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Branching Fractal p-adic Reality as a Replacement for Minkowski Spacetime and Hamiltonian Dynamics

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ABSTRACT

The incompatibility between relativistic spacetime geometry and Hamiltonian quantum dynamics imposes a persistent barrier to a unified physical theory, consuming substantial research resources and limiting predictive power in high-energy and cosmological regimes. Existing frameworks assume an Archimedean continuum and linear time evolution, leaving the structural origin of quantum-gravitational tension unexplained. We formulate a Wheeler–DeWitt-type equation on an infinite rooted p -adic tree, derive its branching solutions, and demonstrate that a coarse-grained limit reproduces approximate Lorentzian geometry and Schrödinger-type evolution. Using the p -adic fractal-string tube formula of Lapidus et al. [2] we compute the Minkowski dimension of the 3-adic Cantor string as $D = \log 2 / \log 3 \approx 0.63093$, and from the p -adic ball volume $V(p^{-n}) = p^{-n}$ we obtain explicit inner-tube volumes. We also derive the first and second moments of the p -adic norm on $\mathbb{Z}_p$, obtaining $\mathbb{E}[|x|_p] = 1/(p+1)$ and $\mathbb{E}[|x|_p^2] = 1/(p^2 + p + 1)$. These results show that a non-Archimedean ultrametric configuration space can encode both geometric oscillations and branching causal structure. If correct, the proposal reinterprets “time” as an epistemic artifact, redirects theoretical effort toward ultrametric dynamics, and suggests concrete experimental signatures in ultrafast dispersion measurements.

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Abstract

The incompatibility between relativistic spacetime geometry and Hamiltonian quantum dynamics imposes a persistent barrier to a unified physical theory, consuming substantial research resources and limiting predictive power in high-energy and cosmological regimes. Existing frameworks assume an Archimedean continuum and linear time evolution, leaving the structural origin of quantum-gravitational tension unexplained. We formulate a Wheeler–DeWitt-type equation on an infinite rooted p -adic tree, derive its branching solutions, and demonstrate that a coarse-grained limit reproduces approximate Lorentzian geometry and Schrödinger-type evolution. Using the p -adic fractal-string tube formula of Lapidus et al. [2] we compute the Minkowski dimension of the 3-adic Cantor string as $D = \log 2 / \log 3 \approx 0.63093$, and from the p -adic ball volume $V(p^{-n}) = p^{-n}$ we obtain explicit inner-tube volumes. We also derive the first and second moments of the p -adic norm on $\mathbb{Z}_p$, obtaining $\mathbb{E}[|x|_p] = 1/(p+1)$ and $\mathbb{E}[|x|_p^2] = 1/(p^2 + p + 1)$. These results show that a non-Archimedean ultrametric configuration space can encode both geometric oscillations and branching causal structure. If correct, the proposal reinterprets “time” as an epistemic artifact, redirects theoretical effort toward ultrametric dynamics, and suggests concrete experimental signatures in ultrafast dispersion measurements.

1. Introduction

Physicists worldwide invest extensive resources in reconciling quantum mechanics with general relativity, yet the prevailing reliance on a smooth Minkowski manifold and Hamiltonian time evolution yields persistent anomalies such as non-renormalizable gravity and the measurement problem. The cost of this impasse is reflected in large research programs and in the inability to design technologies that exploit quantum-gravitational effects, for example in precision

navigation or quantum-enhanced metrology. A decisive change would occur if the underlying spacetime geometry and dynamical law were shown to be emergent from a deeper, non-Archimedean structure in which “time” is not fundamental but an epistemic construct.

In this paper we propose that ontic reality is a branching p -adic fractal, i.e. an infinite rooted p -ary tree equipped with the ultrametric p -adic norm. Minkowski spacetime and Hamiltonian dynamics then appear as coarse-grained approximations. We develop the mathematical framework, derive concrete quantitative properties, and outline experimental pathways.

Contributions.

1. Formulation of a Wheeler–DeWitt equation on a p -adic tree and derivation of its branching solutions (Section 3).
2. Computation of the Minkowski dimension $D = \log 2 / \log 3 \approx 0.63093$ for the 3-adic Cantor string using the tube formula of [2] (Section 4).
3. Explicit inner-tube volume $V(p^{-n}) = p^{-n}$ for a p -adic ball derived from the definition of the p -adic absolute value in [1] (Section 4).
4. Demonstration that coarse-graining yields an effective Lorentzian metric and Schrödinger-type evolution (Section 5).
5. Exact derivation of the first and second moments of the p -adic norm on $\mathbb{Z}_p$, yielding $\mathbb{E}[|x|_p] = 1/(p+1)$ and $\mathbb{E}[|x|_p^2] = 1/(p^2 + p + 1)$ (Section 4).
6. Identification of falsifiable experimental signatures and a concrete next-step prototype (Section 7).

2. Background and Related Work

The p -adic absolute value $|\cdot|_p$ maps $\mathbb{Q}$ to $[0, \infty)$ by $|x|_p = p^{-v}$ for $x = p^v a/b$ with $p \nmid a, b$ (Definition in § 2.1 of [1]). This norm satisfies the strong triangle inequality $|x + y|_p \leq \max\{|x|_p, |y|_p\}$, establishing an ultrametric geometry that lacks the Archimedean property (see § 2.1 of [1]).

Exact tube formulas for p -adic fractal strings express the volume of inner ε -neighbourhoods in terms of complex dimensions. Using these formulas, Lapidus et al. derived explicit Minkowski contents for self-similar strings, including the 3-adic Cantor string (Section 1 of [2]).

The three-state p -adic Potts model on a Cayley tree exhibits a phase transition only when $p = 3$, regardless of interaction strength (Conclusion of [3]). This demonstrates that branching structures on p -adic trees can generate non-trivial macroscopic phenomena tied to the prime p .

A p -adic description of the Higgs mechanism introduces a p -adic square-root function whose convergence radius is non-zero for $p > 2$, and defines a p -adic light cone with radius $N_p(t) = p^k$ (Section 2.1 of [4]). The associated dimensionality $D = 4$ for $p > 2$ provides a concrete link between ultrametric geometry and spacetime-like structures.

The canonical correspondence between p -adic and real numbers maps a p -adic expansion $y = \sum_{k \geq N} y_k p^k$ to a real number $x = \sum_{k \geq N} y_k p^{-k}$, establishing a continuous bridge between the two domains (Section 3 of [5]).

A comparative survey of p -adic fractal strings highlights the role of geometric zeta functions and complex dimensions in generating oscillatory volume terms, directly relevant to the proposed branching dynamics (Section 1 of [6]).

Inequality (1) in [7] bounds the number n of p -adic γ -equiangular lines in $\mathbb{Q}_p^d$ by $|n|^2 \leq |d| \max\{|n|, \gamma^2\}$, illustrating how ultrametric linear algebra imposes quantitative constraints on configurations that may appear in a p -adic field theory.

We assume the Haar measure is normalized so that $\mu(B(0, 1)) = 1$, which implies $\mu(B(0, p^{-n})) = p^{-n}$; this fact directly leads to the inner-tube volume formula (9). Building on this, Lapidus et al. in [2] derived exact tube formulas for p -adic self-similar strings, showing that the volume of an inner ε -neighbourhood can be expressed as a sum over complex dimensions; their Section 1 provides the concrete example of the 3-adic Cantor string; we compute its Minkowski dimension in (7)–(8) from the similarity relation.

The three-state p -adic Potts model on a Cayley tree, examined in [3], demonstrates a sharp phase transition that occurs only for the prime $p = 3$, regardless of interaction strength. This result, stated in the conclusion of [3], supports the hypothesis that the choice of prime may be physically significant, a theme echoed in the present work's focus on $p = 3$ for the Cantor string analysis.

In the context of gauge theories, [4] introduces a p -adic square-root function with a non-zero radius of convergence for $p > 2$ and defines a p -adic light cone $N_p(t) = p^k$ in Section 2.1. The associated dimensionality $D = 4$ for $p > 2$ provides a concrete bridge between ultrametric geometry and the four-dimensional spacetime of relativistic physics, reinforcing the plausibility of emergent Lorentzian metrics from p -adic structures.

The canonical correspondence between p -adic and real numbers described in [5] (Section 3) maps a p -adic expansion $y = \sum_{k \geq N} y_k p^k$ to a real number $x = \sum_{k \geq N} y_k p^{-k}$, establishing a continuous bridge that justifies the coarse-graining procedure of Section 4, where discrete levels on the tree are related to continuous spacetime coordinates.

A broader perspective on p -adic fractal strings is offered by the comparative survey in [6] (Section 1), which highlights the role of geometric zeta functions and complex dimensions in generating oscillatory volume terms. This survey contextualizes the tube-formula calculations performed here and underscores the universality of the oscillatory phenomena across different p -adic constructions.

Returning to the inequality from [7], the bound $|n|^2 \leq |d| \max\{|n|, \gamma^2\}$ quantifies how the number of equiangular lines is limited by the dimension d of the underlying p -adic vector space and the angular parameter γ , illustrating the restrictive nature of ultrametric linear algebra in potential field-theoretic applications.

For completeness, we present an explicit derivation of the characteristic polynomial roots for arbitrary prime p . Starting from (4), $p\lambda^2 - (p+1)\lambda + 1 = 0$, the quadratic formula gives

$$\lambda_{\pm} = \frac{(p+1) \pm \sqrt{(p+1)^2 - 4p}}{2p}.$$

Expanding the discriminant yields $(p+1)^2 - 4p = p^2 - 2p + 1 = (p-1)^2$, so $\sqrt{(p-1)^2} = |p-1| = p-1$ for $p > 1$. Hence

$$\lambda_+ = \frac{(p+1) + (p-1)}{2p} = \frac{2p}{2p} = 1, \quad \lambda_- = \frac{(p+1) - (p-1)}{2p} = \frac{2}{2p} = \frac{1}{p}.$$

Thus the general solution (3) simplifies to $\psi_n = A + Bp^{-n}$, a form that reduces to (5)–(6) for $p = 2$ and underlies the flat and decaying modes discussed in Section 3.

Finally, the derivation of the first and second moments of the p -adic norm in (11)–(12) can be made fully explicit. The Haar measure of the annulus $\{x : |x|_p = p^{-k}\}$ is $(1 - 1/p)p^{-k}$, as follows from the measure of $B(0, p^{-k})$ minus that of $B(0, p^{-k-1})$. Summing over $k \geq 0$ gives

$$\mathbb{E}[|x|_p] = \sum_{k=0}^{\infty} p^{-k} (1 - 1/p) p^{-k} = \left(1 - \frac{1}{p}\right) \sum_{k=0}^{\infty} p^{-2k} = \frac{1 - 1/p}{1 - p^{-2}} = \frac{1}{p+1},$$

and similarly

$$\mathbb{E}[|x|_p^2] = \left(1 - \frac{1}{p}\right) \sum_{k=0}^{\infty} p^{-3k} = \frac{1 - 1/p}{1 - p^{-3}} = \frac{1}{p^2 + p + 1},$$

which confirms the compact expressions quoted in (11)–(12). These detailed steps reinforce the robustness of the moment calculations and their dependence solely on the Haar measure properties established in [1].

Finally, the construction of p -adic multiple L -functions provides analytic tools for handling p -adic measures and series, which are employed in the derivation of the tube formulas used herein (Section 1 of [8]).

3. Methods

3.1 Configuration Space

We model ontic reality as the set $\mathcal{T}_p$ of vertices of an infinite rooted p -ary tree. Each vertex v has p children $v_1, \dots, v_p$ and a unique parent $\text{par}(v)$, except the root r . The ultrametric distance between two vertices is $d(v, w) = p^{-\text{depth}(\text{lca}(v, w))}$, where lca denotes the lowest common ancestor. This distance coincides with the p -adic norm on the associated coordinate representation (cf. [1]).

A wavefunction $\Psi : \mathcal{T}_p \rightarrow \mathbb{C}$ assigns a complex amplitude to each node. Physical observables are defined as functionals on Ψ .

3.2 Wheeler–DeWitt Equation on $\mathcal{T}_p$

The timeless Wheeler–DeWitt operator $\hat{H}$ is taken to be the discrete Laplacian on the tree:

$$(\hat{H}\Psi)(v) = \sum_{u \sim v} [\Psi(u) - \Psi(v)],$$

where the sum runs over the $p + 1$ neighbours (parent and p children). The constraint $\hat{H}\Psi = 0$ yields the recursion

$$(p + 1) \Psi(v) = \Psi(\text{par}(v)) + \sum_{i=1}^p \Psi(v_i). \quad (1)$$

3.3 Homogeneous Ansatz

Assuming homogeneity across levels, we set $\Psi(v) = \psi_n$ for all vertices at depth n (root at $n = 0$). Equation (1) becomes

$$(p + 1)\psi_n = \psi_{n-1} + p\psi_{n+1}, \quad n \geq 1, \quad (2)$$

with boundary condition $\psi_{-1} = 0$ (no parent above the root).

Equation (2) is a linear second-order recurrence. Solving for ψ_n yields a branching solution of the form

$$\psi_n = A \lambda_+^n + B \lambda_-^n, \quad (3)$$

where $\lambda_{\pm}$ are the roots of the characteristic polynomial

$$p \lambda^2 - (p + 1) \lambda + 1 = 0. \quad (4)$$

3.4 Coarse-Graining

To connect with emergent spacetime, we define a coarse-grained field $\Phi(t, \mathbf{x})$ by averaging Ψ over all vertices within a ball of radius p^{-N} at depth N . In the limit $N \rightarrow \infty$ the discrete recursion (2) yields a differential equation that approximates the Schrödinger equation with an effective mass proportional to p (derivation in Section 4).

4. Analysis

4.1 Node Counting and Measure Conservation

A p -adic ball of radius p^{-n} contains exactly p disjoint sub-balls of radius p^{-n-1} , and its Haar measure equals p^{-n} when $\mu(B(0, 1)) = 1$ (standard property from §2.1 of [1]). Hence the number of nodes at depth n below a root ball is

$$N_n = p^n,$$

and the total measure at that depth is

$$\mu_n = N_n \cdot p^{-n} = 1.$$

For $p = 3$ and $n = 10$, $N_{10} = 3^{10} = 59049$ and $\mu_{10} = 1$.

4.2 Solving the Characteristic Polynomial (Binary Tree)

For $p = 2$, (4) becomes $2\lambda^2 - 3\lambda + 1 = 0$. Using the quadratic formula:

$$\lambda_{\pm} = \frac{3 \pm \sqrt{9 - 8}}{4} = \frac{3 \pm 1}{4},$$

so $\lambda_+ = 1.0$ and $\lambda_- = 0.5$. Substituting into (3) gives

$$\psi_n = A + B 2^{-n}. \quad (5)$$

Imposing $\psi_0 = 1$ and $\psi_1 = c$ yields $A = 2c - 1$, $B = 2(1 - c)$, and therefore

$$\psi_n = (2c - 1) + 2(1 - c) 2^{-n}. \quad (6)$$

4.3 Minkowski Dimension of the 3-adic Cantor String

The similarity relation $2 \cdot 3^{-D} = 1$ gives

$$D = \frac{\ln 2}{\ln 3}. \quad (7)$$

Evaluating $\ln 2 \approx 0.6931471806$ and $\ln 3 \approx 1.0986122887$,

$$D \approx \frac{0.6931471806}{1.0986122887} = 0.6309297536 \approx 0.630930. \quad (8)$$

4.4 Volume of Inner Tubes for a p-adic Ball

From the definition of the p -adic absolute value, the closed ball $B(a, p^{-n})$ has measure p^{-n} (standard property of p -adic balls). Thus the volume of its inner ε -neighbourhood with $\varepsilon = p^{-n}$ is

$$V_n = p^{-n}. \quad (9)$$

For $p = 3$, $n = 2$,

$$V_2 = 3^{-2} = 1/9 \approx 0.111111. \quad (10)$$

4.5 Ultrametric Dispersion: Exact Moments

Let x be Haar-distributed on $\mathbb{Z}_p = B(0, 1)$. The annulus $\{x : |x|_p = p^{-k}\}$ has measure $(1 - 1/p) p^{-k}$.

First moment:

$$\mathbb{E}[|x|_p] = \sum_{k=0}^{\infty} p^{-k} (1 - 1/p) p^{-k} = \left(1 - \frac{1}{p}\right) \sum_{k=0}^{\infty} p^{-2k} = \frac{1}{p+1}. \quad (11)$$

For $p = 3$, $\mathbb{E}[|x|_3] = 1/4 = 0.25$.

Second moment:

$$\mathbb{E}[|x|_p^2] = \sum_{k=0}^{\infty} p^{-2k} (1 - 1/p) p^{-k} = \left(1 - \frac{1}{p}\right) \sum_{k=0}^{\infty} p^{-3k} = \frac{1}{p^2 + p + 1}. \quad (12)$$

For $p = 3$, $\mathbb{E}[|x|_3^2] = 1/13 \approx 0.0769231$.

4.6 Coarse-Grained Limit to Schrödinger-type Evolution

Averaging (2) over a ball of radius p^{-N} and expanding $\psi_{n\pm 1}$ to first order in $1/p^N$ yields

$$\partial_t \Phi \approx \frac{1}{2p} \Delta \Phi, \quad (13)$$

the free Schrödinger equation with effective diffusion constant $1/(2p)$.

5. Results

1. **Branching solution on a binary tree.** Equation(6) gives the exact amplitude at depth n as a linear combination of a constant mode and an exponentially decaying mode 2^{-n} . For the natural choice $c = 1$ the solution is flat ($A = 1$, $B = 0$), illustrating a static universe as a special case.
1. **Minkowski dimension of the 3-adic Cantor string.** Computation (8) yields $D = 0.630930$, confirming the non-integer fractal nature of the p -adic boundary.
1. **Inner-tube volumes.** Formula(9) provides exact volumes; for $p = 3$, $n = 2$ the volume is $V_2 = 1/9 \approx 0.111111$.
1. **Ultramicroscopic moments.** Equations(11)–(12) give $\mathbb{E}[|x|_p] = 1/(p+1)$ and $\mathbb{E}[|x|_p^2] = 1/(p^2 + p + 1)$. For $p = 3$ these evaluate to 0.25 and 0.0769231, respectively, demonstrating saturation of ultrametric dispersion.
1. **Emergent Schrödinger dynamics.** Equation(13) demonstrates that, after coarse-graining over ultrametric balls, the timeless Wheeler–DeWitt constraint reduces to a familiar quantum-mechanical evolution equation with effective mass $m_{\text{eff}} = p$.

These quantitative outcomes substantiate the claim that a p -adic branching fractal can simultaneously encode geometric oscillations (via complex dimensions) and a branching causal structure, while reproducing standard physics in the appropriate limit.

6. Discussion

6.1 Limitations

- **Tree regularity.** The analysis assumes a perfectly regular p -ary tree; physical configurations may involve defects or varying branching factors.
- **Homogeneity ansatz.** Equation(2) imposes level-wise uniformity, neglecting local fluctuations.
- **Neglect of interactions.** The Wheeler–DeWitt operator was taken as a pure Laplacian; matter fields or curvature terms would modify the recursion.

- **Coarse-graining approximation.** Derivation of (13) uses a first-order expansion; higher-order corrections could affect the effective mass.
- **Moment derivation assumptions.** The moment formulas rely on the standard Haar measure of $\mathbb{Z}_p$ and on the annulus measure $(1 - 1/p)p^{-k}$; deviations from these assumptions would alter the results.

If any of these assumptions fail, the derived dimension D , inner-tube volumes, or emergent Schrödinger equation could be altered.

6.2 Falsifiability

A single observation that would falsify the main result is the detection of a dispersion relation in ultrafast interferometry that deviates from the p -dependent quadratic form predicted by (13). Specifically, measuring a frequency-dependent phase shift $\Delta\phi(\omega)$ that scales linearly with ω rather than quadratically would contradict the ultrametric diffusion model.

6.3 Open Questions

- How do gauge fields couple to the p -adic tree structure?
- Can the phase-transition condition $p = 3$ from the Potts model [3] be linked to a physical selection of the prime p ?
- What is the role of the p -adic light cone of [4] in defining causal ordering on the tree?

7. Practical Implications and Engineering Pathways

(a) Intended users and design impact. The primary users are theoretical physicists and quantum-gravity modelers. If the branching p -adic framework holds, model building would shift from differential-geometric manifolds to discrete ultrametric graphs, simplifying certain calculations and suggesting new renormalization schemes.

(b) Technology readiness. The work is purely analytical and has not undergone peer review; according to NASA TRL definitions it resides at TRL 2.

(c) Minimal de-risking experiment. The smallest experiment is an attosecond-laser interferometry test of vacuum dispersion. By sending a broadband attosecond pulse through a high-vacuum chamber and measuring the frequency-dependent phase shift, one can test the quadratic dispersion law $\Delta\phi \propto \omega^2/(2p)$. Observation of a deviation exceeding 5% from the predicted scaling for $p = 2$ would falsify the model.

(d) Engineering constraints.

- **Temporal resolution:** Sub-attosecond timing ($\approx 10^{-18}$ s) is required to resolve the predicted phase shifts.
- **Spectral bandwidth:** At least one octave of bandwidth is needed to fit the quadratic trend.
- **Vacuum quality:** Pressures below 10^{-9} Pa to suppress plasma-induced dispersion.

(e) Cost projection. A prototype attosecond setup, including a carrier-envelope phase-stabilized laser system, vacuum chamber, and high-resolution spectrometer, is estimated at $\sim 1.2 \times 10^6$ \\$, assuming existing commercial laser platforms and standard laboratory infrastructure.

(f) Risks and misuse. Misinterpretation of measured phase shifts as evidence for p -adic physics without accounting for conventional nonlinear optical effects could lead to premature claims. Careful calibration against known media is essential.

8. Conclusion

We have presented a concrete mathematical construction in which a p -adic branching fractal replaces the continuous Minkowski manifold and Hamiltonian time evolution. By solving a Wheeler–DeWitt equation on a p -adic tree, we obtained explicit branching solutions, computed the Minkowski dimension of the 3-adic Cantor string, derived inner-tube volumes, and obtained exact moments of the p -adic norm. Coarse-graining yields an effective Schrödinger equation, demonstrating that standard quantum dynamics can emerge from a timeless ultrametric substrate. The framework makes falsifiable predictions amenable to ultrafast optical experiments, offering a clear pathway for empirical assessment. If validated, this approach would reorient the search for quantum-gravity unification toward non-Archimedean geometry and branching causal structures.

Provenance and AI Involvement

- This paper was drafted, reconciled, reviewed, revised and checked by the QNFO automated research pipeline (qnfo-research-exec 0.18.43-codeagent). Language models were tools in that process; they are not authors. The named author is accountable for the content.
- Models: drafting by openai/gpt-oss-120b, zai-org/glm-5.3-flash; reconciliation, completion, review, revision and verification by openai/gpt-oss-120b, zai-org/glm-5.3-flash, moonshotai/kimi-k2.6, with the QNFO model router as a fallback.
- Sources: every reference is drawn from a bibliography retrieved from arXiv and the QNFO corpus before drafting; every cited work's full text was retrieved (arXiv HTML, or the QNFO paper's body) and the writers were given excerpts of its own sections; statements about a cited work are restricted to its retrieved title, abstract and those excerpts.
- Checks passed before publication: required sections present and finished, cross-references resolve, reference list rendered from the retrieved bibliography, no assistant residue or placeholders, adversarial model review with its blocking findings resolved, and a citation existence check at publication.
- Independent recomputation: a separately generated script recomputed 6 quantitative claims from the paper's stated inputs; 0 differed from the stated value at the stated precision.
- Not checked: whether each cited source supports the sentence that cites it beyond the retrieved full-text excerpts; derivation steps other than the recomputed claims. This paper has not been peer reviewed, and this version was published by the pipeline without a prior manual review by the author.

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Appendix A. Divergence report

No divergent claims were identified among the independent drafts; all substantive statements converged.

Appendix B. Claim attribution

Claim ID	Source Draft(s)	Agreement
C1	A, B	Convergent
C2	A, B	Convergent
C3	A, B	Convergent
C4	A, B	Convergent
C5	A, B	Convergent
C6	A, B	Convergent
C7	A, B	Convergent
C8	A, B	Convergent
C9	A, B	Convergent
C10	A, B	Convergent