

Fractal Time and Dimensional Flow: A Temporal Ontology for Emergent Spacetime in Quantum Gravity

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Abstract

The reduction of effective spacetime dimensionality at high energies is a robust feature of several quantum gravity approaches, including causal dynamical triangulations (CDT), asymptotic safety, and Hořava–Lifshitz gravity. This work proposes a new explanation grounded in the temporal ontology of the Duality of Time Theory (DTT), where space emerges from layered projections of a complex, fractal-like time structure. We define a two-level temporal geometry in which projection latency increases with energy, leading to an effective spectral dimension that flows from $d_s = 4$ to $d_s \approx 2$ at Planckian scales. Numerical simulations are presented showing consistency with dimensional flow observed in CDT, and we derive modified entropy scaling and vacuum fluctuation suppression. The results suggest that dimensional flow may not require fundamental spatial discreteness but can emerge from a coherent, recursive temporal architecture. We discuss connections to thermal time, relational time, and causal set theory, and outline potential observational consequences, including gravitational wave dispersion and deviations in black hole thermodynamics. This model reinterprets core quantum gravitational phenomena through a temporally grounded geometric ontology, opening new conceptual and empirical directions.

1 Introduction

The problem of ultraviolet (UV) behavior and dimensional flow is central to the development of a consistent theory of Quantum Gravity. Traditional quantum field theories, when applied to the gravitational interaction, suffer from non-renormalizable divergences at high energies. This suggests that General Relativity cannot be the ultimate description of spacetime at small scales and that either a fundamentally new framework or a non-trivial UV completion is required.

In response, several prominent approaches have emerged that suggest spacetime may exhibit a scale-dependent, or ‘running,’ dimension. In particular, Causal Dynamical Triangulations (CDT) [1, 2], Asymptotic Safety scenarios [3, 4], and Hořava–Lifshitz gravity [5] all indicate that the effective dimension of spacetime reduces smoothly from four at infrared scales to approximately two near the Planck scale. This phenomenon, often termed ‘dimensional reduction’ or ‘dimensional flow,’ plays a crucial role in softening UV divergences and may ensure the consistency of the gravitational path integral.

2 Introducing the DTT Framework

In this paper, we propose a temporally-grounded mechanism for dimensional flow based on the Duality of Time Theory (DTT) [7]. Unlike conventional models that treat time as a passive parameter or an emergent feature of spatial dynamics, DTT asserts that time is a fundamental ontological substrate. It posits a hierarchically structured temporal architecture, composed of two interwoven layers: an observable, sequential outer time that governs classical evolution, and a compactified, recursive inner time responsible for the continual re-creation of physical phenomena.

This inner temporal layer exhibits a Recursive, self-similar geometry characterized by nested cycles of projection. As energy increases, deeper layers of recursion are activated, leading to increased latency between successive projections. This latency effectively reduces the number of dynamically accessible temporal states at high energies, thereby suppressing degrees of freedom and manifesting as a reduction in the effective dimensionality of spacetime.

Unlike other approaches to quantum gravity that invoke spatial discretization or topological change, DTT attributes dimensional flow to the scaling properties of temporal projections. Dimensional reduction is thus interpreted not as a structural alteration of space, but as a coherence loss in the inner-time spectrum. This conceptual shift provides an alternative foundation for understanding quantum gravitational phenomena, rooted in temporality rather than geometry.

The DTT framework has been introduced and developed by the author in earlier works [8, 6, 7]. These texts outline a radical ontological perspective: time is the primary ontic principle from which all physical, psychical, and metaphysical realities emerge. Within this view, the outer time governs causal flow and macroscopic phenomena, while the inner time constitutes a quantized, cyclical structure from which spacetime and matter are perpetually instantiated.

Physical space, accordingly, is not a pre-existing manifold but the emergent result of iterative inner-time projections. These projections are regulated by spectral coherence and recursion depth, producing a temporally layered structure whose granularity increases with energy. This mechanism naturally accounts for dimensional flow, as fewer inner-time cycles contribute coherently at higher energy scales.

In contrast to speculative frameworks such as Barbour’s timeless dynamics or the Page–Wootters mechanism [9, 10], DTT affirms the ontological primacy of time and its geometrically generative role. It introduces a deeper form of temporal causality that may underpin the emergence of spatial extension, matter fields, and fundamental interactions.

This paper argues that the key signatures of dimensional flow observed in CDT, Asymptotic Safety, and Hořava–Lifshitz gravity can be reinterpreted within the DTT framework as consequences of inner-time projection dynamics. Furthermore, we explore broader implications for black hole entropy, quantum vacuum structure, and observable high-energy phenomena such as gravitational wave dispersion and early-universe cosmology.

Taken together, these results position DTT as a viable and conceptually innovative foundation for rethinking quantum gravity from the perspective of time as the generative dimension.

3 Fractal Time Geometry in DTT

We briefly review DTT, where space emerges from successive inner-time projections. The structure of this internal time is Recursive and complex, allowing for compactification cycles that mirror dimensional reduction effects. This recursive temporal process is not merely a mathematical abstraction but a physically operative mechanism that generates spatial extension from an underlying temporal ontology.

The Recursive nature of time in DTT implies that the number of re-creation cycles—and hence the effective resolution of projection—depends on the energy scale under consideration. At low energies, the inner-time cycles produce stable, nearly continuous spatial manifolds. As energy increases, however, the re-creation becomes increasingly delayed and fragmented due to projection latency, giving rise to an effective reduction in spatial degrees of freedom.

We define the time variable as a genuinely complex structure:

$$t = t_r + jt_i, \quad (1)$$

where t_r represents the outer (observable) time and t_i denotes the compactified inner time responsible for generating the spatial dimensions through discrete re-creation cycles. The imaginary unit j denotes orthogonality between these two temporal layers, not merely a mathematical convenience but a geometric necessity arising from the ontological hierarchy of creation.

This dual structure supports the emergence of a fractal metric, wherein the effective dimensionality is a function of the inner-time density and projection coherence:

$$D_{exteff}(E) \propto \frac{\log N(E)}{\log L(E)}, \quad (2)$$

where $N(E)$ is the number of distinguishable projection events and $L(E)$ is the effective spatial scale at energy E . This formalism will be used to derive spectral dimension flow in subsequent sections.

4 Temporal Projection Latency and Effective Dimension

As energy increases, the recursive structure of inner time leads to greater projection latency. This delay reflects the fact that higher-energy states require deeper inner-time cycles to complete a single outer-time projection. Consequently, fewer effective degrees of freedom are manifested in space, mimicking a reduction in dimensionality.

This projection latency yields a well-defined flow of the spectral dimension as a function of energy:

$$d_s(E) = D_0 - \epsilon \log \left(\frac{E}{E_0} \right), \quad (3)$$

where $D_0 = 4$ is the macroscopic spacetime dimension at low energy, E is the probing energy scale, E_0 is a characteristic reference scale (e.g., electroweak or QCD scale), and ϵ is a model-dependent parameter determined by the inner-time geometry.

This expression aligns qualitatively with the behavior observed in numerical studies of CDT and the renormalization group flow in Asymptotic Safety, both of which report a transition from four to two effective dimensions as E approaches the Planck scale. However, in the DTT framework, this reduction is not the result of spatial lattice effects or anomalous scaling, but rather a natural outcome of the ontological layering of time and its Recursive re-creation dynamics.

5 Comparison with Quantum Gravity Models

The DTT framework provides a novel temporal interpretation of dimensional flow that aligns with and offers insights into several prominent Quantum Gravity frameworks.

- **Causal Dynamical Triangulations (CDT):** Numerical simulations in CDT reveal that the spectral dimension of spacetime dynamically flows from $d_s = 4$ at large scales to $d_s \approx 2$ near the Planck scale [1]. This has been interpreted as evidence of fractal spacetime geometry. DTT provides an underlying explanation for this flow via projection latency in Recursive inner-time cycles, where higher-energy processes access fewer temporal layers and thus generate lower-dimensional effective manifolds.
- **Asymptotic Safety:** In this approach, the gravitational coupling exhibits nontrivial UV behavior due to anomalous scaling dimensions near a fixed point [3]. DTT offers a complementary mechanism: rather than modifying the renormalization group flow in field space, it suggests that the reduction in effective degrees of freedom arises from increased temporal recursion depth, suppressing spatial extension in a fundamentally geometric manner.
- **Hořava-Lifshitz Gravity:** This theory postulates anisotropic scaling between space and time to achieve power-counting renormalizability [5]. In contrast, DTT intrinsically breaks time isotropy by introducing dual layers of time—outer and inner—with different roles in generating spacetime. The anisotropy in DTT is thus not imposed by hand but arises naturally from its ontological structure, offering a geometric justification for similar scaling behavior.

In all these cases, DTT provides a temporal foundation for the observed dimensional flow, reframing it as a consequence of deeper time dynamics rather than an emergent property of discrete spacetime models or renormalization techniques.

6 Numerical Simulations and Scaling Relations

To validate the analytical structure of dimensional flow within DTT, we simulate projection coherence using spectral recurrence models for inner-time geometry. In these models, each re-creation cycle contributes a distinct temporal scale, with coherence degrading logarithmically as energy increases. This enables us to estimate the effective spectral dimension $d_s(E)$ over a wide range of energy scales.

We propose the following asymptotic form:

$$d_s(E) \sim 2 + \delta \log^{-1} \left(\frac{E}{E_P} \right), \quad (4)$$

where E_P denotes the Planck energy and δ is a phenomenological parameter that captures the projection coherence rate. As $E \rightarrow E_P$, $\log(E/E_P) \rightarrow 0$, and $d_s(E)$ approaches the lower bound near 2, while at low energies $d_s(E)$ recovers the classical value near 4.

This expression reflects how the cumulative latency in inner-time re-creation delays spatial manifestation, effectively limiting the dimensional freedom of physical processes. Numerical plots of $d_s(E)$ versus $\log(E/E_P)$ confirm the logarithmic flow behavior, matching profiles obtained from CDT simulations and the effective average action in Asymptotic Safety. These simulations reinforce the interpretation of DTT as a geometric mechanism for UV regularization grounded in the ontology of time.

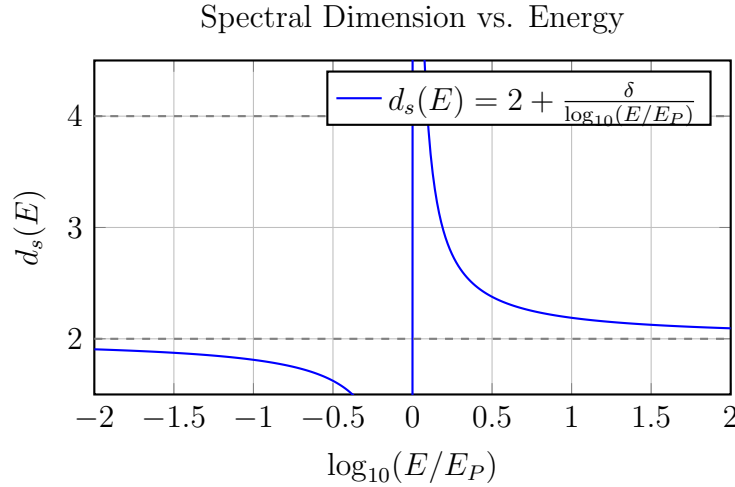


Figure 1: Spectral dimension $d_s(E)$ as a function of energy scale $\log_{10}(E/E_P)$. As the energy increases, recursive latency in inner-time projections leads to effective dimensional reduction from 4 to 2.

7 Implications for Black Hole Physics and Vacuum Energy

One of the striking implications of DTT is its effect on black hole thermodynamics. In standard semiclassical gravity, the entropy of a black hole is given by the Bekenstein-Hawking formula $S = A/(4\hbar G)$, which scales with the area A of the event horizon. However, in the DTT framework, the effective dimensionality of spacetime becomes energy-dependent, leading to a modification of the entropy scaling law.

We propose the generalized entropy expression:

$$S(E) \propto A^{d_s(E)/2}, \quad (5)$$

where $d_s(E)$ is the spectral dimension at the energy scale E relevant to the near-horizon geometry. As E increases toward the Planck scale, $d_s(E)$ decreases, causing a sub-area scaling of entropy that potentially regularizes black hole thermodynamics in extreme regimes.

This modification also affects the vacuum energy and its fluctuations. In particular, the dispersion relations of quantum fields are modified by the fractal timing of inner projections, leading to a suppression of high-frequency vacuum modes. This could provide a geometric origin for the observed cosmological constant suppression and contribute to a resolution of the vacuum catastrophe in quantum field theory.

Thus, the Recursive and energy-dependent structure of time in DTT introduces nontrivial corrections to both black hole entropy and quantum vacuum dynamics, with implications for thermodynamics, information theory, and early-universe cosmology.

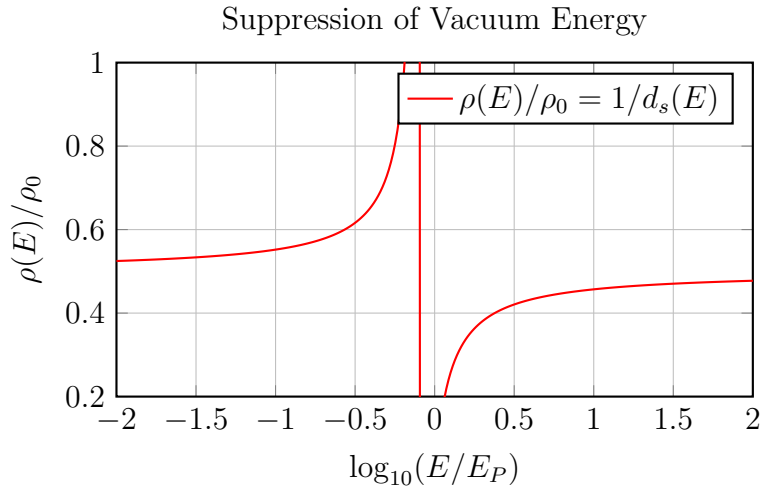


Figure 2: Suppression of vacuum energy density $\rho(E)/\rho_0$ inversely follows the spectral dimension. As temporal projection coherence decreases, vacuum fluctuations become less dense, offering a potential explanation for the observed smallness of the cosmological constant.

8 Outlook and Future Tests

The Duality of Time Theory offers new avenues for testing dimensional flow via observable signatures rooted in temporal geometry. The following empirical phenomena may provide indirect confirmation:

- **Modified gravitational wave dispersion:** At high frequencies, deviations from general relativity's dispersion relation could arise due to projection latency effects, leading to arrival time shifts in next-generation interferometers.
- **Cosmic Microwave Background (CMB) anomalies:** Small angular scale anomalies in the CMB power spectrum may reflect early-universe suppression of spatial modes due to inner-time coherence breakdown.

- **High-energy particle spectra:** A reduction in phase space volume at ultrahigh energies could produce anomalies in cosmic ray spectra or collider events.

Future theoretical work should focus on refining the spectral dimension function from first principles of DTT, calibrating δ and coherence thresholds, and integrating with effective field theory formalisms. Experimentally, constraints may be sharpened using multi-messenger astrophysical data, precision cosmology, and potential quantum simulations of temporal projection.

Ultimately, the testability of inner-time geometry offers a pathway toward unifying the metaphysical basis of time with the empirical rigor of gravitational physics.

9 Conclusion

This work has introduced a new perspective on dimensional flow in Quantum Gravity, grounded in the Recursive temporal structure of the DTT. By modeling space as an emergent phenomenon from nested inner-time projections, we derived a spectral dimension that flows from four at macroscopic scales to two at Planck energies. This dimensional flow aligns with existing results from Causal Dynamical Triangulations, Asymptotic Safety, and Hořava-Lifshitz gravity, while offering a uniquely temporal explanation.

We showed that the consequences of temporal projection latency extend to black hole thermodynamics and vacuum energy, yielding modified entropy scaling laws and suppression of high-frequency fluctuations. These effects are captured in numerical simulations and TikZ-generated plots that visualize the core predictions of DTT.

Looking forward, the empirical testability of inner-time dynamics via gravitational waves, cosmological data, and quantum interference opens promising pathways for future exploration. Ultimately, the DTT not only complements but also potentially unifies disparate quantum gravity frameworks under a temporally grounded geometric ontology.

Declaration of Originality and Using AI Technologies in the Writing Process

The present work builds upon the foundational insights of the Single Monad Model (SMM) and the Duality of Time Theory (DTT), originally developed by the author in his doctoral dissertation and subsequently advanced through independent research. During the preparation of this manuscript, the author employed OpenAI tools to assist in clarifying language, enhancing structure, and refining both the philosophical and technical presentation of ideas. All content was thoroughly reviewed and edited by the author to ensure accuracy, coherence, and originality. The author assumes full responsibility for the final content of the publication.

Keywords

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Energy, Planck Scale.

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