Geometric Annihilation and Cosmic Acceleration: Cosmological Signatures of Latent Geometric Regions

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Abstract

This work proposes a physically grounded framework for cosmic expansion based on the concept of **Latent Geometric Capacity** within Loop Quantum Gravity (LQG). We distinguish between space—the pre-geometric capacity for adjacency and volume—and the universe—the actually occupied classical volume. In LQG spin networks, a connected cluster of vertices with inverse orientation ($\mu_v = -1$) constitutes a *Latent Geometric Region* (LGR): a topological defect in the orientation field that contributes negatively to the volume operator. An isolated $\mu_v = -1$ vertex remains a gauge artifact.

Cosmological expansion is modeled as *geometric annihilation*: the dynamical conversion of latent capacity into positive classical volume at the interface between actualized (V_+) and latent (V_-) domains. The effective 4D dynamics are governed by the Einstein equations supplemented by an energy-momentum tensor sourced by the domain wall. We present an explicit analytical calculation of the volume operator on a minimal tetrahedral spin-network graph (all spins $j = 1/2$), demonstrating exact cancellation of volume when one vertex is inverted. An effective Ising-like Hamiltonian describes the large-scale orientation dynamics, enabling a statistical estimate of the macroscopic latent fraction.

The framework yields falsifiable predictions for (i) oscillatory features in the primordial power spectrum at high multipoles, (ii) fractional shifts in quasinormal mode frequencies of binary black hole mergers, and (iii) negative expectation values of the volume operator in few-qubit quantum simulations. We perform a detailed comparison with recent cosmological data (Planck 2018, DESI DR2) and outline a phased research roadmap.

The primary contribution is conceptual and interpretative, but is anchored to a tractable computational core. The framework offers a novel perspective on cosmic expansion as the progressive actualization of pre-geometric potential, identifying a unifying category—latent geometric capacity—that bridges LQG and M-theory.

Contents

1 Introduction: Space as Capacity

Contemporary cosmology faces a profound challenge: to reconcile the discrete, background-independent description of spacetime suggested by quantum gravity with the smooth, accelerating expansion of the universe. The standard ΛCDM model, while remarkably successful, rests on the assumption of a cosmological constant or dynamical dark energy whose microphysical origin remains obscure. Moreover, recent observational hints—such as the H_0 tension and the DESI results suggesting evolving dark energy—motivate the exploration of alternatives that do not merely add a new fluid, but reexamine the nature of cosmic expansion itself.

This work advances a specific hypothesis grounded in Loop Quantum Gravity (LQG): that cosmic expansion corresponds to the *actualization of latent geometric capacity*. In this picture, space is not merely a stage on which physics unfolds, but an entity with a pre-geometric phase—a reservoir of potential volume stored in the quantum geometry of spin networks. The conversion of this latent capacity into classical volume drives the observed expansion, offering a qualitatively new mechanism for dark energy.

The idea that information or geometry underlies physical reality has a long history. Wheeler's famous dictum "it from bit" [14] posited that the physical world arises from immaterial information. Here we propose a variation: "it from geometry"—specifically, from the orientation structure of LQG spin networks. The central construct is the **Latent Geometric Region** (LGR), a coherent domain of vertices with inverted orientation ($\mu_v = -1$). While an isolated inverted vertex is a gauge artifact, a connected cluster forms a topological domain wall and contributes negatively to the volume operator. This negative contribution represents unactualized geometric capacity—a blueprint for future volume.

The conversion of LGR capacity into positive volume proceeds via *geometric annihilation* at the domain boundaries. On cosmological scales, this process can be described by an effective energy-momentum tensor that modifies the Friedmann equations. The framework makes concrete, testable predictions for the cosmic microwave background (CMB) power spectrum, the quasinormal mode (QNM) spectrum of black hole mergers, and quantum simulations of spin-network volumes.

Relation to prior work. The concept of Latent Geometric Regions and their characterization in Loop Quantum Gravity is developed in detail in a companion paper [15]. The present work builds upon that foundation, focusing on the cosmological implications of LGR conversion dynamics. While we briefly review the essential LQG construction in Section 2 to keep this paper self-contained, the reader is referred to [15] for a comprehensive treatment of gauge invariance, the minimal tetrahedral model, and the effective orientation dynamics. The central novelty of the present paper lies in Sections 3–4, where we embed the LGR mechanism into a full cosmological model and derive observational constraints.

This paper is organized as follows. Section 2 provides a rigorous definition of Latent Geometric Regions in LQG, including the minimal tetrahedral model and the effective Ising dynamics. Section 2.6 briefly discusses the M-theory dual in terms of negative-tension branes. Section 3 develops the cosmological framework: modified Friedmann equations, conversion rate parameterization, and numerical solutions. Section 4 confronts the model with current observational data (Planck, DESI) and forecasts future constraints. Section 5 discusses the philosophical implications of “space as capacity” and outlines open problems. Section 6 concludes. Appendices provide detailed derivations and numerical code.

Throughout, we adopt natural units $c = \hbar = 1$ unless otherwise stated, and the Planck length is denoted $\ell_P = \sqrt{G}$.

2 Latent Geometric Regions in Loop Quantum Gravity

This section provides a concise summary of the Latent Geometric Region framework in Loop Quantum Gravity, with an emphasis on the aspects most relevant to cosmology. A complete exposition, including detailed derivations of the volume operator spectrum, the gauge-invariant characterization of inverse-orientation domains, and the effective Ising dynamics, can be found in the companion paper [15]. Here we recall only the essential definitions and results needed to formulate the cosmological model of Section 3.

2.1 Spin Networks and the Volume Operator

In the kinematical Hilbert space of LQG, quantum states of 3D geometry are described by *spin networks*—graphs whose edges are labeled by $SU(2)$ representations (spins) $j_e \in \frac{1}{2}\mathbb{N}$ and whose vertices are labeled by intertwiners [1]. At each vertex v, the volume operator $\hat{V}_v$ is constructed from the flux operators $\hat{J}^i_e$ associated with the incident edges. A standard expression (in the large-j limit or with a specific regularization) is:

$$\hat{V}_v = \left(\frac{8\pi\gamma\ell_P^2}{6}\right)^{3/2} \sqrt{\frac{1}{8 \cdot 3!} \sum_{e_I, e_J, e_K} \epsilon(e_I, e_J, e_K)\epsilon_{ijk} \hat{J}^i_{e_I} \hat{J}^j_{e_J} \hat{J}^k_{e_K}}, \tag{1}$$

where γ is the Barbero–Immirzi parameter, $\epsilon(e_I, e_J, e_K)$ is the orientation of the triple of edges, and $\hat{J}^i_e$ are the right-invariant vector fields on $SU(2)$.

The sign of the volume eigenvalue at a vertex depends on the relative orientation of the triad. In the spin-network basis, this is encoded in an orientation factor $\mu_v = \pm 1$. The standard convention assigns $\mu_v = +1$ to the “positive” orientation (right-handed triad) and $\mu_v = -1$ to the “negative” orientation (left-handed triad). The volume operator can then be written schematically as:

$$\hat{V}_v = \mu_v \, \hat{v}_v, \tag{2}$$

where $\hat{v}_v$ is a positive semi-definite operator constructed from the absolute values of the flux triple products.

2.2 Gauge Invariance and Physical Domains

In canonical LQG, a single vertex with $\mu_v = -1$ is considered a gauge artifact. A local $O(3)$ rotation (or a parity transformation) combined with an $SU(2)$ gauge transformation can flip the sign of the triad at that vertex without affecting the physical geometry elsewhere. Therefore, isolated negative orientations are unobservable in the kinematical Hilbert space.

However, the situation changes when a *connected cluster* of vertices shares the inverted orientation. A gauge transformation that flips the sign at one vertex cannot be smoothly extended across the cluster boundary without creating a discontinuity in the triad field—a topological defect. This is completely analogous to the impossibility of rotating all spins in a ferromagnetic domain without creating a domain wall: the relative orientation between domains is a physical, diffeomorphism-invariant observable.

The transition from gauge artifact to physical domain is governed by the correlation length ξ of the spin-foam amplitude. A connected set of inverted vertices forms a physical LGR if its linear size L exceeds ξ. At scales $L \ll \xi$, quantum fluctuations restore gauge invariance; at $L \gg \xi$, the domain wall becomes a semiclassical topological defect. In the cosmological context, ξ is expected to be of order ℓ_P during the Planck era, possibly growing to macroscopic scales during inflation. A precise determination of ξ requires numerical spin-foam simulations (see Section 2.7).

2.3 Gauge-Invariant Characterization

To strengthen the physical interpretation, we introduce a gauge-invariant characterization of LGRs based on correlation functions of the orientation field. Define the coarse-grained orientation over a region Ω:

$$M(\Omega) = \frac{1}{N_\Omega} \sum_{v \in \Omega} \mu_v, \tag{3}$$

where N_Ω is the number of vertices in Ω. While individual μ_v are gauge-dependent, the two-point correlation function

$$C(r) = \langle \mu_v \mu_{v+r} \rangle \tag{4}$$

is invariant under local gauge transformations that act independently at each vertex. A coherent inverse-orientation domain is then a region Ω such that:

$$\lim_{|r| \to L} C(r) \to +1 \quad \text{with} \quad M(\Omega) < 0, \tag{5}$$

i.e., long-range correlation with negative average orientation. This condition cleanly separates physical domains from gauge fluctuations, for which $C(r) \to 0$ at large separations.

Relation to the volume operator: The orientation flux through a surface Σ bounding Ω can be expressed in terms of the volume operator [4]:

$$\Phi(\Sigma) \propto \frac{\langle \hat{V}_\Omega \rangle}{v_0}, \tag{6}$$

where v_0 is the elementary volume scale. A vanishing $\langle \hat{V}_\Omega \rangle$ in the presence of non-zero local contributions signals cancellation between $\mu_v = \pm 1$ regions, identifying an LGR.

Thus, coherent $\mu_v = -1$ regions correspond to symmetry-broken phases of the orientation field, characterized by non-vanishing long-range order. This provides a diffeomorphism-invariant criterion for the existence of Latent Geometric Regions.

2.4 Minimal Computational Model: The Tetrahedral Graph

To demonstrate the physical consequences of a coherent inverse-orientation domain, we compute the volume operator expectation for the simplest non-trivial spin-network graph: two vertices connected by four edges, topologically a tetrahedron. We assign all edges the spin $j = 1/2$ representation. This allows an explicit analytical diagonalisation of the volume operator [3].

2.4.1 Graph and State Space

Consider two vertices v_A, v_B and four edges $\{e_1, e_2, e_3, e_4\}$ connecting them. The flux operators $\hat{J}_i^{(e)}$ act on the $j = 1/2$ representation space of each edge. The gauge-invariant state space at each vertex is the singlet subspace of the tensor product of four spin-1/2 representations. For a vertex with four edges carrying spin 1/2, the eigenvalues of the volume operator are known analytically [1, 2]. The non-zero eigenvalues are $\pm(\sqrt{3}/2)\ell_P^3$ (up to an overall normalisation convention). The sign is determined by the orientation factor $\mu_v = \pm 1$.

2.4.2 Orientation Configurations and Volume Expectation

We consider three configurations of the two-vertex graph:

(1) **Both vertices actualised** ($\mu_A = +1, \mu_B = +1$). The total volume operator $\hat{V}_\Omega = \hat{V}_A + \hat{V}_B$ has eigenvalues

$$V_{\text{tot}} = +\frac{\sqrt{3}}{2}\ell_P^3 + \frac{\sqrt{3}}{2}\ell_P^3 = \sqrt{3}\ell_P^3 \approx 1.732\,\ell_P^3. \tag{7}$$

(2) **Single inverted vertex** ($\mu_A = +1, \mu_B = -1$). The total volume becomes:

$$V_{\text{tot}} = +\frac{\sqrt{3}}{2}\ell_P^3 - \frac{\sqrt{3}}{2}\ell_P^3 = 0. \tag{8}$$

The positive and negative contributions cancel exactly. This configuration represents a *domain wall* between actualized and latent phases.

(3) **Coherent domain of inverse orientation** ($\mu_A = -1, \mu_B = -1$). The total volume is:

$$V_{\text{tot}} = -\sqrt{3}\ell_P^3. \tag{9}$$

This corresponds to a *bulk latent region* with negative volume.

2.4.3 Latent Fraction Estimate

The latent fraction $|V_-|/V_+$ can be estimated by comparing the volume deficit in configuration (2) to the maximal positive volume. If we define $V_+ = \sum_v |V_v| = \sqrt{3}\ell_P^3$ (the sum of absolute volumes of the two vertices), then in the presence of a single inverted vertex we have an effective volume $V_{\text{eff}} = 0$, so the latent fraction is:

$$|V_-|/V_+ = \frac{\sqrt{3}\ell_P^3}{\sqrt{3}\ell_P^3} = 1 \quad \text{(for this microscopic graph).} \tag{10}$$

This value saturates the stability bound $|V_-|/V_+ < 1/2$ because the two-vertex graph is too small to exhibit the partial annihilation characteristic of larger networks. In a realistic cosmological setting, the fraction is expected to be much smaller due to the low probability of forming large coherent inverse-orientation domains (see next subsection).

2.4.4 Statistical Scaling to Macroscopic Latent Fractions

To extrapolate to cosmological scales, we assume that coherent inverse-orientation domains form with a probability governed by a perimeter law (appropriate for a percolating geometry):

$$P(\text{domain of linear size } L) \propto \exp\left(-\frac{\sigma L^2}{T_{\text{eff}}}\right), \tag{11}$$

where σ is a domain-wall tension (in Planck units) and T_{eff} is an effective temperature of the quantum geometry. The macroscopic latent fraction is then obtained by integrating over domain sizes:

$$\frac{|V_-|}{V_+} \sim \int_{L_{\min}}^{\infty} dL\, L^3 \cdot \exp\left(-\frac{\sigma L^2}{T_{\text{eff}}}\right) \sim \left(\frac{T_{\text{eff}}}{\sigma}\right)^{5/2} \exp\left(-\frac{\sigma L_{\min}^2}{T_{\text{eff}}}\right). \tag{12}$$

While σ and T_{eff} are not computable from first principles here, this parametric scaling shows that even exponentially small microscopic probabilities can yield finite macroscopic fractions. A rigorous determination of f_{inv} is deferred to the numerical simulations outlined in the roadmap (Section 2.7).

2.4.5 Implications for Phenomenological Parameters

The exact cancellation in configuration (2) demonstrates that the effective volume can be significantly reduced (or even made negative) by the presence of latent geometric regions. In a large graph with $N \gg 1$ vertices, a small fraction f_{inv} of inverted vertices would lead to a net volume deficit:

$$|V_-| \sim f_{\text{inv}} N \ell_P^3, \tag{13}$$

consistent with the order-of-magnitude estimate used in later sections. This provides a concrete, albeit simplified, computational foundation for the heuristic placeholders used in earlier phenomenological discussions.

2.5 Effective Orientation Dynamics: Ising Model

The large-scale behavior of the orientation field μ_v can be modeled by an effective Ising-like Hamiltonian on the spin network. This provides a minimal dynamical mechanism for the formation and stability of coherent $\mu_v = -1$ regions, and allows a statistical estimate of the macroscopic latent fraction.

Consider a graph with vertices v and edges $\langle v, w\rangle$. Define the effective Hamiltonian:

$$H_{\text{eff}} = -J \sum_{\langle v,w\rangle} \mu_v \mu_w + h \sum_v \mu_v, \tag{14}$$

where:

- $J > 0$ is a ferromagnetic coupling that favors aligned orientations (i.e., expansion of the actualized phase);
- h is an external field that mimics the cosmological "pressure" toward conversion, with $h \propto \Gamma$, the conversion rate introduced below.

Microscopically, the coupling J is related to the gradient of the volume operator across adjacent vertices, while the external field h is tied to the global curvature:

$$J \sim \ell_P^3 \cdot \frac{\ell_P}{L_{\text{curv}}}, \qquad h \sim \ell_P^3 \cdot \Lambda_{\text{eff}} = \ell_P^3 \cdot \max(H_{\text{dS}}^2, H_{\text{Planck}}^2). \tag{15}$$

For a de Sitter phase, $h \sim \ell_P^3 H_{\text{dS}}^2 = \ell_P^3 / L_{\text{dS}}^2$.

In this picture, inverse-orientation domains correspond to metastable excitations separated by domain walls with tension $\sigma \sim J$. The probability of finding a domain of size N (number of vertices) at temperature T_{eff} is given by the Boltzmann factor:

$$P(N) \propto \exp\left(-\frac{\sigma N}{T_{\text{eff}}}\right). \tag{16}$$

Here T_{eff} is an effective temperature of the quantum geometry, which may be related to the de Sitter temperature $T_{\text{dS}} = H/2\pi$ during inflation, or to the Planck temperature T_P in the early universe.

The macroscopic fraction of inverted vertices is then:

$$f_{\text{inv}} = \langle \mu_v = -1 \rangle \sim \exp\left(-\frac{\sigma}{T_{\text{eff}}}\right). \tag{17}$$

This yields a latent fraction

$$\frac{|V_-|}{V_+} \sim f_{\text{inv}} \sim e^{-\sigma/T_{\text{eff}}}. \tag{18}$$

The conversion rate Γ introduced in the cosmological dynamics (Section 3) is proportional to the domain-wall velocity, which in turn is set by the energy difference between the V_+ and V_- phases. In the Ising model, this is related to the external field h. A microscopic derivation of Γ from spin-foam amplitudes is part of the roadmap (Section 2.7).

The Ising Hamiltonian (14) also provides a natural stability condition. To prevent runaway conversion (collapse of all latent capacity into immediate actualization), the latent fraction must satisfy:

$$\frac{|V_-|}{V_+} < \frac{1}{2}. \tag{19}$$

This bound arises from the requirement that the domain wall tension be positive and that the latent phase be metastable. It will be used to constrain cosmological parameters in Section 4.

2.6 M-theory Dual: Negative-Tension Branes as Compressed Capacity

The concept of latent geometric capacity finds a natural parallel in M-theory compactifications. In flux compactifications on Calabi-Yau manifolds, orientifold planes with negative tension arise as boundary conditions for the compactified dimensions. These negative-tension objects contribute negatively to the effective 4D volume, providing a higher-dimensional analogue of LGRs.

Consider a p-brane with tension $T_p < 0$. Its contribution to the 4D volume can be written schematically as [7, 8]:

$$\delta V_{\mathrm{4D}} = -\kappa |T_p| \int_{\mathrm{CY}_3} \star_6 (e^{-\phi} \mathrm{Re}\, \Omega_3), \tag{20}$$

where κ is a dimensionful constant, ϕ is the dilaton, and Ω_3 is the holomorphic 3-form on the Calabi-Yau. The negative sign indicates that the brane stores geometric capacity in the compactified dimensions—capacity that can be released, for instance, through brane annihilation or decompactification.

In this picture, the latent fraction $|V_-|/V_+$ is related to the total negative tension in the compactification. While a detailed derivation of the effective 4D volume deficit from a stabilized flux compactification remains an open problem, the structural parallel reinforces the idea that latent capacity is a robust concept across quantum gravity approaches.

Cautionary note: The connection to M-theory presented here is schematic and serves as a conceptual parallel to the LQG construction. The LGR framework does not rely on the internal consistency of any particular string compactification; rather, it identifies a shared mathematical structure—negative contributions to the volume operator or effective action—as a potential signature of pre-geometric capacity. The validity of the LGR hypothesis rests on its own phenomenological coherence and falsifiable predictions, not on the ultimate fate of string theory.

2.7 Open Problems and Near-Term Roadmap for LGR

The LGR framework presented in this section is physically grounded but remains programmatic in several respects. The following open problems define a near-term research roadmap focused specifically on the quantum-gravitational aspects of LGRs. A broader roadmap including cosmology and observations is given in Section 5.4.

2.7.1 Phase 1: Analytical Benchmarks (2026–2027)

Goal: Replace the illustrative estimates of the latent fraction with order-of-magnitude calculations derived from simplified LQG models.

Actions:

- Extend the minimal tetrahedral graph calculation (Section 2.4) to graphs with 4–10 vertices and varying spins ($j \leq 1$).
- Compute the expectation value $\langle \hat{V}_\Omega \rangle$ for coherent states peaked on a classical geometry containing an inverse-orientation domain.
- Derive an analytical bound on the latent fraction $|V_-|/V_+$ in the large-volume limit using random tensor network techniques.

Deliverable: A revised estimate of $|V_-|/V_+$ and the conversion rate Γ that, while still model-dependent, is grounded in explicit LQG kinematics rather than dimensional analysis.

2.7.2 Phase 2: Numerical Spin-Foam Simulations (2027–2029)

Goal: Estimate the dynamical probability $P(\mu_v = -1)$ from the spin-foam path integral.

Actions:

- Implement tensor network renormalization algorithms for the EPRL spin-foam amplitude on small 2-complexes, focusing on 3D gravity as a tractable toy model.
- Compute the relative amplitude of histories containing a connected cluster of orientation-reversed vertices versus histories with uniform orientation.
- Extrapolate to larger triangulations using coarse-graining methods developed for spin foams [6].

Deliverable: A numerically determined probability distribution for the size and abundance of coherent inverse-orientation domains.

2.7.3 Phase 3: Phenomenological Constraints (2028–2030)

Goal: Use the derived parameter ranges to confront LGR predictions with current and forthcoming observational data. This phase overlaps with the cosmological analysis of Section 4 and is detailed further in Section 5.4.

Actions:

- Perform a Bayesian fit of the LGR primordial power spectrum to Planck 2018 and DESI DR2 data, treating Γ as a free parameter derived from the Phase 2 probability.
- Develop a hierarchical model for the LIGO/Virgo/KAGRA population to constrain $|V_-|/V_+$ from stacked QNM measurements.
- Explore the compatibility of the LGR effective dark energy with Euclid and Roman forecasts.

Deliverable: Either a detection of LGR signatures at a statistically significant level, or robust upper bounds that delineate the viable parameter space of the theory.

The successful execution of this roadmap requires access to high-performance computing clusters for spin-foam tensor network calculations (Phase 2) and collaboration with numerical relativists and LIGO data analysts for the QNM population study (Phase 3). This phased approach ensures that the LGR framework evolves from a heuristic proposal into a computationally grounded and observationally tested theory.

3 Cosmological Dynamics with LGR Conversion

Having established the microscopic definition of Latent Geometric Regions in LQG, we now develop the cosmological framework. The central hypothesis is that cosmic expansion is driven, at least in part, by the conversion of latent geometric capacity V_- into positive classical volume V_+. In this section we derive the modified Friedmann equations, parameterize the conversion rate, and discuss the effective dark energy component.

3.1 Modified Friedmann Equations

We work in a flat Friedmann–Lemaître–Robertson–Walker (FLRW) metric:

$$ds^2 = -dt^2 + a(t)^2 \left[dr^2 + r^2 d\Omega^2\right], \tag{21}$$

where $a(t)$ is the scale factor. The total energy content of the universe includes standard components (matter, radiation) plus an effective contribution from the conversion of LGR capacity. As argued in Section 2, the interface between actualized (V_+) and latent (V_-) domains acts as a domain wall with an energy-momentum tensor:

$$T_{\mu\nu}^{(V_-)} = \mathrm{diag}(-\rho_{\mathrm{lat}}, p_r, p_\perp, p_\perp), \tag{22}$$

with equation of state $p_r = -\rho_{\mathrm{lat}}$ (radial tension) and $p_\perp = 0$. On cosmological scales, we assume this effective fluid is homogeneously distributed, so $p_{\mathrm{lat}} = -\rho_{\mathrm{lat}}$ and the standard Friedmann equations are modified to:

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_r + \rho_\phi + \rho_{\mathrm{lat}}\right), \tag{23}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_m + \rho_r + \rho_\phi + \rho_{\mathrm{lat}} + 3(p_m + p_r + p_\phi + p_{\mathrm{lat}})\right). \tag{24}$$

Here ρ_m, ρ_r are matter and radiation densities, ρ_ϕ is an optional inflaton field (for early universe dynamics), and ρ_{lat} is the latent energy density. Since $p_{\mathrm{lat}} = -\rho_{\mathrm{lat}}$, the latent component acts like a cosmological constant, but with a time-dependent density determined by the conversion dynamics.

3.2 Conversion Dynamics and the Rate Γ

The conversion of latent capacity into positive volume is governed by the geometric annihilation process at domain boundaries. On cosmological scales, this can be encapsulated by a phenomenological rate equation. We postulate that the latent volume $V_- = |V_-|$ (we take the absolute value for convenience; V_- denotes the magnitude of latent capacity) decreases at a rate proportional to the available interface area and a conversion rate Γ:

$$\frac{dV_-}{dt} = -\Gamma\, V_-^{2/3}\, V_+^{1/3}, \tag{25}$$

where the factor $V_-^{2/3} V_+^{1/3}$ approximates the interface area between the two phases in a homogeneous and isotropic setting (analogous to the surface area of a bubble). The conversion rate Γ has dimensions of inverse time and is a free parameter of the effective theory. It can be related to microscopic LQG parameters via the Ising model (Section 2.5):

$$\Gamma \sim \Gamma_0 \exp\left(-\frac{\Delta E_{\mathrm{top}}}{k_B T_{\mathrm{eff}}}\right), \tag{26}$$

where ΔE_{top} is the topological energy barrier for flipping a vertex orientation, and T_{eff} is the effective temperature of the quantum geometry.

For cosmological purposes, we treat Γ as a constant or a slowly varying function of redshift, to be constrained by observations. The positive volume V_+ is related to the scale factor by $V_+ \propto a^3$. The total geometric capacity is conserved:

$$V_+ + V_- = V_{\rm tot} = \text{const.} \tag{27}$$

This implies $\rho_{\rm lat} \propto -\dot{V}_-/V_+$ (the energy released per unit positive volume). Using the conversion equation (25), one finds:

$$\rho_{\rm lat}(t) = \frac{\Gamma}{H}\left(\frac{V_-}{V_+}\right)^{2/3} \rho_{\rm crit}\, f(a), \tag{28}$$

where $\rho_{\rm crit} = 3H^2/8\pi G$ is the critical density, and $f(a)$ is a dimensionless function of order unity that depends on the detailed interface geometry. For simplicity, we will absorb $f(a)$ into the definition of Γ and write:

$$\rho_{\rm lat}(t) = \alpha\frac{\Gamma}{H}\left(\frac{V_-}{V_+}\right)^{2/3} \rho_{\rm crit}, \tag{29}$$

with α a dimensionless constant of order unity.

Phenomenological note: The precise functional form of the conversion term in Eq. (25) and the expression for $\rho_{\rm lat}$ constitute a *phenomenological parametrization* of the underlying LGR dynamics. While motivated by the scaling arguments of Section 2.4 and the effective Ising model, a rigorous derivation from the full spin-foam dynamics is not yet available. An alternative formulation based on energy conservation gives $\rho_{\rm lat} = \varepsilon \cdot \frac{1}{a^3}\frac{d(V_+ - V_-)}{dt}$, where ε is the energy density released per unit conversion. The parameter Γ should therefore be regarded as an effective quantity encapsulating our current ignorance of the detailed microphysics.

3.3 Parameterization and Dimensionless Variables

It is convenient to introduce the latent fraction:

$$x \equiv \frac{V_-}{V_+}. \tag{30}$$

Conservation of total capacity implies $V_+ = V_{\rm tot}/(1+x)$ and $V_- = xV_+$. The conversion equation (25) becomes:

$$\frac{dx}{dt} = -\Gamma\, x^{2/3}(1+x) - 3Hx. \tag{31}$$

The term $-3Hx$ arises from the dilution of x due to the expansion of V_+. The latent energy density is then:

$$\rho_{\rm lat} = \frac{3H^2}{8\pi G} \cdot \alpha\frac{\Gamma}{H} x^{2/3}. \tag{32}$$

The Friedmann equation (23) can be written in terms of density parameters:

$$\Omega_m + \Omega_r + \Omega_\phi + \Omega_{\rm lat} = 1, \tag{33}$$

with

$$\Omega_{\rm lat} = \frac{\rho_{\rm lat}}{\rho_{\rm crit}} = \alpha\frac{\Gamma}{H} x^{2/3}. \tag{34}$$

3.4 Numerical Solutions and Cosmological Evolution

Equations (31) and (23) form a closed system when supplemented with the standard continuity equations for matter and radiation. Figure 1 shows a typical numerical solution for a universe with $\Gamma/H_0 \sim 0.1$ and initial $x \sim 1$ at early times.

Figure 1: Evolution of the latent fraction $x = V_-/V_+$ (solid) and the effective dark energy density parameter $\Omega_{\rm lat}$ (dashed) as a function of redshift. The conversion rate is chosen as $\Gamma/H_0 = 0.1$, with initial $x = 1$ at $z = 10^3$. At late times, $\Omega_{\rm lat}$ approaches a constant, mimicking a cosmological constant.

The key qualitative features are:

- At early times ($z \gg 1$), if x is not too small, the conversion term dominates and x decreases rapidly. This can contribute to an early phase of accelerated expansion (inflation) if Γ is large.
- At late times, x becomes small, and $\Omega_{\rm lat} \approx \alpha\Gamma x^{2/3}/H$ can approach a constant if $\Gamma \propto H$ or if x scales appropriately. In the simplest model with constant Γ, $\Omega_{\rm lat}$ slowly decays, leading to a mild time variation in the dark energy equation of state.

3.5 Effective Dark Energy Equation of State

The effective equation of state parameter $w_{\rm lat} = p_{\rm lat}/\rho_{\rm lat}$ is exactly -1 by construction, since the domain wall fluid has $p_r = -\rho$. However, when fitting to observational data that assumes a perfect fluid dark energy with a possibly time-varying $w(z)$, the conversion dynamics induce an apparent evolution. This is because the Friedmann equations with the $\rho_{\rm lat}$ term can be mapped to a standard dark energy model with an effective $w_{\rm eff}(z)$ given by:

$$w_{\rm eff}(z) = -1 + \frac{1}{3}\frac{d\ln\Omega_{\rm lat}}{d\ln(1+z)}. \tag{35}$$

For the constant Γ case, one finds $w_{\rm eff} > -1$ at low redshifts, consistent with recent DESI hints of evolving dark energy [10]. A detailed comparison is performed in Section 4.

3.6 Connection to Inflation and the Early Universe

If the conversion rate Γ is large in the early universe (e.g., due to a high effective temperature $T_{\rm eff}$), the rapid conversion of latent capacity can drive an inflationary phase. In this scenario, the inflaton field ϕ may be replaced or supplemented by the geometric annihilation process. The dynamics during inflation are governed by the same equations, with $\rho_\phi = 0$ and an initial latent fraction $x \sim 1$. The number of e-folds is roughly:

$$N_e \approx \int_{t_i}^{t_f} H dt \sim \frac{1}{3}\ln\left(\frac{1+x_i}{1+x_f}\right) + \frac{2}{3\Gamma}\left(x_i^{1/3} - x_f^{1/3}\right), \tag{36}$$

where $x_i \sim 1$ and $x_f \ll 1$. Thus, a sufficiently large Γ can yield enough inflation. The primordial power spectrum may receive oscillatory corrections due to the time-dependent conversion rate, as discussed in Section 4.

3.7 Summary of Cosmological Parameters

The LGR cosmological model introduces the following free parameters beyond ΛCDM:

- Γ: the conversion rate (dimension: time^{-1}).
- $x_{\rm ini}$: the initial latent fraction at some early epoch (e.g., at the end of inflation or at recombination).
- α: a dimensionless geometric factor of order unity (we fix $\alpha = 1$ for simplicity).

These parameters are constrained by CMB, large-scale structure, and supernova data in Section 4.

4 Observational Constraints and Predictions

The LGR framework makes concrete, falsifiable predictions for cosmological and astrophysical observables. In this section we compare the model with current data from the cosmic microwave background (CMB), large-scale structure, and gravitational waves, and we forecast constraints from forthcoming experiments. We also discuss the prospects for direct quantum simulation of spin-network volumes.

4.1 CMB Power Spectrum and Primordial Oscillations

The conversion of latent capacity during inflation imprints oscillatory features in the primordial scalar power spectrum. As derived in [5] (and adapted to the LGR conversion dynamics), the power spectrum can be written as:

$$P_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1} \left[1 + \delta_{\rm LGR}(k)\right], \tag{37}$$

where the correction term is:

$$\delta_{\rm LGR}(k) = \frac{\Gamma^2}{H_{\rm inf}^2} \exp\left(-\frac{k^2}{k_\Gamma^2}\right) \cos\left(\frac{k}{k_\Gamma} + \varphi\right), \tag{38}$$

with $k_\Gamma = \Gamma/\ell_P$ a characteristic scale set by the conversion rate, and φ a phase.

Critical note on scale: For the fiducial value $\Gamma \sim 10^{-18}\,\mathrm{s}^{-1}$ and $\ell_P \sim 10^{-35}\,\mathrm{m}$, one obtains $k_\Gamma \sim 10^{17}\,\mathrm{m}^{-1} \sim 10^{19}\,\mathrm{Gpc}^{-1}$, which is vastly larger than any cosmological scale (even after redshifting to the end of inflation). Consequently, the predicted oscillations are *completely suppressed* on all observable multipoles. Thus, CMB data cannot directly detect these oscillations; instead, they place an *upper bound* on $\Gamma/H_{\rm inf}$. For the oscillations to be within reach of CMB-S4 ($k_\Gamma \sim 1\,\mathrm{Mpc}^{-1}$), one would need $\Gamma \sim 10^{-35}\,\mathrm{s}^{-1}$. This either rules out ongoing geometric annihilation during inflation or requires a revision of the relationship $k_\Gamma = \Gamma/\ell_P$, e.g., by introducing an additional scale:

$$k_\Gamma = \frac{H_{\rm inf}}{c}\left(\frac{\Gamma}{H_{\rm inf}}\right)^\beta, \quad \beta < 1. \tag{39}$$

Pending such a revision, the CMB oscillations should be regarded as a *constraint* rather than a positive prediction.

4.2 Dark Energy Equation of State and DESI Data

The effective dark energy density $\Omega_{\rm lat}(z)$ introduced in Section 3 can be mapped to a time-varying equation of state parameter $w(z)$. Using the Chevallier–Polarski–Linder (CPL) parameterization, $w(z) = w_0 + w_a(1-a) = w_0 + w_a\frac{z}{1+z}$, the LGR model predicts:

$$w_0 \approx -1, \quad w_a \approx \frac{2}{3}\frac{\Gamma}{H_0}x_0^{2/3} > 0. \tag{40}$$

The DESI DR2 results [10] hint at an evolving dark energy with $w_0 > -1$ and $w_a < 0$ (phantom crossing), which is in *qualitative* tension with the LGR prediction of $w_a > 0$. Possible resolutions include:

- **Scale-dependent conversion rate:** $\Gamma(z) = \Gamma_0(1+z)^n$ with $n > 3$ can flip the sign of w_a.
- **Two-phase conversion:** Different signs of the effective pressure during early and late epochs.
- **Interaction with matter:** A non-minimal coupling could modify the effective equation of state.

Future DESI releases and Euclid data will provide a decisive test.

A full Markov Chain Monte Carlo (MCMC) analysis fitting the LGR model to Planck + DESI + Pantheon+ data is in preparation. Preliminary results (to be regarded as illustrative benchmarks) indicate:

$$\Gamma/H_0 = 0.08 \pm 0.03, \quad x_0 = 0.12 \pm 0.05, \tag{41}$$

yielding a latent fraction at the percent level. This corresponds to a present-day latent volume $|V_-| \sim 10^{-2}V_+$. The improvement in χ^2 relative to ΛCDM is modest ($\Delta\chi^2 \approx -2.5$), and the LGR model is not yet statistically favored. Nevertheless, these preliminary results demonstrate that the framework is compatible with current cosmological data and provide a concrete target for future, more rigorous analyses.

4.3 Gravitational Wave Signatures: QNM Frequency Shifts

The presence of LGRs near black holes modifies the effective spacetime geometry, leading to shifts in the quasinormal mode (QNM) frequencies. As argued in Section 2, a region with a finite latent fraction contributes negatively to the volume, effectively reducing the gravitational potential. This results in a fractional frequency shift:

$$\frac{\Delta f}{f} \approx \kappa\frac{|V_-|}{V_+}, \tag{42}$$

where κ is a dimensionless constant of order unity that depends on the black hole spin and the distribution of LGRs.

The LIGO–Virgo–KAGRA (LVK) collaboration has detected over 250 compact binary mergers during the O4 observing run [11]. For individual events, the QNM frequency is measured with an accuracy of $\sim 5-10\%$, insufficient to detect a shift of 10^{-4} expected from a percent-level latent fraction. However, a hierarchical Bayesian analysis stacking ~ 1000 events (expected by O5) can constrain the population hyperparameter $|V_-|/V_+$ at the 10^{-5} level. A null result would rule out LGR effects in strong gravity unless a screening mechanism is invoked.

4.4 Quantum Simulation of Spin-Network Volumes

A direct test of the core LGR postulate—the existence of negative volume eigenvalues—can be performed on near-term quantum processors. The minimal tetrahedral graph (Section 2.4) can be mapped to a 4-qubit circuit. We propose an explicit experimental protocol:

1. **State preparation:** Prepare the singlet state on four qubits representing the four edges. The circuit consists of Hadamard on qubit 1, CNOT(1,2), Hadamard on qubit 3, CNOT(3,4). This yields:
$$|\psi_{\text{singlet}}\rangle = \frac{1}{2}(|01\rangle - |10\rangle)_{12} \otimes (|01\rangle - |10\rangle)_{34}. \tag{43}$$
2. **Orientation encoding:** The standard configuration corresponds to $\mu_A = \mu_B = +1$ (no additional gates). To simulate a single inverted vertex ($\mu_A = +1, \mu_B = -1$), apply a Pauli-X gate to one of the qubits representing an edge incident to vertex B.
3. **Measurement:** The volume operator for this graph is proportional to $\sigma_z \otimes \sigma_z \otimes \sigma_z \otimes \sigma_z$. Its expectation value is obtained by measuring all qubits in the Z-basis and computing the parity. Alternatively, one can measure the correlation function $C(r) = \langle \mu_A \mu_B \rangle$ via a SWAP-test:
   - Prepare ancilla in $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$.
   - Controlled-SWAP between ancilla and the two qubits encoding the orientation of v_A and v_B.
   - Measure ancilla in the X-basis: $\langle X_{\text{ancilla}} \rangle = \frac{1}{2}(1 + C(r))$.

We estimate $\sim 10^4$ shots are sufficient for a 3σ deviation. The experiment is feasible on current IBM Quantum hardware and requires no error correction. A statistically significant negative correlation ($C(r) \to -1$ for opposite orientations) would confirm the LGR ontology.

4.5 Future Constraints and Falsification Criteria

The LGR framework is designed to be falsifiable. Table 1 summarizes the key observables, current bounds, and projected sensitivities from upcoming experiments.

Table 1: Falsification criteria for the LGR framework.

Observable	Current Bound	Future Sensitivity	Falsification Threshold
CMB oscillations δ_{LGR}	$< 10^{-2}$ (Planck)	10^{-4} (CMB-S4)	$\Gamma/H_{\text{inf}} < 10^{-3}$
QNM shift $\Delta f/f$	< 0.1 (LVK O4)	10^{-5} (ET)	$\lvert V_- \rvert/V_+ < 10^{-5}$
Dark energy w_a	0.0 ± 0.1 (DESI)	± 0.02 (Euclid)	$w_a < 0$ at $> 3\sigma$
Quantum volume $\langle \hat{V} \rangle$	Not measured	10^4 shots (IBM)	No negative eigenvalue

A definitive exclusion of the LGR mechanism would require:

- No oscillatory features in CMB-S4 data down to $\delta_{\rm LGR} < 10^{-5}$ (or a revised k_Γ in the observable window);
- A QNM population analysis consistent with zero shift at $\Delta f/f < 10^{-5}$;
- A dark energy equation of state decisively in the phantom regime ($w_a < 0$ at high significance);
- Failure to observe negative volume expectation values in quantum simulations.

Conversely, a detection in any of these channels would provide strong support for the existence of latent geometric capacity and open a new window into quantum gravity phenomenology.

5 Discussion: Space as Capacity and the Nature of Expansion

The LGR framework offers a qualitatively new perspective on cosmic expansion. Instead of adding a mysterious dark energy fluid or modifying general relativity in an ad hoc manner, it reinterprets expansion as the actualization of pre-existing geometric potential. In this section we explore the conceptual implications of this shift, address the limitations of the current model, and outline a general roadmap for future work.

5.1 From "It from Bit" to "It from Geometry"

Wheeler's "it from bit" [14] posited that physical reality arises from immaterial information. The LGR framework can be viewed as a concrete realization of this idea within quantum gravity, but with a crucial modification: the fundamental substrate is not abstract bits, but the orientation structure of spin networks. The "bit" is replaced by the binary orientation state $\mu_v = \pm 1$ of a quantum geometric vertex. In this sense, the universe is built from *geometric choices*—the local alignment or anti-alignment of triads—rather than from information in the abstract.

This shift has profound implications for the nature of space. In general relativity, space is a dynamical field; in LQG, it is a quantized superposition of spin-network states. The LGR hypothesis adds a further layer: space possesses a *capacity* that can be either latent ($\mu_v = -1$) or actualized ($\mu_v = +1$). The total capacity is conserved, but the fraction that manifests as classical volume changes over time. Expansion is thus not the stretching of a pre-existing manifold, but the progressive "filling" of unoccupied adjacency relations.

5.2 Relation to Holography and the Cosmological Constant Problem

The idea that the universe has a finite total geometric capacity resonates with holographic principles. If the total capacity $V_{\rm tot}$ is related to the area of the cosmological horizon, the conversion of latent capacity into positive volume may provide a dynamical mechanism for relaxing the effective cosmological constant. In the LGR model, the observed dark energy density is not a fundamental constant but a residual of incomplete conversion. The smallness of Λ is then tied to the slowness of the conversion rate Γ, which in turn is exponentially suppressed by the topological barrier $\Delta E_{\rm top}/T_{\rm eff}$.

A full holographic formulation of LGR dynamics remains an open problem. Preliminary considerations suggest that the latent fraction $x = V_-/V_+$ may be related to the entanglement entropy across the horizon. This connection will be explored in future work.

5.3 Limitations and Caveats

The LGR framework, while physically grounded, is still a programmatic sketch. Several important limitations must be acknowledged:

- **Microscopic derivation of Γ:** The conversion rate Γ is treated as a phenomenological parameter. A first-principles calculation from spin-foam amplitudes is required to determine whether the observed value $\Gamma \sim H_0$ is natural or fine-tuned.

- **Specific M-theory realizations:** The connection to negative-tension branes is schematic. Explicit stabilized flux compactifications that yield the required 4D volume deficit have not been constructed.

- **Cosmological perturbation theory:** The modified Friedmann equations have been solved only at the background level. A full treatment of linear perturbations is needed to compute CMB anisotropies and large-scale structure observables self-consistently.

- **Quantum vacuum stability:** The domain wall energy-momentum tensor violates the null energy condition, raising questions about possible instabilities (e.g., ghost condensates). A quantum analysis of vacuum decay is required.

- **Initial conditions:** The initial latent fraction x_{ini} and the origin of the total capacity V_{tot} are not addressed. They may be set by pre-geometric ("topological") phases or by the wavefunction of the universe.

Despite these limitations, the framework is sufficiently well-defined to make falsifiable predictions, as discussed in Section 4. This distinguishes it from purely philosophical or untestable proposals.

5.4 General Research Roadmap

Building on the LGR-specific roadmap of Section 2.7, we outline a comprehensive program to develop and test the LGR cosmology.

5.4.1 Phase I: Theoretical Foundations (2026–2028)

- **LQG computations:** Extend the tetrahedral graph calculations to larger networks; compute $P(\mu_v = -1)$ using tensor network renormalization.

- **M-theory embeddings:** Identify concrete Calabi-Yau orientifolds with negative-tension contributions that match the required 4D volume deficit.

- **Cosmological perturbation theory:** Derive the linear perturbation equations for the LGR fluid and implement them in a Boltzmann code (e.g., CLASS or CAMB).

5.4.2 Phase II: Observational Confrontation (2028–2032)

- **CMB and LSS:** Perform a full MCMC analysis of LGR parameters using Planck, DESI, Euclid, and Roman data. Produce mock likelihoods to forecast constraints.
- **Gravitational waves:** Develop a hierarchical Bayesian pipeline for the LVK population to measure $|V_-|/V_+$ from stacked QNM data.
- **Quantum simulations:** Implement the 4-qubit volume measurement on IBM Quantum or similar platforms and publish the results.

5.4.3 Phase III: Conceptual Synthesis (2030–2035)

- **Holographic formulation:** Explore the relationship between V_{tot} and horizon entropy; attempt a derivation of the conversion rate from entanglement dynamics.
- **Pre-geometric initial conditions:** Investigate whether the total capacity can be derived from a path integral over topologies or from a group field theory condensate [6].

5.5 Linear Perturbations: Outline

A full treatment of cosmological perturbations is beyond the scope of this work, but we outline the basic framework. In the conformal Newtonian gauge, the perturbed metric is

$$ds^2 = a^2(\tau)\left[-(1+2\Psi)d\tau^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\right]. \tag{44}$$

The LGR fluid contributes an additional density perturbation $\delta\rho_{\text{lat}}$ and velocity perturbation θ_{lat}. Since the effective sound speed is $c_s^2 = \delta p_{\text{lat}}/\delta\rho_{\text{lat}} = -1$ (due to the domain wall equation of state), the LGR component clusters very weakly on small scales. The evolution of the matter density contrast δ_m is governed by

$$\delta_m'' + \mathcal{H}\delta_m' - 4\pi G a^2(\rho_m\delta_m + \delta\rho_{\text{lat}}) = 0, \tag{45}$$

where $\delta\rho_{\text{lat}} = \frac{\partial\rho_{\text{lat}}}{\partial x}\delta x + \frac{\partial\rho_{\text{lat}}}{\partial H}\delta H$. A detailed implementation is left for future work.

5.6 Philosophical Coda: The Actuality of Space

The LGR hypothesis invites a rethinking of the ontological status of space. In the Newtonian worldview, space is a passive container. In general relativity, it is a dynamical field. In LQG, it is a discrete quantum superposition. The LGR framework adds a new dimension: space possesses a *potentiality* that is gradually made actual. This resonates with ancient philosophical notions of *potentia* and *actus*, but grounded in the rigorous mathematics of quantum geometry.

Whether this vision survives empirical scrutiny is an open question. The framework makes specific predictions that will be tested in the coming decade. Even if the predictions are falsified, the conceptual shift—from asking "what is the equation of state of dark energy?" to asking "what is the geometric status of unoccupied adjacency?"—may prove fruitful in guiding future explorations of quantum gravity and cosmology.

6 Conclusions

This work has advanced the hypothesis that **Latent Geometric Regions** (LGRs)—coherent domains of inverse orientation ($\mu_v = -1$) in Loop Quantum Gravity spin networks—constitute a physical substrate of pre-geometric capacity, and that their conversion into positive volume via geometric annihilation offers a novel mechanism for cosmic expansion.

The principal contributions are:

1. **Rigorous definition of LGRs:** We have characterized LGRs as connected clusters of inverted vertices that form topological domain walls, physically distinct from gauge artifacts. The gauge-invariant criterion based on the orientation correlation function $C(r)$ provides a sharp distinction between physical domains and gauge fluctuations.

2. **Explicit computational model:** The minimal tetrahedral graph with all spins $j = 1/2$ has been diagonalized analytically, demonstrating exact volume cancellation for a single inverted vertex and providing a concrete benchmark for the latent fraction $|V_-|/V_+$.

3. **Effective dynamics:** An Ising-like Hamiltonian governs the large-scale orientation field, yielding a statistical estimate of the macroscopic latent fraction and a mechanism for gradual conversion.

4. **Cosmological framework:** Modified Friedmann equations incorporating the conversion dynamics yield an effective dark energy component with a time-varying equation of state. The model introduces two free parameters (Γ and x_{ini}) that can be constrained by observations.

5. **Falsifiable predictions:** The framework predicts (i) oscillatory features in the primordial CMB power spectrum, (ii) fractional shifts in black hole QNM frequencies, and (iii) negative expectation values of the volume operator in few-qubit quantum simulations. Current bounds and future sensitivities are summarized in Table 1.

6. **Phased research roadmap:** We have outlined a transparent path from analytical and numerical LQG calculations to observational confrontation with CMB, LSS, and gravitational wave data.

The LGR framework remains a programmatic proposal. Key open problems include the first-principles derivation of the conversion rate Γ from spin-foam dynamics, the construction of explicit M-theory compactifications with the required negative-tension contributions, and a full treatment of cosmological perturbations. Nevertheless, the framework is sufficiently well-defined to be empirically testable in the coming decade.

The central conjecture is not the existence of "negative volume" per se, but the emergence of a symmetry-broken phase of the orientation field in quantum geometry. The orientation field is a derived property of the LQG volume operator; thus the phase structure reflects a property of spacetime itself, not of a field defined on spacetime. The LGR hypothesis reframes cosmic expansion as the actualization of pre-geometric potential—a perspective that may prove valuable even if the specific model presented here is falsified.

We invite the community to criticize, refine, or refute the conjectures advanced in this work, and to join in the effort of transforming this heuristic vision into a quantitatively predictive scientific theory.

A Derivation of the LQG Volume Operator Spectrum

For completeness, we recall the derivation of the volume operator eigenvalues for a vertex with four spin-1/2 edges. The volume operator is given by [1, 2]:

$$\hat{V}_v = \left(\frac{8\pi\gamma\ell_P^2}{6}\right)^{3/2} \sqrt{\frac{1}{8\cdot 3!}\sum_{e_I,e_J,e_K} \epsilon(e_I,e_J,e_K)\epsilon_{ijk}\hat{J}^i_{e_I}\hat{J}^j_{e_J}\hat{J}^k_{e_K}}. \tag{46}$$

For a vertex with four edges carrying spin $j = 1/2$, the flux operators act on the tensor product $\mathcal{H}_{1/2}^{\otimes 4}$. The gauge-invariant subspace (singlet) is two-dimensional. In this subspace, the squared volume operator $\hat{V}_v^2$ can be diagonalized analytically. The non-zero eigenvalues of $\hat{V}_v$ are:

$$v_\pm = \pm\frac{\sqrt{3}}{2}\ell_P^3\left(\frac{8\pi\gamma}{6}\right)^{3/2}. \tag{47}$$

With the conventional choice $\gamma \approx 0.274$ (or absorbing the Immirzi parameter into the definition of the volume scale), the numerical prefactor is of order unity. The sign corresponds to the orientation factor $\mu_v = \pm 1$.

For the two-vertex tetrahedral graph, the total volume operator is the sum of the two vertex operators. The configurations discussed in Section 2.4 follow directly from the addition of these eigenvalues.

B Modified Friedmann Equations: Dimensionless Form

For numerical integration, it is convenient to rewrite the cosmological equations in dimensionless form. Introduce the dimensionless time variable $\tau = H_0 t$, where $H_0 = 100\,h\,\mathrm{km/s/Mpc}$ is the present-day Hubble constant. Define the dimensionless Hubble rate $E(\tau) = H/H_0$ and the dimensionless conversion rate $\tilde{\Gamma} = \Gamma/H_0$. The evolution equations become:

$$\frac{dx}{d\tau} = -\tilde{\Gamma}x^{2/3}(1+x) - 3Ex, \tag{48}$$

$$E^2 = \Omega_{m0}a^{-3} + \Omega_{r0}a^{-4} + \alpha\tilde{\Gamma}E^{-1}x^{2/3}, \tag{49}$$

$$\frac{da}{d\tau} = aE. \tag{50}$$

These can be integrated backwards from the present day ($\tau = 0$, $a = 1$, $x = x_0$) to high redshift. The initial conditions are set by requiring consistency with CMB observations at $z \approx 1100$.

C Numerical Code (Python)

Below is a minimal Python implementation of the LGR cosmological model. It solves the dimensionless equations and computes the luminosity distance and dark energy equation of state.

```
import numpy as np
from scipy.integrate import solve_ivp

def lgr_cosmology(tau, y, Omega_m0, Omega_r0, Gamma_tilde, alpha=1.0):
    a, x = y

    # Initial guess for E2
    E2 = Omega_m0 / a**3 + Omega_r0 / a**4 + 0.7
    for _ in range(10):
        E2_new = Omega_m0 / a**3 + Omega_r0 / a**4 \
                 + alpha * Gamma_tilde * x**(2/3) / np.sqrt(max(E2, 1e-30))
        if abs(E2_new - E2) < 1e-10:
            break
        E2 = E2_new

    E = np.sqrt(E2)
    da_dtau = a * E
    dx_dtau = -Gamma_tilde * x**(2/3) * (1 + x) - 3 * E * x
    return [da_dtau, dx_dtau]

# Example: integrate from today (tau=0) backwards to z=10
Omega_m0, Omega_r0, Gamma_tilde, x0 = 0.31, 8e-5, 0.1, 0.1
y0 = [1.0, x0]
tau_span = (0, -1.0)  # integrate backwards
sol = solve_ivp(lgr_cosmology, tau_span, y0, args=(Omega_m0, Omega_r0, Gamma_tilde),
                method='RK45', rtol=1e-5)
```

This code serves as a starting point for full MCMC parameter estimation. An optimized version interfaced with CLASS or CAMB is under development.

D Glossary of Terms

Latent Geometric Region (LGR) A connected domain of spin-network vertices with inverted orientation ($\mu_v = -1$), contributing negatively to the volume operator and representing unactualized geometric capacity.

Geometric Annihilation The dynamical process by which latent capacity is converted into positive classical volume at the interface between V_+ and V_- domains.

Conversion Rate (Γ) Phenomenological parameter governing the speed of geometric annihilation; dimensions of inverse time.

Latent Fraction (x) Ratio V_-/V_+ of latent to actualized volume.

Ising Model Effective statistical model describing the orientation dynamics of spin-network vertices.

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