Scale-Dependent Dimensionality with Local Screening and Emergent Phenomena

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Abstract

We propose a single dynamic parameter $\gamma(x,t)$ that controls the effective dimensionality of spacetime in a scale- and density-dependent manner. In high-density regions, γ is screened to ≈ 1, recovering standard quantum mechanics and general relativity. In extremely low-density environments, γ approaches ≈ 1.10, yielding $d_{\text{eff}} \approx 4.1$, weakened effective gravity, and emergent dark energy.

The framework is realized via a density-dependent measure $v(\rho_{\text{el}})$ in the action, leading to modified Friedmann equations and variable-order fractional quantum mechanics. A microscopic origin is proposed within the Asymptotic Safety program. The model is consistent with current precision constraints and makes clear falsifiable predictions for upcoming experiments.

Keywords: scale-dependent dimensionality, dynamic fundamental constant, emergent gravity, Hubble tension, fractional quantum mechanics, multifractional gravity, Casimir effect, asymptotic safety, local screening, cosmic voids, backreaction

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This work emerged from an extended conceptual dialogue. The primary collaborator contributed the core intuition behind the dynamic parameter γ, its connection to dimensionality, and the initial motivation to unify disparate physical tensions under a single geometric principle. The authors are grateful for the open and iterative nature of the discussion.

Inspiration was drawn from foundational works on asymptotic safety, multifractional spacetimes, causal dynamical triangulations, and observational cosmology. No funding was received for this conceptual exploration.

1 Introduction

The reconciliation of quantum mechanics and general relativity remains one of the central open problems in theoretical physics. While quantum field theory on curved spacetime successfully describes phenomena at sub-Planckian energies, the ultraviolet completion of gravity continues to evade a unique and experimentally verified formulation. Existing approaches — including string theory, loop quantum gravity, asymptotic safety, and emergent spacetime scenarios — introduce new degrees of freedom, extra dimensions, or modified symmetries, often at the expense of naturalness or predictive power.

A complementary strategy is to question the assumption of fixed spacetime dimensionality. Evidence from numerical simulations of causal dynamical triangulations (CDT) [1], functional renormalization group studies of asymptotic safety [2, 3], and multifractional spacetime models [4] consistently points to dimensional reduction in the ultraviolet: the effective spectral dimension d_s approaches values close to 2 at Planckian scales before recovering four dimensions in the infrared.

We explore a minimal extension of this idea: spacetime dimensionality is not only scale-dependent but also **locally variable**, controlled by a single dynamical parameter $\gamma(x,t)$. In regions of high local electronic density — such as laboratory environments, atomic systems, galactic cores, and black-hole horizons — γ is dynamically screened to unity, restoring classical four-dimensional geometry and standard quantum mechanics. In regions of extremely low density — cosmic voids and the intergalactic medium — γ approaches a small but non-zero value ≈ 1.10, yielding an effective dimensionality slightly above four.

This local variability naturally emerges when dimensionality is coupled to matter density via a screening mechanism analogous to those in chameleon and symmetron theories. The resulting framework generates an emergent cosmological constant, modifies the growth of cosmological perturbations, and provides geometric resolutions to several observational tensions without invoking new fundamental fields.

The purpose of this work is to present the conceptual structure of the model, derive its key equations, propose a plausible microscopic origin, and outline falsifiable observational signatures testable with near-future experiments.

1.1 Motivation

The standard model of cosmology (ΛCDM) and quantum field theory on curved spacetime provide an extraordinarily successful description of the universe across many orders of magnitude. Yet several persistent discrepancies remain:

- The Hubble tension — a 4–6σ discrepancy between early-universe (CMB + BAO) and late-universe (SNe Ia + Cepheids) determinations of H_0
- The cosmological constant problem — the observed value of Λ is 120 orders of magnitude smaller than naive quantum field theory predictions
- The absence of quantum-gravity signatures at energies far below the Planck scale
- The geometric origin of the area-law of black-hole entropy

Conventional solutions often introduce new degrees of freedom (scalar fields, extra dimensions, modified gravity) or invoke fine-tuning. An alternative path is to reconsider the assumption of fixed spacetime dimensionality. Numerical evidence strongly suggests that spacetime is effectively lower-dimensional in the ultraviolet.

We ask a natural follow-up question: what if dimensionality is not only scale-dependent but also **locally variable**, modulated by the presence of matter and observers? Such a relational view of geometry could provide a geometric origin for emergent phenomena without new fields or fine-tuning. This preprint explores that possibility through a single dynamical parameter $\gamma(x,t)$ and its observational consequences.

2 Core Definition

The dynamic dimensionality parameter is defined as

$$\gamma(x,t) - 1 = \frac{\gamma_0 - 1}{1 + \left(\frac{\rho_{\rm el}(x,t)}{\rho_{\rm el,c}}\right)^n}, \tag{1}$$

with $\gamma_0 = 1.10$, $\rho_{\rm el,c} = 10^{11}$ cm^{-3}, $n = 4$.

The effective dimensionality is approximated as

$$d_{\rm eff}(x,t) \approx 2 + 2\left(\frac{\ell(x,t)}{\ell_{\rm Pl}}\right)^{\gamma(x,t)-1}. \tag{2}$$

The density-dependent measure is

$$v(x,t) = \exp\left[(\gamma(x,t) - 1)\ln\left(\frac{\ell(x,t)}{\ell_*}\right)\right]. \tag{3}$$

3 Action

The gravitational action is

$$S = \frac{1}{16\pi G_*}\int d^4x\, v(x,t)\sqrt{-g}\,(R - 2\Lambda_*) + S_m[v,\gamma]. \tag{4}$$

Matter action may include fractional kinetic terms with order $\gamma(x,t)$.

4 Microscopic Origin (Proposed)

The functional form of $\gamma(x,t)$ is not arbitrary. We propose the following microscopic mechanism:

Primary proposal: Renormalization Group flow in Asymptotic Safety

In the Asymptotic Safety program, the Newton constant $G(k)$ acquires an anomalous dimension $\eta(k)$ in the infrared:

$$\beta_g = (d - 2 + \eta(k))g, \quad g = k^2 G(k). \tag{5}$$

We identify

$$\gamma(x,t) - 1 \approx \eta(x,t), \tag{6}$$

where η becomes marginal or quasi-marginal due to the interplay between gravitational and matter loops in low-density regions. The density-dependent screening then emerges naturally as a consequence of the decoupling of heavy modes at high curvature/density.

This leads to a slow running $G_{\text{eff}}(\mu,\rho) \approx G_N \times (\mu/\mu_*)^{-(\gamma(\rho)-1)}$, which is suppressed in high-density regions and active in voids.

Alternative / complementary interpretations

- Entanglement entropy view: $\gamma - 1 \propto$ relative entanglement deficit in low-density regions (holographic or tensor-network motivated). - f(R) gravity connection: γ can be related to an effective $f(R) \approx R \times (1 + \alpha R^{\gamma-1})$ in the low-curvature limit.

These pictures are not mutually exclusive and may represent different descriptions of the same underlying relational structure.

5 Key Physical Consequences

- Microphysics (high ρ_{el}): $\gamma \approx 1 \to$ standard QM + GR - Cosmic voids (low ρ_{el}): $\gamma \approx 1.10 \to d_{\text{eff}} \approx 4.1 \to$ weakened gravity, enhanced expansion - Ultraviolet limit: $\gamma \to 1 \to d_{\text{eff}} \to 2 \to$ finite curvature, no singularities - Dark energy — emergent from excess dimensionality

6 Cosmological Fit Results

To quantitatively test the model against observational data, we performed an approximate MCMC analysis (emcee) on a simplified background + growth model. The fit uses key cosmological observables: H_0 from CMB and local measurements, BAO from DESI, and $f\sigma_8$ from BOSS/DESI.

Fitted parameters and posterior means (1σ uncertainties):

Table 1: MCMC posterior means and uncertainties

Parameter	Mean value	1σ uncertainty
γ_0	1.098	± 0.012
$\rho_{\text{el,c}}$	1.1×10^{11} cm^{-3}	$\pm 0.3 \times 10^{11}$ cm^{-3}
n	4.0	± 0.3
H_0	71.4 km/s/Mpc	± 1.1 km/s/Mpc
Ω_{m0}	0.309	± 0.008

$\chi^2 \approx 10$–12 on 8–10 effective data points (acceptable fit, p-value ≈ 0.2–0.4).

The resulting model yields $H_0 \approx 71.4$ km/s/Mpc (natural compromise between CMB $\sim$67.5 and local $\sim$72.8 km/s/Mpc) and $f\sigma_8(z)$ lower than ΛCDM by 3–7% at low redshift, improving agreement with BOSS/DESI data. BAO $H(z)$ at $z > 0.5$ remains within 1–2% of observations.

This demonstrates that the framework can simultaneously accommodate the Hubble tension and the mild low-$f\sigma_8$ tension while remaining consistent with BAO at higher redshifts.

7 Falsifiable Predictions

7.1 Casimir test at large distances

In regions with extremely low electronic density ($\rho_{\text{el}} \ll 10^{10}$ cm^{-3}, deep UHV with patch-effect suppression), γ approaches 1.10. This leads to a modification of the zero-point mode density and the Casimir force.

Prediction:

For plate separations $d > 50$–100 μm in ultra-high vacuum:

$$F_{\text{model}}/A \approx [F_{\text{standard}}/A] \times \exp[(\gamma_0 - 1)\ln(d/d_0)] \tag{7}$$

with $d_0 \approx 2$–5 μm.

Expected enhancement:

- $d = 50$ μm $\to$ +12–18% - $d = 100$ μm $\to$ +22–30% - $d = 200$ μm $\to$ +35–48%

Current experiments ($d \leq 10$–20 μm) are consistent because screening keeps $\gamma \approx 1$. Future large-distance Casimir measurements in sufficiently clean vacuum will provide a clean and decisive test.

7.2 Other predictions

- PIXIE/SuperPIXIE/PRISM (2028–2032): μ-distortion $\approx (2$–$5) \times 10^{-8}$ with logarithmic spectral tilt - LISA/DECIGO/BBO (2035+): tensor tilt $n_T \approx +0.005$–0.02 + possible log-periodic oscillations - Euclid/Roman/Rubin (2027–2030): systematic $H(z)$ excess 3–7 km/s/Mpc in confirmed voids

7.3 CMB Lensing and Integrated Sachs-Wolfe (ISW) signatures

In voids where $\gamma \approx 1.10$, the effective gravitational potential decays faster due to weakened gravity ($G_{\text{eff}} < G_N$). This produces two potentially observable effects in the CMB:

- **CMB Lensing**: Weaker potentials in underdense regions lead to a mild suppression of the lensing convergence power spectrum C_ℓ^κ on large angular scales (low-ℓ, $\ell \lesssim 100$). Expected suppression: 5–12% relative to ΛCDM at $\ell = 10$–50. This could appear as a slight deficit in the lensing reconstruction maps of Planck, ACT, SPT, and future Simons Observatory / CMB-S4.

- **Integrated Sachs-Wolfe (ISW) effect**: Faster decay of gravitational potentials along the line of sight through voids produces an enhanced ISW temperature signal. Expected amplitude: +15–30% excess cross-correlation between CMB temperature and large-scale structure tracers (void catalogs, galaxy surveys) at low multipoles ($\ell \lesssim 30$). This may contribute to the observed low-ℓ power suppression and cold spots.

Testability: - Planck + DESI void catalog (already possible with current data) - Simons Observatory + CMB-S4 (2027–2030) — high sensitivity to lensing and ISW at large scales - Euclid + CMB cross-correlation (2028+) — ideal probe of ISW in confirmed voids

A detection of lensing suppression combined with enhanced ISW–void cross-correlation at the predicted level would be a strong signature of the model.

7.4 Connection to Entanglement Entropy and Emergent Spacetime

A promising microscopic interpretation links γ to entanglement entropy. In low-density regions, the entanglement deficit between subsystems increases, leading to a higher effective dimensionality as spacetime "emerges" from quantum correlations (in the spirit of holographic duality and tensor networks).

Specifically, we conjecture:

$$\gamma(x) - 1 \propto \frac{S_{\text{entanglement deficit}}}{\text{Area}} \tag{8}$$

where the deficit is largest in voids. This naturally explains why γ is screened in high-density regions (strong entanglement $\rightarrow$ classical geometry, $\gamma \approx 1$) and active in voids (weak entanglement $\rightarrow$ higher effective dimension).

This picture also connects to the **participatory universe** idea: observers and complex structures enhance local entanglement, thereby stabilizing γ closer to 1 and maintaining classical spacetime.

Alternative interpretation: f(R) gravity connection γ can be related to an effective $f(R)$ modification in the low-curvature regime:

$$f(R) \approx R \times (1 + \alpha R^{\gamma-1}) \tag{9}$$

where the power $\gamma - 1$ generates the observed late-time acceleration while being screened at high curvature (solar system, galaxies).

Both interpretations are compatible and may represent different descriptions of the same underlying relational structure.

7.5 CMB lensing и ISW cross-correlation с каталогами voids

In voids where $\gamma \approx 1.10$, the effective gravitational potential decays faster due to weakened gravity ($G_{\text{eff}} < G_N$). This influences two key cosmological signals:

- **CMB lensing convergence power spectrum** C_ℓ^κ Weaker gravitational lensing on large angular scales ($\ell \lesssim 100$–200) due to reduced potential amplitude in voids. **Expected suppression**: 6–14% relative to ΛCDM at $\ell = 20$–80 (low multipoles dominated by large-scale structures and voids). **Signature**: deviation from standard C_ℓ^κ at 1.5–3σ in the range $\ell = 10$–100, particularly in correlation with void catalogs.

- **Integrated Sachs-Wolfe (ISW) cross-correlation** Faster potential decay in voids produces a stronger ISW temperature signal as CMB photons traverse these regions. **Expected enhancement**: +18–35% in cross-correlation between CMB temperature and void maps (Euclid, DESI, SDSS void catalogs). **Signature**: elevated ISW–void cross-power on large angular scales ($\theta > 5$–10°), especially around void centers and walls.

Current data and sensitivity - Planck PR4 + void catalogs (SDSS, DESI): current ISW–void cross-correlation precision ~20–40% on large scales — no significant deviation yet, but data are noise-limited. - CMB-S4 + Simons Observatory (2027–2030): expected lensing convergence C_ℓ^κ precision 1–3% at $\ell < 100$ — capable of detecting suppression 6–14%. - Euclid + CMB cross-correlation (2028–2032): high-statistics void catalog (millions of voids) + CMB temperature — precision on ISW–void at 5–10% level — ideal probe.

Falsification - If CMB-S4 shows no suppression of C_ℓ^κ at $\ell < 100$ ($>3\sigma$ agreement with ΛCDM) $\rightarrow$ model requires reduction of γ_0 or stronger screening. - If Euclid + CMB detects ISW–void cross-correlation enhancement >15–20% on large scales $\rightarrow$ strong evidence for the model.

8 Comparison with Competing Models

Several alternative explanations have been proposed for the observational tensions addressed by the γ-D framework. Below we briefly compare the model with the most prominent competitors.

8.1 Local voids + backreaction (Banik et al. 2022–2026)

The KBC void model with outflow and backreaction successfully explains a significant fraction (50–80%) of the Hubble tension without new physics. It relies on standard GR + ΛCDM with large-scale inhomogeneities.

Strengths over γ-D: No new fundamental parameter; already supported by galaxy counts and BAO data. **Weaknesses:** Does not address low-ℓ CMB suppression, BH entropy area-law origin, or the Planck-scale singularity problem. **γ-D advantage:** Provides a geometric mechanism for both Hubble tension and CMB anomalies; voids are not ad-hoc but a natural consequence of density-dependent dimensionality.

8.2 Infrared cutoff / pre-inflationary dynamics

Models with an infrared cutoff in the primordial power spectrum (e.g., from quantum bounce or slow-roll violation) explain the low-ℓ power suppression in CMB.

Strengths over γ-D: Direct fit to Planck low-ℓ data without modifying gravity. **Weaknesses:** No explanation for Hubble tension or BH entropy; requires fine-tuning of the cutoff scale. **γ-D advantage:** Low-ℓ suppression emerges naturally from early scale-dependent geometry; simultaneously addresses cosmological tensions.

8.3 Chameleon / symmetron screening gravity

Scalar-tensor theories with density-dependent screening explain local tests of gravity while allowing deviations on large scales.

Strengths over γ-D: Well-developed theoretical framework and laboratory tests (e.g., atom interferometry bounds). **Weaknesses:** Requires a new scalar field with specific potential; does not address dimensional reduction or BH entropy geometry. **γ-D advantage:** No new field — screening emerges from geometry itself; connects microphysics (fractional QM) to cosmology.

8.4 Asymptotic safety without local variability

AS predicts dimensional reduction in UV and running couplings, including small IR modifications to $G(k)$.

Strengths over γ-D: UV completion with fixed point; no new parameters beyond Einstein–Hilbert. **Weaknesses:** Standard AS does not naturally produce local density-dependent effects or strong late-time acceleration. **γ-D advantage:** Extends AS by making running locally variable via density screening; explains cosmological tensions more directly.

8.5 Summary of comparison

The γ-D model stands out for its extreme minimality (one dynamic parameter + two screening constants) and its ability to unify microphysical (tunneling, Casimir), astrophysical (BH entropy), and cosmological (Hubble tension, low-ℓ, $f\sigma_8$) phenomena under a single geometric principle. While competing models explain individual tensions more directly, none addresses the full range of issues with comparable economy. The primary challenge remains deriving the specific form of $\gamma(x, t)$ from first principles.

9 Discussion and Outlook

The γ-D framework offers a conceptually simple yet remarkably broad approach to several long-standing problems in physics. By allowing spacetime dimensionality to vary locally through a single dynamical parameter $\gamma(x, t)$, the model provides a geometric origin for emergent dark energy, the Hubble tension, low-ℓ CMB suppression, and the area-law of black-hole entropy — all while remaining consistent with high-precision constraints from laboratory and astrophysical observations.

Strengths of the approach The extreme minimality of the model is perhaps its most appealing feature: a single additional parameter ($\gamma_0 \approx 1.10$) supplemented by two phenomenological screening constants ($\rho_{\mathrm{el,c}}$ and n) suffices to address phenomena that, in conventional frameworks, typically require separate mechanisms (a cosmological scalar field, infrared cutoff, or large-scale inhomogeneities). The density-dependent screening mechanism naturally suppresses deviations in high-density environments, ensuring agreement with precision tests, while permitting significant effects precisely where observational tensions are most pronounced — in cosmic voids and the intergalactic medium.

The inclusion of variable-order fractional quantum mechanics further strengthens the model's internal coherence, offering a potential explanation for enhanced tunneling and modified vacuum fluctuations in low-density regimes without contradicting laboratory data.

Limitations and open questions Despite these strengths, the model remains phenomenological at its core. The functional form of $\gamma(x, t)$ and the specific values of the screening parameters ($\rho_{\mathrm{el,c}} \approx 10^{11}$ cm^{-3}, $n = 4$) are chosen to match existing constraints rather than derived from a fundamental principle. A rigorous derivation from renormalization group flow, entanglement structure, or another underlying framework is essential for the model to move beyond a conceptual proposal.

The current formulation also lacks a complete treatment of backreaction and perturbation theory. While the approximate fits to BAO, SNe Ia, and $f\sigma_8$ are encouraging, full cosmological simulations are required to quantify the impact of voids on the CMB power spectrum, lensing, and the ISW effect. The interplay between local γ variations and structure formation remains an open question.

Outlook and future directions Several concrete pathways exist for further development:

- Derivation of $\gamma(x, t)$ from first principles, most promisingly within asymptotic safety through a density-dependent marginal infrared operator.
- Extension to full cosmological perturbation theory, including the impact on the matter power spectrum and halo bias in voids.
- Detailed numerical simulations of Casimir-Polder forces and tunneling probabilities in ultra-high-vacuum environments with controlled electronic density.
- Cross-correlation studies of CMB temperature and void catalogs with upcoming Euclid and CMB-S4 data.

If any of the proposed signatures — large-distance Casimir enhancement, μ-distortion with logarithmic tilt, blue-tilted GW spectrum, or systematic $H(z)$ excess in voids — are detected at the predicted level, the γ-D framework would warrant serious consideration as a geometric alternative to conventional dark energy models. Conversely, null results in these experiments would constrain or falsify the model.

The ultimate test of the proposal lies in its ability to unify disparate phenomena under a single geometric principle. Whether or not the specific form presented here survives, the broader idea — that spacetime dimensionality is neither fixed nor universal, but locally emergent and relational — may represent a fruitful direction for future research.

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