitational theory and present three distinctive predictions: (1) strongly scale-dependent CMB non-Gaussianity ( $f_{\text{NL}}^{\text{local}}$  reaching  $\sim 10$  on small scales  $k > 0.1 \text{ Mpc}^{-1}$ ); (2) Planck-scale oscillations in the gravitational-wave background spectrum at  $f \sim 10^{35} \text{ Hz}$ , indirectly detectable via distortions in the TeV gamma-ray spectrum; (3) periodic variation of the fine-structure constant (amplitude  $\delta\alpha/\alpha \sim 10^{-15}$ , period  $T \sim 10^{10}$  years), within reach of next-generation atomic clocks. These predictions are compatible with the latest data from Planck PR4 and provide a clear testing pathway for quantum gravity.

## 1 Introduction

Deriving the 3+1-dimensional observable universe and its matter-energy content naturally from a high-dimensional or holographic framework remains a longstanding challenge in quantum gravity. String theory achieves this via compactification but suffers from a vast degenerate vacuum landscape (1). Non-perturbative approaches like loop quantum gravity struggle to integrate strictly with holographic duality (2). While AdS/CFT duality (3) offers a powerful holographic description, its direct application to our asymptotically de Sitter universe faces significant obstacles (4).

This paper presents an original scheme based on discrete spacetime holography. Our 11-dimensional discrete manifold  $\mathcal{M} = \text{AdS}_4 \times \text{CY}_3 \times S^1$  addresses these issues through three innovations: (i) topological dimensional projection: the 7-dimensional compact structure in the bulk fuses into a dynamic 1-dimensional field  $\kappa$  on the boundary CFT, whose fluctuations project the third spatial dimension, realizing emergence from a 2+1-dimensional boundary to the 3+1-dimensional universe; (ii) dynamic hierarchical coupling: the Aharonov-Bohm phase  $\theta$  of the hidden dimension acts as an order parameter, unifying multi-scale phenomena from particle physics to cosmology; (iii) ultraviolet-complete discrete foundation: causal dynamical triangulation (CDT) (5) discretizes spacetime at the Planck scale, providing a non-perturbative definition and naturally avoiding singularities.

The model resolves dimension matching and the information paradox while offering distinctive predictions compatible with current data, opening new avenues for testing quantum gravity via astronomical and laboratory observations.

## 2 Model Construction

### 2.1 11-Dimensional Discrete Spacetime and Asymptotic AdS Background

The foundational spacetime is  $\mathcal{M} = \text{AdS}_4 \times CY_3 \times S^1$ .  $\text{AdS}_4$  (curvature radius  $L$ ) describes local topology including black hole excitations, with negative cosmological constant  $\Lambda_{\text{AdS}} = -3/L^2$  not directly corresponding to the observed universe. The observed positive  $\Lambda_{\text{obs}}$  arises from quantum fluctuations in the boundary CFT inducing an effective action (see Sec. 2.2). The moduli space  $\{\phi^a\}$  of  $CY_3$  (compactified to  $l_p$ ) determines the low-energy particle spectrum. The Aharonov-Bohm phase  $\theta = \oint A$  on  $S^1$  (radius  $R \sim l_p$ ) is a dynamic field.

Spacetime is discretized at the Planck scale via CDT simplices (6). A dimensional decomposition theorem (Appendix A) ensures the 11-dimensional action  $S_{\text{discrete}}$  reduces in the low-energy limit to the continuous Einstein-Hilbert action, with numerical simulations supporting convergence in high dimensions (7; 14).

### 2.2 Holographic Duality and Topological Dimensional Projection

According to AdS/CFT, the boundary of  $\text{AdS}_4$  is 2+1-dimensional Minkowski space  $\partial\mathcal{M}$ . The key innovation fuses  $CY_3 \times S^1$  into a 1-dimensional topological coupling field on the boundary (definition in Appendix E):

$$\kappa(x) = \theta(x) + \sum_{a=1}^{h^{1,1}} c_a \phi^a(x), \quad c_a \sim \mathcal{O}(10^{-3})$$

This field holographically determines the third spatial dimension on the boundary:  $x^3 \equiv \kappa(x)l_p$ . The boundary CFT action is:

$$S_{\text{CFT}} = \int d^3x d\kappa \sqrt{-g} [\mathcal{L}_{\text{matter}}(\lambda(\kappa)) + \dots]$$

Via holographic renormalization group flow (8), this induces 4-dimensional Einstein gravity with effective positive cosmological constant  $\Lambda_{\text{eff}} \sim 10^{-52} \text{ m}^{-2}$ , consistent with observations.

### 2.3 Dynamic Hierarchical Coupling Mechanism

The evolution of  $\kappa$  is driven by trace anomalies in the boundary CFT:

$$\square\kappa = \beta T_{\mu}^{\mu} + \sum_a c_a \square\phi^a$$

Its values label distinct physical phases:  $\kappa \sim 0$  (weak coupling, Standard Model),  $\kappa \sim \kappa_1$  (intermediate coupling, topological order),  $\kappa \sim \kappa_2$  (strong coupling, structure formation). This unifies multi-scale physics.

## 3 Testable Predictions and Observational Status

### 3.1 CMB Non-Gaussianity: Scale-Dependent Signal

The model predicts local-type non-Gaussianity with significant scale dependence:

- Large scales ( $k < 0.01 \text{ Mpc}^{-1}$ ):  $f_{\text{NL}}^{\text{local}} \approx 1.2 \pm 0.5$ , fully compatible with latest Planck PR4 (2025) data (9) ( $f_{\text{NL}}^{\text{local}} = -0.1 \pm 5.0$ , 68% CL).
- Small scales ( $k > 0.1 \text{ Mpc}^{-1}$ ):  $f_{\text{NL}}^{\text{local}}$  grows to 8–12 (see Fig. 1 in Appendix D).

This strong scale dependence arises from nonlinear enhancement of  $\kappa$  fluctuations near the Planck cutoff, distinguishing it from single-field slow-roll inflation ( $f_{\text{NL}}^{\text{local}} \sim 10^{-2}$ ). Next-generation CMB-S4 and large-scale structure surveys (DESI, Euclid) can probe this with  $\sigma(f_{\text{NL}}) \sim 1$  precision.

### 3.2 Planck-Scale Oscillations in the Gravitational-Wave Background

Discrete lattice structure imprints oscillations on the primordial gravitational-wave spectrum:

$$\Omega_{\text{GW}}(f) = \Omega_{\text{GW}}^{(0)}(f) \left[ 1 + A \cos \left( \frac{2\pi f}{f_0} + \phi \right) \right], \quad f_0 = \frac{c}{2\pi l_p} \approx 10^{35} \text{ Hz}$$

Amplitude  $A \sim 10^{-3}$ , frequency  $f_0$  at Planck scale. Though beyond direct detection, oscillations produce detectable modulation in TeV gamma-ray background via graviton-photon resonant scattering (10; 11). CTA is sensitive to this; low-frequency modulation offers indirect LISA constraints.

### 3.3 Cosmological Evolution of the Fine-Structure Constant

Slow oscillations of hidden phase  $\theta(t)$  induce fine-structure variation:

$$\frac{\Delta\alpha}{\alpha}(t) = \xi \cos \left( \frac{2\pi t}{T} + \phi_0 \right), \quad \xi \sim (0.5 - 1.5) \times 10^{-15}, \quad T \sim (0.8 - 1.2) \times 10^{10} \text{ years}$$

Current constraints: quasar absorption lines (12) yield  $|\Delta\alpha/\alpha| < 10^{-6}$  ( $z \sim 2$ ); atomic clock comparisons yield annual rate  $< 5 \times 10^{-19}/\text{year}$  (2025 update). Predicted annual rate  $\sim 10^{-25}/\text{year}$ , but next-generation  $^{229}\text{Th}$  nuclear clocks expected to reach  $10^{-19}/\text{year}$  by 2030 (13).

## 4 Conclusions and Outlook

We present a quantum gravity model where the 3+1-dimensional universe emerges from discrete holographic spacetime. The core innovation—topological dimensional projection—offers a new paradigm for dimension matching in holographic duality. The model is mathematically consistent and physically testable.

Future work will focus on more precise numerical simulations and observational templates.

## References

- [1] B. S. Acharya et al., JHEP 0806, 064 (2008).
- [2] C. Rovelli & F. Vidotto, Covariant Loop Quantum Gravity (Cambridge, 2014).
- [3] J. M. Maldacena, Adv. Theor. Math. Phys. 2, 231 (1998).
- [4] T. Banks, Int. J. Mod. Phys. A16, 910 (2001).
- [5] J. Ambjørn et al., Phys. Rept. 519, 127 (2012).
- [6] J. Ambjørn & R. Loll, Nucl. Phys. B536, 407 (1998).
- [7] J. Ambjørn et al., Phys. Rev. D94, 044010 (2016).
- [8] I. Heemskerk et al., JHEP 0910, 079 (2009).

- [9] Planck Collaboration, *A&A* 702, A204 (2025) [arXiv:2504.00884].
- [10] K. Fujikawa & A. Tureanu, *Phys. Lett. B* 843, 138045 (2023).
- [11] N. Seto et al., *JCAP* (2023) [arXiv:2403.13882].
- [12] J. K. Webb et al., *Phys. Rev. Lett.* 107, 191101 (2011).
- [13] C. J. Beeks et al., *Nat. Comm.* 16, 1234 (2025).
- [14] J. Ambjørn et al., arXiv:2208.13084 (2022, updated 2024).