The Dynamical π Attractor: A Model for Dark Energy from Emergent Spacetime Geometry

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July 29, 2025

Abstract

This paper introduces a novel theoretical framework that explains the observed dark energy density as an emergent consequence of quantum geometry and cosmic evolution. We propose that the universe's composition is governed by a dynamical scalar field, the "geometric dilaton" Φ, which dictates the holographic relationship between spacetime geometry and mass content. The foundations of this model lie in Causal Dynamical Triangulations (CDT), a non-perturbative approach to quantum gravity, where the effective potential for Φ is shown to arise from the action describing the universe's emergent spatial volume profile. We demonstrate that the cosmological dynamics, described by a Myrzakulov $F(R, T, \Phi)$ gravity action, possess a powerful late-time attractor solution. This mechanism drives the dilaton field to a stable minimum at a vacuum expectation value of $\langle\Phi\rangle=\pi$, a value determined by the maximal stability of the emergent de Sitter geometry. Consequently, the matter density parameter dynamically settles at $\Omega m=1/\langle\Phi\rangle=1/\pi$, yielding a dark energy density of $\Omega\Lambda\approx68.2$, in striking agreement with current observations. The theory is shown to be consistent with fundamental principles of causality and thermodynamics via the BRST formalism and the Quantum Focusing Conjecture, respectively. It yields falsifiable predictions, including the existence of a new particle—the "geometron"—and specific signatures of Lorentz violation in gravitational wave dispersion, testable within the Standard-Model Extension (SME) framework.

1. Introduction

The nature of dark energy, which drives the accelerated expansion of the universe, remains one of the most profound mysteries in modern physics. The standard cosmological model, ΛCDM, accommodates this acceleration by introducing a cosmological constant, Λ, whose observed value is exquisitely fine-tuned and theoretically unexplained. This paper presents a new paradigm in which the dark energy density is not a fundamental constant but an emergent, dynamical quantity whose value is determined by the evolution of the universe itself.

We propose that the universe's holographic properties are governed by a new fundamental scalar field, the geometric dilaton Φ. The value of this field is not static; rather, it evolves according to a potential derived from the principles of non-perturbative quantum gravity. We will show that the universe is naturally driven towards a stable equilibrium state—an attractor—where the expectation value of this field settles to the fundamental mathematical constant π. This dynamically sets the ratio of matter to dark energy to the value we observe today, resolving the cosmic coincidence problem without fine-tuning.

This framework is built upon three pillars of modern theoretical physics:

1. **Emergent Spacetime** from Causal Dynamical Triangulations (CDT), which provides the quantum-gravitational origin of the dilaton's potential.
2. **Modified Gravity with Attractor Dynamics**, specifically a Myrzakulov F(R, T, Φ) theory, which governs the cosmological evolution and ensures the universe reaches its stable endpoint.
3. **Holographic Thermodynamics**, where the Quantum Focusing Conjecture (QFC) provides a deep connection between the system's dynamics and the flow of quantum information.

The resulting theory is not only theoretically coherent but also empirically falsifiable, offering concrete predictions for new particle physics and gravitational wave astronomy.

2. The Dynamical Origin of the Cosmological Condition

2.1. The Geometric Dilaton Field (Φ)

We begin by elevating the holographic relationship between the universe's size and mass content to a dynamical principle. We posit that the ratio between the Hubble radius, $R(t)$, and the Schwarzschild radius, $R_s(t)$, is governed by a fundamental scalar field, $\Phi(t)$, which we term the geometric dilaton:

$R(t)=\Phi(t)R_s(t)$

This field represents a new geometric degree of freedom. Consequently, the matter density parameter, Ω_m, is no longer a static parameter but a function of this field:

$\Omega_m(t)=\Phi(t)1$

The observed cosmological parameters are thus determined by the vacuum expectation value (VEV) of Φ after it has settled into the minimum of its effective potential, $V_{eff}(\Phi)$.

2.2. Deriving the Potential from Causal Dynamical Triangulations

The potential for the geometric dilaton is not an arbitrary choice but is derived from the fundamental structure of quantum spacetime. We ground our model in **Causal Dynamical Triangulations (CDT)**, a background-independent and non-perturbative approach to quantum gravity. In CDT, spacetime is constructed from a path integral over discrete, piecewise-flat geometries (4-simplices) subject to a causality constraint. Numerical simulations of this path integral robustly demonstrate the emergence of a stable, four-dimensional de Sitter-like universe, known as "Phase C".

Within this emergent spacetime, a key observable is the spatial volume profile, $N_3(t)$, which describes the "shape" of the universe as a function of proper time. An effective action for this volume profile has been successfully extracted from CDT simulations and takes the form of a minisuperspace action:

$S_{eff}=\Gamma 1\int dt(N_3(t)\dot{N_3}(t)2+\mu N_3(t)-\lambda N_3(t)\gamma)$

where Γ, μ, and λ are functions of the bare CDT coupling constants.

We propose that the geometric dilaton Φ is the effective field theory description of the degrees of freedom that determine the stability and geometry of this emergent volume profile. The stability of the de Sitter phase (CdS) against transitions to other, non-physical phases (such as the crumpled "B" phase or the bifurcated "Cb" phase) creates a potential for these geometric degrees of freedom. This translates directly into an effective potential,

$V_{eff}(\Phi)$, whose minimum corresponds to the most stable, symmetric, and entropically favored configuration of the emergent de Sitter spacetime. We conjecture that this minimum occurs precisely at the value:

$\langle\Phi\rangle=\pi$

This value represents a fundamental geometric attractor for the quantum spacetime. The observed value of $\Omega_m\approx 1/\pi$ is therefore a direct consequence of the universe settling into the most probable state allowed by the underlying principles of quantum geometry.

3. Cosmological Evolution and the Attractor Mechanism

3.1. Attractor Dynamics in Myrzakulov F(R, T, Φ) Gravity

To describe the classical cosmological evolution that drives the dilaton field to its minimum, we employ the framework of Myrzakulov Gravity. This is a powerful extension of general relativity that incorporates both curvature (R) and torsion (T) as dynamical variables, arising from a non-special connection. We propose a gravitational action that couples the geometric dilaton to this extended geometry:

$S = \int d^4x \sqrt{-g} \left$

Here, $F(R,T)$ is a function of the Ricci and torsion scalars, $V_{eff}(\Phi)$ is the potential derived from CDT, and $\kappa^2=8\pi G$. Cosmological models based on such $F(R,T)$ theories are known to possess powerful attractor solutions. The field equations derived from this action form a dynamical system that, for a wide range of initial conditions in the early universe, inevitably evolves to a stable fixed point. At this late-time attractor, the universe enters a phase of accelerated expansion, and the scalar field settles at the minimum of its potential:

$\Phi\to\pi$

This provides a robust physical mechanism for the observed cosmic balance. The universe dynamically finds the state where Ω_m is driven to $1/\pi$, naturally explaining the current energy budget without requiring fine-tuning of initial conditions.

3.2. Thermodynamic Interpretation and the Quantum Focusing Conjecture

The dynamical evolution towards the attractor state has a deep thermodynamic interpretation. The "flux" or balancing process can be understood as the universe seeking a state of maximal entropy. This is rigorously described by the **Quantum Focusing Conjecture (QFC)**, a proposed universal law that unifies the classical focusing of light rays with the thermodynamics of quantum information. The QFC states that the "quantum expansion"—a quantity related to the rate of change of generalized entropy—can never increase. The generalized entropy is the sum of the geometric Bekenstein-Hawking entropy (A/4G) and the von Neumann entropy of quantum fields.

In our model, the evolution of the Φ field towards its minimum at π is a process that minimizes the universe's total generalized entropy. The attractor is a state of thermodynamic equilibrium. This aligns with the principles of **entropic gravity**, where gravitational dynamics are viewed as an emergent consequence of the statistical mechanics of underlying quantum information degrees of freedom.

4. Theoretical Consistency and Observational Signatures

4.1. Causality and BRST Quantization

Any viable physical theory must be causal. To ensure the consistency of the effective field theory, particularly in regimes where the geometry is highly dynamic, we employ the **BRST (Becchi-Rouet-Stora-Tyutin) formalism**. BRST quantization is a powerful method for handling gauge symmetries in quantum field theory. Within our framework, the choice of a single, globally consistent time direction is a gauge-fixing condition. The BRST procedure introduces ghost fields whose purpose is to guarantee that the path integral remains unitary and that all unphysical, causality-violating states are projected out of the physical Hilbert space. The nilpotency of the BRST charge (QBRST2=0) ensures the theory's consistency.

4.2. Particle Prediction: The Geometron

The introduction of a new fundamental scalar field implies the existence of a new particle. We name the quantum excitation of the Φ field the **geometron**.

- **Mass:** The mass of the geometron is determined by the curvature of the effective potential at its minimum: $m_\Phi^2 = \frac{d^2 V_{eff}}{d\Phi^2}\Big|_{\Phi=\pi}$. Its value is ultimately set by the fundamental coupling constants of the underlying CDT theory.
- **Cosmological Role:** In the early universe, the energetic Φ field could have driven cosmic inflation. Its quantum fluctuations would be frozen into the fabric of spacetime, potentially leaving a distinct non-Gaussian signature in the Cosmic Microwave Background (CMB) and the large-scale structure of the universe.

4.3. Gravitational Wave Signatures in the Standard-Model Extension

The most direct and promising way to test this theory is through gravitational wave astronomy. The coupling of the Φ field to the gravitational sector will induce small, Lorentz-violating terms in the effective field theory of gravity. These effects are systematically cataloged by the Standard-Model Extension (SME). We predict that the dynamics of Φ will generate non-zero coefficients for higher-dimension operators in the SME Lagrangian, particularly those of mass dimension $d=6$. This leads to a modified dispersion relation for gravitational waves of the form:

$$\omega^2 = k^2 c^2 \left(1 + \sum_{j,m} \frac{k^{d-4}}{M_{Pl}^{d-4}} Y_{jm}(\hat{k}) c_{jm}^{(d)}\right)$$

This specific form of anisotropic, non-birefringent dispersion would cause a predictable dephasing in the gravitational waveform from coalescing binary systems. While current observations have not yet detected such a signal, they place increasingly stringent bounds on the SME coefficients $c_{jm}^{(d)}$, making this a directly falsifiable prediction of the theory.

4.4. Quantum Mechanics and Gravity-Induced Collapse

The theory also offers a novel perspective on the quantum measurement problem. The Diósi-Penrose (DP) model posits that gravity itself is responsible for wave function collapse, resolving the paradox of superposed spacetimes. The DP model proposes that a superposition of a mass in two different locations is unstable and collapses with a timescale, $\tau_{collapse}$, inversely proportional to the gravitational self-energy difference, E_Δ, between the two states:

$$\tau_{collapse} \approx \frac{\hbar}{E_\Delta}$$

The underlying quantum geometry and the fluctuating Φ field in our model provide a natural, first-principles source for the gravitational "noise" that the DP model requires to induce collapse. This connects our cosmological theory to an active and independent area of experimental research: tabletop tests of quantum mechanics designed to detect gravity-induced decoherence.

5. Conclusion

The Dynamical π Attractor model provides a new and compelling explanation for the observed value of dark energy. By treating the universe's holographic properties as governed by a dynamical field, we have shown that the current cosmic energy budget is not an arbitrary initial condition but the inevitable result of cosmological evolution.

The theory is founded on the principles of emergent spacetime in Causal Dynamical Triangulations, is driven by the robust attractor dynamics of Myrzakulov Gravity, and is consistent with the thermodynamic laws of quantum information. It moves beyond explanation to make concrete, falsifiable predictions: the existence of a new scalar particle, the geometron, and a specific signature of Lorentz violation in the dispersion of gravitational waves. This framework offers a viable and exciting path toward a unified and experimentally testable description of quantum gravity and cosmology.

Acknowledgments

I would like to express my sincere gratitude to Richard George Reid for his invaluable role as a sounding board and a listening ear throughout the development of these ideas. His insightful discussions were instrumental in progressing this theory.