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

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Abstract

We study coherent aggregates of orientation-reversed contributions in the spectrum of the Loop Quantum Gravity (LQG) volume operator and investigate their possible coarse-grained statistical description. These configurations correspond to sectors of the kinematical Hilbert space where orientation-dependent contributions to the volume operator change sign.

We develop an effective description in which cosmic evolution is governed by a dynamical redistribution between positive and negative orientation sectors. In this phenomenological picture, the macroscopic expansion of space can be modeled as an emergent phenomenon arising from the gradual conversion of latent geometric capacity into positive-volume-dominated configurations, mediated by domain-wall-like structures in the orientation field.

An effective statistical model based on an Ising-like representation of vertex orientations is introduced to describe the coarse-grained dynamics of LGRs. This leads to modified Friedmann equations with an additional time-dependent contribution that behaves similarly to dark energy at the background level. We derive the associated dynamical system and identify the relevant dimensionless parameters governing the conversion process.

The framework yields phenomenological implications for cosmological observables, including late-time expansion history and possible signatures in gravitational wave spectra and quantum geometric simulations. However, we emphasize that these predictions depend on an effective coarse-graining of LQG dynamics and should not be interpreted as direct consequences of a complete quantum gravitational theory.

The work is intended as a kinematically grounded but phenomenological extension of LQG, aiming to explore whether orientation-sector dynamics can provide an alternative interpretation of dark-energy-like behavior. 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, and outline a set of observational probes that could constrain or falsify the effective framework.

Contents

1 Introduction

The nature of cosmic expansion and the origin of dark energy remain among the central unresolved problems in modern cosmology. While the ΛCDM model provides an excellent phenomenological description of observational data, the physical origin of the cosmological constant and its extraordinarily small value remains unexplained within standard quantum field theory and general relativity. 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.

Loop Quantum Gravity (LQG) offers a non-perturbative quantization of spacetime geometry in which geometric observables such as area and volume acquire discrete spectra [2]. In this framework, geometric quantities are defined on spin-network states, and the volume operator exhibits a dependence on the orientation structure of vertices through sign-sensitive combinatorial factors.

In this work, we investigate the possibility that the orientation degree of freedom in LQG spin networks admits a physically meaningful coarse-grained interpretation beyond gauge redundancy. In particular, we consider sectors of the volume operator corresponding to opposite orientation states and interpret coherent regions dominated by such configurations as **Latent Geometric Regions** (LGRs). These regions contribute effectively negative expectation values to the volume operator at the kinematical level, not as a violation of geometric consistency, but as a reflection of the orientation-dependent structure of quantum geometry.

We emphasize that the phrase "negative volume" in this context does not imply a literal negative spatial extension, but rather encodes an orientation-reversed contribution within the quantum geometric Hilbert space. The central hypothesis of this work is that such sectors may undergo a dynamical coarse-grained evolution, leading to an effective redistribution between orientation states at macroscopic scales.

To describe this process, we introduce an effective statistical model in which spin-network vertex orientations are mapped to an Ising-like field on the underlying graph structure. The resulting domain formation dynamics generate interface contributions that can be interpreted as a conversion process between latent (orientation-reversed) and actualized (orientation-aligned) geometric configurations. At large scales, this leads to an effective fluid description that modifies the standard Friedmann equations through a time-dependent contribution associated with the latent sector.

Scope and status of this work. The goal of this paper is not to provide a complete quantum gravitational derivation of cosmological dynamics, but rather to explore whether orientation-sector structure in LQG can consistently give rise to an effective cosmological component with properties resembling dark energy. We therefore treat the framework as a phenomenological extension of LQG kinematics, subject to further refinement once a full dynamical treatment of spin-foam evolution becomes available. Throughout, we distinguish carefully between: (i) results that follow rigorously from LQG kinematics; (ii) effective models motivated by analogy and dimensional analysis; and (iii) speculative phenomenological extensions whose connection to the microscopic theory remains to be established.

This work builds on the kinematic framework of Latent Geometric Regions introduced in [1], retaining its core constructs—inverse-orientation domains, the tetrahedral volume calculation, and the Ising-like orientation dynamics—while discarding the M-theory parallel, wormhole conditions, and non-cosmological phenomenology as speculative scaffolding. The cosmological model developed here is entirely new; the kinematic foundations are not.

This paper is organized as follows. Section 2 states the hierarchy of assumptions. Section 3 provides a precise working definition of Latent Geometric Regions in LQG, including the minimal tetrahedral model and the effective Ising dynamics. Section 4 develops the cosmological framework: modified Friedmann equations, conversion rate parameterization, and numerical solutions. Section 5 derives phenomenological consequences and observational constraints. Section 6 discusses conceptual implications, limitations, and possible extensions. Section 7 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 Hierarchy of assumptions

To avoid ambiguity, we explicitly state the logical layers of this work:

1. **Exact LQG kinematics:** The volume operator, its spectrum, orientation factors $\mu_v = \pm 1$, and the analytical diagonalization on the tetrahedral graph (Section 3.4) are rigorous results within the kinematical Hilbert space of LQG.

2. **Heuristic extrapolations (coarse-grained statistical model):** The clustering of orientation-reversed vertices into coherent macroscopic domains, the Ising-like Hamiltonian, the domain-wall picture, and the phenomenological conversion rate Γ are not derived from LQG dynamics. They are introduced as a minimal parametrization of possible large-scale correlation structures.

3. **Phenomenological cosmological mapping:** The identification of the coarse-grained orientation distribution with a fluid-like stress-energy tensor, the modified Friedmann equations, and the observational implications are speculative and intended as an exploration of a possible effective description.

All equations and claims in the following sections are to be understood within this hierarchy. In particular, statements that appear to describe physical reality are to be read as *we investigate whether* or *we parametrize as.*

3 Latent Geometric Regions in Loop Quantum Gravity

In this section we provide a precise working definition of Latent Geometric Regions (LGRs) within the mathematical framework of Loop Quantum Gravity. We begin by recalling the structure of the volume operator in LQG and the role of vertex orientation. We then characterize LGRs as coherent domains of inverse orientation, distinguish them from gauge artifacts, and present an explicit computational model on a minimal graph.

Terminological note. Throughout this paper, the phrase “negative volume” refers exclusively to a sector of the LQG volume operator eigenvalue spectrum corresponding to orientation-reversed intertwiners. It does not imply a literal negative spatial extension or a violation of geometric consistency. The sign is a property of the quantum state within the kinematical Hilbert space, not of classical spacetime geometry.

3.1 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 [2]. 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.

3.2 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 3.6).

Status of the gauge argument. The above discussion is heuristic. In standard LQG, the sign μ_v is locally gauge-removable. However, in a coarse-grained description over many vertices, a global imbalance between $+1$ and -1 orientations may become an effective order parameter if the gauge symmetry is spontaneously broken or if the system is restricted to a physical sector by boundary conditions. This situation is analogous to ferromagnets: individual spins are gauge-equivalent under rotations, but the net magnetization is a physical observable. Here we *conjecture* that for sufficiently large correlated clusters, the average orientation $M(\Omega)$ can be treated as a physical variable. This assumption underlies the phenomenological model; a rigorous justification would require a non-perturbative analysis of the spin-foam path integral.

3.3 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:

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

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.

3.4 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 [4].

3.4.1 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 [2, 3]. 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 $\mu_v = \pm 1$.

3.4.2 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 microscopic "latent region" of size comparable to the Planck volume.

(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 macroscopic (relative to the graph) region of negative volume.

3.4.3 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 exceeds the stability bound $|V_-|/V_+ < 1/2$ introduced in Section 3.5, which signals that the two-vertex graph is too minimal to serve as a realistic model: it is too small to exhibit the partial cancellation characteristic of larger networks where most vertices remain actualized. 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).

3.4.4 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 Boltzmann-like factor

$$P(\text{domain of size } N) \approx \exp(-\sigma N/T_{\text{eff}}), \tag{11}$$

where σ is a domain-wall tension (in Planck units) and T_{eff} is an effective temperature of the quantum geometry, possibly set by the de Sitter horizon or the Planck temperature. In the thermodynamic limit, the fraction of inverted vertices is

$$f_{\text{inv}} \sim \exp(-\sigma/T_{\text{eff}}), \tag{12}$$

yielding a macroscopic latent fraction

$$|V_-|/V_+ \sim f_{\text{inv}} \sim \exp(-\sigma/T_{\text{eff}}). \tag{13}$$

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 quantitative determination of f_{inv} is deferred to the numerical simulations outlined in the research directions (Section 3.6).

3.4.5 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:

$$|V_-| \sim f_{\text{inv}} N \ell_P^3, \tag{14}$$

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.

3.5 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:

$$H_{\text{eff}} = -J \sum_{\langle v,w\rangle} \mu_v \mu_w + h \sum_v \mu_v, \tag{15}$$

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.

Status: This Hamiltonian is not derived from LQG dynamics; it is introduced as a phenomenological parametrization of possible correlation structures among orientation variables. A microscopic derivation of J and h would require computing matrix elements of the Hamiltonian constraint between spin-network states with different orientation patterns; this is left for future work.

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 4) 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 3.6).

The Ising Hamiltonian (15) 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 5.

3.6 Open Problems and Future Research Directions

The LGR framework presented in this section is physically grounded but remains programmatic in several respects. The following open problems define possible directions for future research focused on the quantum-gravitational aspects of LGRs.

3.6.1 Analytical Benchmarks

The most immediate theoretical priority is to replace the illustrative estimates of the latent fraction with order-of-magnitude calculations derived from simplified LQG models. This includes extending the minimal tetrahedral graph calculation (Section 3.4) to graphs with 4–10 vertices and varying spins ($j \leq 1$), computing the expectation value $\langle \hat{V}_\Omega \rangle$ for coherent states peaked on a classical geometry containing an inverse-orientation domain, and deriving an analytical bound on the latent fraction $|V_-|/V_+$ in the large-volume limit using random tensor network techniques.

3.6.2 Numerical Spin-Foam Simulations

A longer-term numerical program, contingent on suitable computational resources, would aim to estimate the dynamical probability $P(\mu_v = -1)$ from the spin-foam path integral. This would involve tensor network renormalization algorithms for the EPRL spin-foam amplitude on small 2-complexes, with extrapolation to larger triangulations using coarse-graining methods [5]. Such simulations would provide a numerically grounded probability distribution for the size and abundance of coherent inverse-orientation domains.

3.6.3 Phenomenological Constraints

If the analytical and numerical programs above yield concrete parameter estimates, a natural subsequent step would be a Bayesian fit of the LGR background evolution to CMB and large-scale structure data, and a hierarchical analysis of gravitational wave observations to constrain $|V_-|/V_+$. These directions are detailed further in Section 6.4.

4 Cosmological Dynamics with LGR Conversion

Having established the microscopic definition of Latent Geometric Regions in LQG, we now develop the effective cosmological framework. The central hypothesis is that cosmic expansion can be modeled, at least in part, as emerging from a dynamical redistribution between orientation sectors—specifically, the gradual 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 contribution to the dark energy budget. We emphasize throughout that this is an effective description; the connection to the full spin-foam dynamics remains to be established.

4.1 Modified Friedmann Equations

We work in a flat Friedmann–Lemaître–Robertson–Walker (FLRW) metric as a convenient simplification; spatial curvature could be included without affecting the qualitative dynamics. The metric is:

$$ds^2 = -dt^2 + a(t)^2 \left[dr^2 + r^2 d\Omega^2\right], \tag{20}$$

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 3, the interface between actualized (V_+) and latent (V_-) domains acts as a domain wall with an energy-momentum tensor. At the level of effective field theory, we parametrize this contribution as an anisotropic fluid:

$$T_{\mu\nu}^{(V_-)} = \mathrm{diag}(-\rho_{\mathrm{lat}}, p_r, p_\perp, p_\perp), \tag{21}$$

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:

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_r + \rho_\phi + \rho_{\mathrm{lat}}\right), \tag{22}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_m + \rho_r + \rho_\phi + \rho_{\mathrm{lat}} + 3(p_m + p_r + p_\phi + p_{\mathrm{lat}})\right). \tag{23}$$

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 behaves similarly to a cosmological constant at the background level, but with a time-dependent density determined by the conversion dynamics.

4.2 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:

$$\frac{dV_-}{dt} = -\Gamma\, V_-^{2/3}\, V_+^{1/3}, \tag{24}$$

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 3.5):

$$\Gamma \sim \Gamma_0 \exp\left(-\frac{\Delta E_{\mathrm{top}}}{k_B T_{\mathrm{eff}}}\right), \tag{25}$$

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

$V_+ \propto a^3$.

Conservation of total capacity: two working assumptions

The total geometric capacity is assumed to be conserved or to scale with volume. We consider two limiting cases:

$$\text{(A)} \quad V_+ + V_- = V_{\text{tot}} = \text{const}, \tag{26}$$

$$\text{(B)} \quad V_+ + V_- \propto a^3. \tag{27}$$

Case (A) corresponds to a fixed total number of spin-network vertices (e.g., for a fixed triangulation). Case (B) would arise if new vertices are created as the universe expands. In the following we adopt case (A) for definiteness, but note that the qualitative dynamics are similar; only the detailed evolution of the latent fraction changes slightly. A more rigorous derivation would require a spin-foam analysis of vertex number conservation.

Linking Γ to the Hubble rate

To reduce the number of free parameters, we explore the natural ansatz $\Gamma = \Gamma_0 \left(\frac{H}{H_0}\right)^n$. The case $n = 1$ (i.e., $\Gamma \propto H$) is particularly interesting because it makes the combination Γ/H constant, leading to $\Omega_{\text{lat}} = \alpha\Gamma_0 x^{2/3}$. In the following we keep Γ general but will comment on the $n = 1$ case when discussing observables.

Derivation of ρ_{lat}

Using the conversion equation (24) and energy conservation $\dot{\rho}_{\text{lat}} + 3H(\rho_{\text{lat}} + p_{\text{lat}}) = \dot{Q}$ (where $\dot{Q}$ is the energy release from conversion), one obtains:

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

where $\rho_{\text{crit}} = 3H^2/8\pi G$ and $F(a)$ is a dimensionless function of order unity that encodes the detailed interface geometry (e.g., domain wall shape). In the minimal model we absorb $F(a)$ into the definition of an effective coupling α, but we keep it explicit to show the inherent uncertainty. Thus

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

with α of order unity.

4.3 Parameterization and Dimensionless Variables

It is convenient to introduce the latent fraction:

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

Under assumption (A) (conserved V_{tot}), we have $V_+ = V_{\text{tot}}/(1+x)$ and $V_- = xV_+$. The conversion equation (24) 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:

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

The Friedmann equation (22) can be written in terms of density parameters:

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

with

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

4.4 Numerical Solutions and Cosmological Evolution

Equations (31) and (22) 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 Ω_{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, Ω_{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. In principle, this could be consistent with an early phase of accelerated expansion if Γ is sufficiently large, though this connection remains speculative.
- At late times, x becomes small, and $\Omega_{\text{lat}} \approx \alpha\Gamma x^{2/3}/H$ can approach a constant if $\Gamma \propto H$ or if x scales appropriately. In the simplest model with constant Γ, Ω_{lat} slowly decays, leading to a mild time variation in the dark energy equation of state.

4.5 Effective Dark Energy Equation of State

The effective equation of state parameter $w_{\text{lat}} = p_{\text{lat}}/\rho_{\text{lat}}$ is, at the local domain-wall level, approximating $w \approx -1$ due to the tension-dominated behavior. 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 ρ_{lat} term can be mapped to a standard dark energy model with an effective $w_{\text{eff}}(z)$ given by:

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

For the constant Γ case, one finds $w_{\text{eff}} > -1$ at low redshifts. A comparison with DESI data is discussed in Section 5.2. Note that this mapping is an effective reparameterization and does not by itself constitute a derivation of a fluid equation of state.

4.6 Summary of Cosmological Parameters

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

- Γ (or Γ_0 if linked to H): the conversion rate (dimension: time^{-1}). In this phenomenological model, Γ is treated as a free parameter to be constrained by observations; its relation to LQG microphysics is left for future work.
- x_{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).

At the present stage, this framework should be interpreted as an effective phenomenological parametrization of orientation-sector dynamics rather than a UV-complete predictive theory. The parameters Γ and x_{ini} encode our current ignorance of the detailed microphysics and are to be constrained empirically. Their natural values, fine-tuning, and relation to fundamental LQG quantities remain open problems addressed in the research directions of Section 3.6.

5 Observational Constraints and Phenomenological Implications

The LGR framework yields phenomenological implications that are in principle testable against cosmological and astrophysical data. In this section we discuss possible observational probes. The epistemic status of each observable is indicated in Table 1.

5.1 CMB Power Spectrum: Background Constraints

The LGR conversion dynamics affect the primordial power spectrum in principle through a time-dependent modification of the inflationary background. However, a careful dimensional analysis shows that the characteristic scale associated with the conversion rate is $k_\Gamma = \Gamma/\ell_P$. For $\Gamma \sim 0.1 H_0$ and $\ell_P \sim 10^{-35}\,\text{m}$, we find $k_\Gamma \sim 10^{-60}\,\text{Mpc}^{-1}$, which is vastly larger than the observable CMB scales ($k_{\text{CMB}} \sim 10^{-3}\,\text{Mpc}^{-1}$). Consequently, the LGR framework does not predict directly detectable primordial oscillations in the CMB power spectrum within the observable window.

The CMB data therefore serve primarily as a consistency check on the background conversion dynamics. An order-of-magnitude estimate suggests that any excess contribution from LGR conversion during recombination must satisfy $\Omega_{\text{lat}}(z_{\text{rec}}) \lesssim 0.01$ to remain compatible with the smoothness of the observed CMB. A full likelihood analysis would be required to turn this into a rigorous bound.

5.2 Dark Energy Equation of State and DESI Data

The effective dark energy density $\Omega_{\text{lat}}(z)$ introduced in Section 4 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:

$$w_0 \approx -1, \quad w_a \approx \frac{2}{3}\frac{\Gamma}{H_0}x_0^{2/3} > 0, \tag{36}$$

where x_0 is the present-day latent fraction. If we adopt the ansatz $\Gamma = \Gamma_0(H/H_0)^n$ with $n = 1$, then $\Gamma/H_0 = \Gamma_0$ is constant and

$$w_a \approx \frac{2}{3}\Gamma_0\, x_0^{2/3}. \tag{37}$$

For the illustrative values $\Gamma_0 = 0.1$ and $x_0 = 0.12$ we find $w_a \approx 0.015$.

We have performed a simplified comparison with DESI DR2 data. Using a Gaussian approximation to the DESI DR2 CPL constraint at fixed $w_0 = -1$ ($w_a = 0.0 \pm 0.1$), we obtain $\Delta\chi^2 \approx 0.02$, i.e., the model is well within the 1σ region. A full MCMC exploration of the (w_0, w_a) plane is deferred to future work. Thus the LGR prediction is **not excluded by current DESI constraints**.

Important note: The numbers $\Gamma_0 = 0.1$ and $x_0 = 0.12$ are chosen for illustration only; they do not represent a fit to observational data. The model does not postulate spatial flatness; the total density parameter $\Omega_{\text{tot}}(z = 0)$ is a prediction that can be compared with CMB and BAO measurements. A full parameter determination is required before any claim of consistency or inconsistency can be made.

5.3 Gravitational Wave Signatures: QNM Frequency Shifts

If LGRs are present in the vicinity of black holes, they would in principle modify the effective local geometry, potentially leading to shifts in the quasinormal mode (QNM) frequencies. Within the effective framework, a region with a finite latent fraction contributes negatively to the volume, which can be modeled as reducing the effective gravitational potential. We estimate that, if such effects couple to perturbations of black hole spacetimes, they could in principle induce fractional frequency shifts of order

$$\frac{\Delta f}{f} \approx \kappa\,\frac{|V_-|}{V_+}, \tag{38}$$

where κ is a dimensionless constant of order unity. For a percent-level latent fraction ($|V_-|/V_+ \sim 0.1$), the expected shift is of order 10^{-4}. A detailed numerical calculation for realistic black hole parameters and LGR distributions would be required to determine κ precisely; this order-of-magnitude estimate is presented only to assess possible detectability.

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}. However, a hierarchical Bayesian analysis stacking ~ 1000 events (expected by O5) could constrain the population hyperparameter $|V_-|/V_+$ at the 10^{-5} level. A null result at that sensitivity would place strong constraints on LGR effects in the strong-gravity regime within this effective framework.

5.4 Quantum Simulation of Spin-Network Volumes

A proof-of-principle analogue test of the core LGR kinematic postulate—the orientation-dependence of volume operator eigenvalues—can be performed on near-term quantum processors. The minimal tetrahedral graph (Section 3.4) can be mapped to a 4-qubit circuit, with the flux operators $\hat{J}_i^{(e)}$ represented as Pauli matrices.

We stress that such an experiment constitutes an *analogue simulation* of the toy model: a qubit encoding of orientation states is not equivalent to physical quantum geometry, and a positive result would confirm the consistency of the orientation-sensitive volume structure in this simplified representation, not the physical reality of LGRs in spacetime.

With that caveat clearly stated, we propose the following experimental protocol:

1. Prepare the singlet state of four qubits (representing the four spin-1/2 edges) using standard CNOT and Hadamard gates.
2. Measure $\langle \hat{V} \rangle$ in the all-actualized configuration ($\mu_A = \mu_B = +1$). This should yield a positive value proportional to $\sqrt{3}\ell_P^3$.
3. Apply a Pauli-X gate to one qubit to simulate a single inverted vertex ($\mu_A = +1, \mu_B = -1$). Remeasure $\langle \hat{V} \rangle$. The LQG prediction is exact cancellation to zero.

The experiment is feasible on current IBM Quantum hardware with $\sim 10^4$ shots. A result consistent with volume cancellation in configuration (3) would provide a toy-model realization of the orientation-dependent volume structure underlying the LGR construction.

5.5 Linear perturbations and structure formation

To make contact with large-scale structure observations, we outline the linear perturbation theory for the LGR fluid. In the conformal Newtonian gauge,

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

the stress-energy tensor of the LGR fluid is that of a perfect fluid with equation of state $w_{\rm lat} = -1$ and negligible anisotropic stress. The pressure perturbation is $\delta p_{\rm lat} = c_s^2 \delta\rho_{\rm lat}$. For a fluid with $w = -1$ that is not a pure cosmological constant, the sound speed can be set to zero if the fluid is non-adiabatic. We adopt the minimal assumption $c_s^2 = 0$ (i.e., no pressure perturbations), which suppresses clustering on subhorizon scales. (A non-zero sound speed would require modeling the microphysics of domain-wall oscillations, which is beyond the scope of this effective description.)

The continuity and Euler equations for the LGR component become

$$\delta'_{\rm lat} + 3\mathcal{H}(c_s^2 - w_{\rm lat})\delta_{\rm lat} = -(1+w_{\rm lat})\theta_{\rm lat}, \qquad \theta'_{\rm lat} + \mathcal{H}(1-3c_s^2)\theta_{\rm lat} = \frac{k^2}{1+w_{\rm lat}}\Phi,$$

where primes denote derivatives with respect to conformal time. For $w_{\rm lat} = -1$ and $c_s^2 = 0$, the equations simplify: $\delta'_{\rm lat} = 0$ (constant comoving density perturbation) and $\theta_{\rm lat} = 0$. Consequently, the LGR fluid does not contribute to the growth of structure on subhorizon scales; its only effect is through the background expansion. This behaviour differs from quintessence models and provides a potential observational discriminant. A full implementation in Boltzmann codes (e.g., CLASS) is required to derive precise CMB and matter power spectrum constraints, which we leave for future work.

5.6 Future Constraints and Falsification Criteria

The LGR framework yields observable signatures that could in principle constrain its parameters. Table 1 summarizes the key observables, current order-of-magnitude bounds, and projected sensitivities from upcoming experiments.

Table 1: Observational constraints and falsification criteria for the LGR framework (order-of-magnitude estimates).

Observable	Current Estimate	Future Sensitivity	Falsification Threshold
CMB background $\Omega_{\text{lat}}(z_{\text{rec}})$	< 0.01 (consistency)	$< 10^{-3}$ (CMB-S4)	$\Omega_{\text{lat}} > 0.01$
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 cancellation

A definitive exclusion of the LGR effective framework would require:

- A CMB-S4 measurement of background parameters inconsistent with any positive Ω_{lat} at recombination;
- 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), which would be in tension with the basic LGR prediction $w_a > 0$.

Conversely, an anomalous QNM population shift or a dark energy equation of state with $w_a > 0$ confirmed at high significance would motivate further investigation of orientation-sector dynamics.

6 Discussion: Interpretational Summary and Future Work

The LGR framework suggests a qualitatively different perspective on cosmic expansion. Rather than postulating a new dark energy fluid or modifying general relativity, it offers an interpretation in which expansion emerges from a redistribution of geometric orientation states. In this section we summarize the limitations and outline directions for future work.

6.1 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_{tot} is related to the area of the cosmological horizon, the conversion of latent capacity into positive volume could in principle provide a dynamical mechanism for relaxing the effective cosmological constant. We stress that this remains a speculative suggestion; no quantitative connection to the cosmological constant problem has been established.

6.2 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.
- **Cosmological perturbation theory:** We have outlined the linear perturbation equations (Section 5.5), but a full numerical implementation in a Boltzmann code is needed to compute precise CMB and matter power spectra.
- **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 $x_{\rm ini}$ and the origin of the total capacity $V_{\rm tot}$ are not addressed. They may be set by pre-geometric ("topological") phases or by the wavefunction of the universe.
- **Background expansion and spatial curvature:** The model does not assume spatial flatness a priori. The illustrative parameters $\Gamma_0 = 0.1, x_0 = 0.12$ lead to $\Omega_{\rm tot}(z = 0) \approx 0.33$, corresponding to an open universe. Whether such a value is compatible with CMB and BAO data is an open question that requires a dedicated parameter fit. This is not a flaw but a structural prediction of the framework.

Despite these limitations, the framework is sufficiently well-defined to make phenomenological implications, some of which may be falsifiable, as discussed in Section 5. This distinguishes it from purely philosophical or untestable proposals.

6.3 Interpretational Status of the Model

To avoid ambiguity, we summarize the epistemic status of the main ingredients of the LGR framework.

Established LQG ingredients (derived from the standard kinematical framework):

- The volume operator and its discrete spectrum [2, 3];
- The orientation dependence of volume eigenvalues ($\mu_v = \pm 1$);
- The analytical diagonalization of the volume operator on the tetrahedral graph (Section 3.4).

Heuristic extrapolations (motivated by analogy; not derived from spin-foam dynamics):

- The clustering of orientation-reversed vertices into coherent macroscopic domains;
- The Ising-like mapping and the associated domain-wall picture;

- The phenomenological conversion rate Γ and the conservation of total capacity.

Speculative phenomenology (dependent on the heuristic extrapolations above):

- The effective dark energy interpretation of Ω_{lat};
- QNM frequency shifts from LGR distributions near black holes;
- Any connection to inflation (speculative, not developed in this work).

At the present stage, the framework should be interpreted as an effective phenomenological parametrization of orientation-sector dynamics rather than a UV-complete predictive theory. The parameters Γ, α, and x_{ini} encode our ignorance of the detailed microphysics and should be constrained empirically rather than derived top-down.

6.4 Future Research Directions

We outline possible directions for future work, ordered roughly by theoretical proximity to the established LQG foundations. Recent advances in numerical LQG provide a foundation for our effective approach: the numerical implementation of the Hamiltonian constraint by Guedes et al. [6], the two-vertex model analysis by Cendal et al. [7], and the parametrization of the primordial power spectrum by Guillén et al. [8] demonstrate that the necessary computational tools are actively being developed.

Theoretical priorities:

- **LQG computations:** Extend the tetrahedral graph calculations to larger networks; compute $P(\mu_v = -1)$ using tensor network renormalization.
- **Cosmological perturbation theory:** Implement the LGR fluid in a Boltzmann code (e.g., CLASS) to derive precise constraints.
- **Conservation law:** Provide a justification of $V_{\text{tot}} = \text{const}$ from spin-foam dynamics or identify the correct replacement.
- **Effective scaling of ρ_{lat}:** Investigate whether different exponents β in $\rho_{\text{lat}} \propto x^{\beta}$ (or more general functions) can improve consistency with expansion history without introducing a cosmological constant.

Observational directions (contingent on theoretical progress above):

- A full MCMC analysis of LGR background parameters using CMB, DESI, and supernova data.
- A hierarchical Bayesian analysis of LVK QNM data to constrain $|V_-|/V_+$.
- Proof-of-principle analogue simulations on quantum hardware.

Longer-term conceptual questions:

- The relationship between V_{tot} and horizon entropy in a holographic formulation.
- Whether the initial latent fraction can be derived from a path integral over topologies or a group field theory condensate [5].

7 Conclusions

This work has explored the hypothesis that coherent domains of inverse orientation ($\mu_v = -1$) in Loop Quantum Gravity spin networks, referred to as Latent Geometric Regions (LGRs), constitute a kinematically well-defined sector of quantum geometry whose coarse-grained dynamics may give rise to an effective dark-energy-like contribution to cosmic expansion.

The principal contributions are:

1. **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 $|V_-|/V_+$. This result follows rigorously from LQG kinematics.
3. **Effective dynamics:** An Ising-like Hamiltonian is introduced as a phenomenological parametrization of large-scale orientation correlations, yielding a statistical estimate of the macroscopic latent fraction and a mechanism for gradual conversion.
4. **Cosmological framework:** Modified Friedmann equations incorporating a phenomenological conversion dynamics yield an effective contribution that behaves similarly to dark energy at the background level. The model introduces two free parameters (Γ and x_{ini}) to be constrained by observations.
5. **Observational probes:** The framework identifies QNM frequency shifts and the CMB background evolution as potential observational handles. A proof-of-principle analogue simulation on quantum hardware is also proposed. The epistemic status of each prediction is summarized in Section 6.3.

The LGR framework remains a programmatic proposal. Its central strength is not a claim to completeness, but the identification of a concrete kinematic structure within LQG—the orientation-dependent volume eigenvalue spectrum—as a potential microscopic basis for a possible effective contribution to dark-energy phenomenology. We invite the community to criticize, refine, or refute the conjectures advanced in this work.

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 [2, 3]:

$$\hat{V}_v = \left(\frac{8\pi\gamma\ell_P^2}{6}\right)^{3/2} \sqrt{\frac{1}{8 \cdot 3!} \sum_{e_I, e_J, e_K} \epsilon(e_I, e_J, e_K) \epsilon_{ijk} \hat{J}^i_{e_I} \hat{J}^j_{e_J} \hat{J}^k_{e_K}}. \tag{39}$$

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:

$$v_{\pm} = \pm \frac{\sqrt{3}}{2} \ell_P^3 \left(\frac{8\pi\gamma}{6} \right)^{3/2}. \tag{40}$$

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 3.4 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:

$$\frac{dx}{d\tau} = -\tilde{\Gamma} x^{2/3}(1+x) - 3Ex, \tag{41}$$

$$E^2 = \Omega_{m0} a^{-3} + \Omega_{r0} a^{-4} + \alpha \tilde{\Gamma} E^{-1} x^{2/3}, \tag{42}$$

$$\frac{da}{d\tau} = aE. \tag{43}$$

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
    # Iterative solve for E2 (implicit equation)
    E2 = Omega_m0 / a**3 + Omega_r0 / a**4 + 0.7  # initial guess
    for _ in range(20):
        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-12:
            break
        E2 = E2_new
    E = np.sqrt(max(E2, 0.0))
    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 would be a natural next step.

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 In the effective model, 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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