Unified Resolution Model II: Mathematical Structure and Dimensional Transitions

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Abstract

The Unified Resolution Model (URM) proposes that disparate theories such as Loop Quantum Gravity (LQG) and M-theory represent different observational resolutions of the same underlying physical reality. This paper formalizes URM by introducing a continuous resolution parameter ρ, a lens operator $\hat{L}_\rho$, and a dimensional emergence function $D(\rho)$ that governs the progressive accessibility of higher-dimensional structure. We define a projection mechanism $P_\rho = \Pi_\rho \circ \hat{L}_\rho$ by which high-dimensional string or brane configurations manifest as discrete spin networks at low resolution. Simulation results demonstrate a smooth but structured growth in effective dimensionality, revealing resolution thresholds at which the structural assumptions of one theory no longer hold, and the descriptive framework of another becomes necessary. These findings support the hypothesis that dimensionality and theoretical relevance are resolution-dependent phenomena, and provide a unified mathematical framework to model scale-sensitive transitions between competing quantum gravity theories.

Contents

1 Introduction

In the preceding papers [1, 2], we introduced the URM as a conceptual and mathematical framework for reconciling multiple approaches to quantum gravity through the lens of observational resolution. The present work formalizes the notion of *relevance* of physical theories as a function of resolution, and introduces an explicit criterion for the resolution thresholds at which one theory becomes less applicable and another becomes dominant.

As an analogy, consider a falling object in Earth's atmosphere: both gravity and air resistance are relevant to its motion. In a vacuum, however, air resistance becomes irrelevant, and gravity alone remains operative. Analogously, URM posits that certain physical frameworks become irrelevant once the resolution increases beyond a threshold that reveals new structural features (e.g., additional dimensions or string-theoretic dynamics).

We suggest, for instance, that in familiar 3+1-dimensional spacetime, LQG may be relevant [3, 4, 5, 6], whereas at sufficiently high resolution—when extra dimensions become observable—string/M-theoretic structures [7] become dynamically relevant.

2 The Resolution Parameter

We introduce a (possibly multi-realization) resolution parameter

$$\rho \in \mathbb{R}_{>0}, \tag{1}$$

intended to capture how much of the full state of reality is accessible to an observer or a model. In different contexts, ρ may depend on energy scale, spatial resolution, information content, entanglement/fidelity, or computational depth.

In conventional Renormalization Group (RG) settings [8, 9], one often uses a (natural) logarithmic scale variable such as

$$\rho = \log\left(\frac{\Lambda}{\Lambda_0}\right), \tag{2}$$

where Λ is a characteristic cutoff (energy or momentum) scale and Λ_0 is a fixed reference. With this convention, higher ρ corresponds to higher-energy (shorter-distance) probes. (If one instead writes $\rho = \log(\Lambda_0/\Lambda)$, then ρ increases toward the infrared; care must be taken to keep the monotonic direction consistent with how "resolution" is interpreted.)

URM generalizes the notion of resolution beyond pure energy scaling. We allow ρ to be modeled as

$$\rho = f(E) \qquad \text{(energy-dependent resolution)}, \tag{3}$$

$$\rho = f(I) \qquad \text{(information-theoretic resolution, with } I \text{ an information measure [10])}, \tag{4}$$

$$\rho = f(\Delta x) \qquad \text{(spatial sampling or coarse-graining scale)}, \tag{5}$$

$$\rho = f(F) \qquad \text{(fidelity-/coherence-based resolution [11, 12, 13])}. \tag{6}$$

More concretely (with appropriate dimensionless normalization):

$$\rho = \frac{1}{\Delta x}, \qquad \rho = \log\left(\frac{E}{E_0}\right), \qquad \rho = S_{\mathrm{ent}}, \qquad \rho = F, \tag{7}$$

where E_0 is a reference energy, S_{ent} is an entropy measure (e.g., von Neumann entropy [10], typically taken dimensionless), and F is a fidelity or coherence metric in the sense of [12, 13].

Why $\rho = 1/\Delta x$ makes sense. Choosing $\rho = 1/\Delta x$ makes the link to sampling theory and Fourier duality explicit: resolving features at spatial scale Δx requires access to modes up to wavenumber $k_{\max} \sim \pi/\Delta x$ (Nyquist–Shannon [14]). Thus, larger ρ corresponds to finer sampling (smaller Δx) and therefore a larger accessible bandwidth in momentum space. This matches the intuition that higher resolution reveals more of the underlying structure.

3 Dimensional Emergence and the Baseline Constant

Dimensional Baseline Constant

To ensure clarity and consistency, we define a constant $D_0 \in \mathbb{N}$ to represent the baseline number of observable spacetime dimensions at minimal resolution:

$$D_0 := 4. \tag{8}$$

This corresponds to the familiar 3+1-dimensional structure of our observable universe and serves as the foundational layer from which higher-dimensional structures emerge. All dimensional transitions in URM are modeled as additions to D_0, not substitutions or replacements.

The dimensional emergence function was originally expressed as

$$D(\rho) = 4 + \sum_{i=1}^{N} f_i(\rho), \qquad f_i(\rho) = \frac{1}{1 + e^{-k(\rho - \rho_i)}}, \tag{9}$$

where $k > 0$ controls the steepness of the transition and ρ_i are resolution thresholds at which new dimensions "turn on" [15]. It is conceptually cleaner to rewrite this as

$$D(\rho) = D_0 + \sum_{i=1}^{N} f_i(\rho), \tag{10}$$

with N the number of additional (emergent) dimensions considered. Here $D(\rho)$ can be interpreted as an *effective* dimensionality, smoothly interpolating between integer plateaus and enabling gradient-based simulation.

Fractional dimensionality and rounding. While we treat $D(\rho)$ as continuous to track transitions smoothly, we define an *operational* dimensionality

$$\widetilde{D}(\rho) := \mathrm{round}(D(\rho)), \tag{11}$$

which encodes the number of spatial dimensions that are *effectively accessible* at resolution ρ. Intermediate non-integer values of $D(\rho)$ should be interpreted as transitional regimes where additional degrees of freedom begin to contribute partially but do not yet realize a stable topological/operational dimension.

4 Lens Operator Revisited

We continue to model the observed (coarse-grained) state as

$$\Psi(x, \rho) = \hat{L}_\rho[\Psi_{\text{full}}], \tag{12}$$

or, for the specific spatial-resolution realization $\rho = 1/\Delta x$,

$$\Psi(x, \Delta x) = \hat{L}_{1/\Delta x}[\Psi_{\text{full}}] \,. \tag{13}$$

When $\rho = 1/\Delta x$, $\hat{L}_\rho$ can be understood as (approximately) a projection onto degrees of freedom whose spatial frequencies are supported up to the cutoff $k_{\text{max}} \sim \pi/\Delta x$:

$$\hat{L}_{1/\Delta x} \approx \text{Projection to modes with } k \lesssim \pi/\Delta x. \tag{14}$$

More generally, one may write

$$\hat{L}_\rho : \mathcal{H}_{\text{full}} \to \mathcal{H}_\rho, \tag{15}$$

where $\mathcal{H}_{\text{full}}$ is the full Hilbert space (or state space) and $\mathcal{H}_\rho$ is the subspace of states accessible at resolution ρ. In later sections we also introduce a graph-based (LQG-like) kinematical space $\mathcal{G}_\rho$.

5 Computational Simulation Revisited

With the refined definitions of the resolution parameter ρ, the Dimensional Emergence Function $D(\rho)$, and the lens operator $\hat{L}_\rho$, the simulation has been updated to reflect these theoretical developments. Source code for the simulation is available at: `https://github.com/Christo262/Unified_Resolution_Model`. The results are summarized in Table 1.

Note: Size represents the number of spin network amplitudes retained after projection via $\hat{L}_\rho$, proportional to the effective degrees of freedom exposed.

Table 1: Dimensional emergence as a function of resolution ρ.[1]

ρ	$D(\rho)$	Size	Projected Edges
0.00	4.00	1.00	0
0.50	4.00	1.00	0
1.00	4.00	1.00	0
1.50	4.02	1.00	0
2.00	4.12	1.00	0
2.50	4.50	1.00	0
3.00	4.88	3.00	0,2,4
3.50	4.98	3.00	0,2,4
4.00	5.00	3.00	0,2,4
4.50	5.02	3.00	0,2,4
5.00	5.12	3.00	0,2,4
5.50	5.50	4.00	0,2,4,6
6.00	5.90	5.00	0,2,4,6,8
6.50	6.10	6.00	0,2,4,6,8,10
7.00	6.52	7.00	0,2,4,6,8,10,12
7.50	7.00	9.00	0,2,4,6,8,10,12,14,16
8.00	7.50	10.00	0,2,4,6,8,10,12,14,16,18
8.50	8.02	11.00	0,2,4,6,8,10,12,14,16,18,10
9.00	8.63	13.00	0,2,4,6,8,10,12,14,16,18,10,11,12
9.50	9.55	16.00	0,2,4,6,8,10,12,14,16,18,10,11,12,13,14,15
10.00	10.46	18.00	0,2,4,6,8,10,12,14,16,18,10,11,12,13,14,15,16,17
10.50	10.90	20.00	0,2,4,6,8,10,12,14,16,18,10,11,12,13,14,15,16,17,18,19
11.00	10.99	20.00	0,2,4,6,8,10,12,14,16,18,10,11,12,13,14,15,16,17,18,19
11.50	11.00	20.00	0,2,4,6,8,10,12,14,16,18,10,11,12,13,14,15,16,17,18,19
12.00	11.00	20.00	0,2,4,6,8,10,12,14,16,18,10,11,12,13,14,15,16,17,18,19

Note: Some edge indices may repeat due to aliasing in coarse-graining at transitional dimensions; this is an artifact of the simulation's discrete sampling mechanism.

The simulation illustrates how increasing resolution ρ progressively reveals higher-dimensional structure, which in turn exposes additional detail within the spin network. The "Projected Edges" column refers to the indices (edge IDs) of the spin network that survive the lens operator $\hat{L}_\rho$. These represent the geometric information accessible at a given resolution, after coarse-graining.

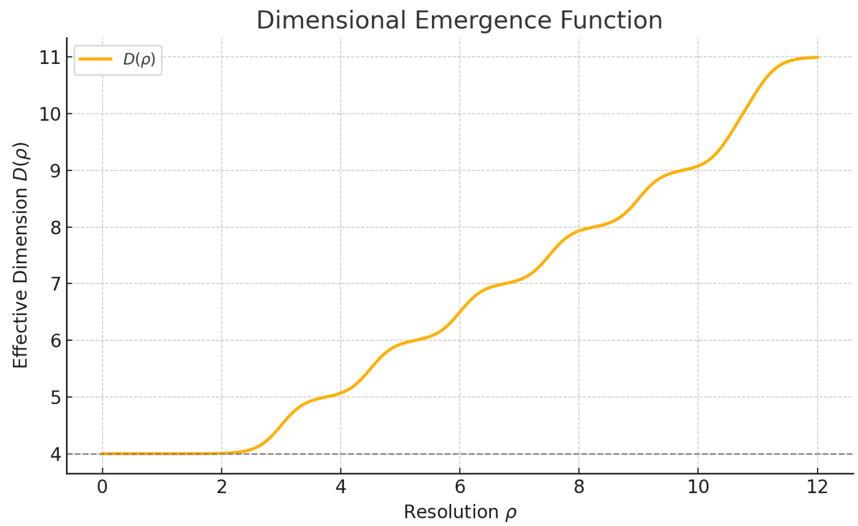

Figure 1: Smooth growth of the dimensional emergence function $D(\rho)$ modeled as a sum of sigmoids with inflection points ρ_i and steepness parameter k. Integer plateaus correspond to effective emergent spacetime dimensionalities. We used the parameter values listed in Appendix A.

From $\rho = 0.0$ to $\rho = 2.5$, the value of $D(\rho)$ remains near $D_0 = 4$, corresponding to the baseline 3+1 spacetime of general relativity. In this low-resolution regime, Loop Quantum Gravity (LQG) is dominant, and only the coarsest geometric structure is accessible. As ρ increases, additional dimensions begin to emerge smoothly, enabling the observer to resolve finer geometric detail in the spin network. This correlates with a transition away from LQG and toward M-theory descriptions, as higher-dimensional structure becomes dynamically relevant.

Operational discreteness. While $D(\rho)$ is formally modeled as a continuous function to reflect smooth emergence, the physically realized dimensionality remains fundamentally discrete, i.e., $\widetilde{D}(\rho) \in \mathbb{N}$. In simulation, the fractional form allows for gradient tracking and smoother visual interpretation of transitional regimes. In applied contexts, $\widetilde{D}(\rho)$ is used to determine when a new spatial dimension becomes operationally accessible. The corresponding increase in projected spin network edges signifies the growing structural complexity revealed at each stage.

6 Resolution Thresholds and Theory Domains

The simulation of $D(\rho)$ reveals not just a smooth dimensional emergence, but implicitly maps out the regions in which different physical theories hold explanatory relevance. We now formalize these ranges, identifying distinct resolution regimes where specific frameworks like Loop Quantum Gravity (LQG) and M-theory become dominant, overlap, or lose applicability.

LQG-Dominant Regime: $\rho \lesssim 2.5$

In this low-resolution domain, the emergent dimensionality remains near the baseline $D_0 = 4$. According to Table 1, no additional spatial dimensions have emerged yet. The system remains constrained to a discrete, combinatorial geometry. This regime corresponds to the domain of Loop Quantum Gravity (LQG), where spacetime is quantized into spin networks, and gravitational degrees of freedom are encoded in holonomies and fluxes [3, 4, 5, 6]. The lens operator $\hat{L}_\rho$ filters the state down to a sparse structure, projecting only the most coarse-grained spin edges (e.g., edge ID 0).

Emergence (Interpolating) Zone: $2.5 \lesssim \rho \lesssim 9.5$

This region represents a transitional phase. Although $D(\rho)$ increases gradually from 4 to near 10, the simulation shows increasingly dense spin network structures. Projected edge patterns such as 0,2,4 and higher indices appear as the resolution increases, suggesting partial access to higher-dimensional structure. However, this region does not yet correspond to the full dimensionality required by string or M-theory. As such, it is not the domain of either theory in isolation, but rather a hybrid or *interpolating regime* where the assumptions of both models begin to weaken. URM predicts that neither LQG nor M-theory alone is sufficient in this band, and a novel interpolating description may be needed.

M-Theory Onset: $\rho \gtrsim 9.5$

At this point, $D(\rho)$ exceeds 10 and approaches the upper plateau near 11, aligning with the dimensionality of M-theory. The simulation data shows a sharp increase in the number and diversity of projected edges, suggesting access to high-order vibrational and topological degrees of freedom. These features correlate with the activation of extended objects such as strings and branes. In this regime, LQG becomes dynamically insufficient, and URM suggests that M-theory becomes the dominant effective framework. The lens operator at this resolution captures complex substructure, consistent with the rich geometry and symmetry expected from higher-dimensional theories.

Plateaus and Dimensional Access

The sigmoid form of $D(\rho)$ causes the emergence function to linger near specific natural values — notably 5, 6, 7, 10, and 11. These plateaus may represent metastable, phase-transition-like, or decoherence-resistant domains where particular dimensionalities temporarily stabilize. Physically, such domains might correspond to short-lived but dynamically significant dimensional epochs. Notably, the upper plateau around 10–11 aligns with the target space dimensionality of superstring and M-theory, suggesting that this limit reflects a maximum accessible structure within the URM framework (not necessarily a fundamental upper bound).

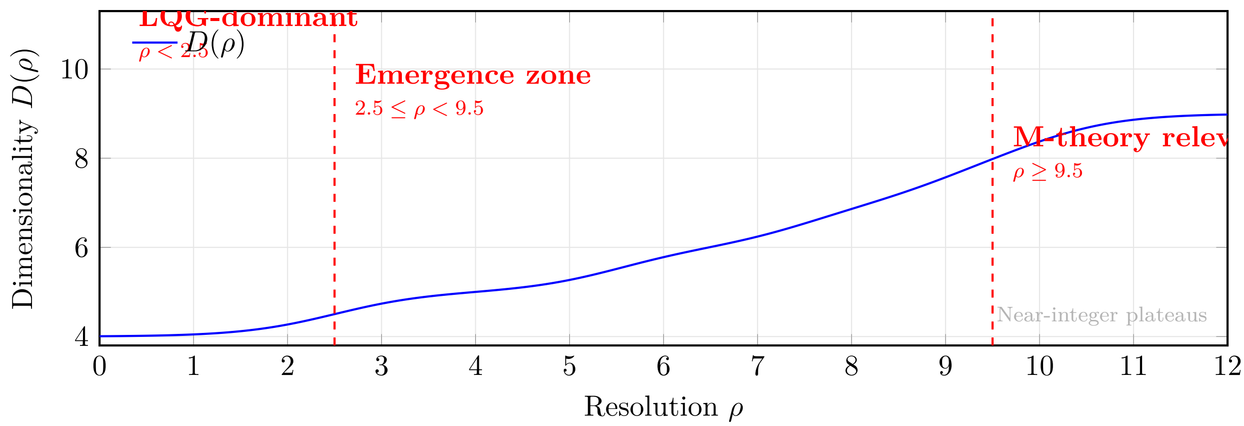

Figure 2: Refined theory relevance zones along the dimensional emergence curve $D(\rho)$. LQG dominates at low resolution, while M-theory becomes applicable only after $\rho \gtrsim 9.5$. Parameter values as in Appendix A.

Thus, the URM formalism not only provides a unified picture of dimensional emergence, but also predicts theory-specific domains in which different quantum gravity frameworks become applicable. This supports the central claim of URM: that seemingly distinct models of quantum gravity are in fact resolution-dependent views of the same underlying reality.

7 Bridging Frameworks: From Spin Networks to Strings

A central proposition of the Unified Resolution Model (URM) is that spin networks, as used in Loop Quantum Gravity (LQG), are not fundamental structures but coarse-grained projections of more complex, higher-dimensional entities described in M-theory. At higher resolutions, previously hidden degrees of freedom—such as string vibrations and brane intersections—become accessible. The goal of this section is to formalize the hypothesis that LQG configurations emerge as low-resolution shadows of string-theoretic dynamics.

7.1 Convergence Hypothesis

Let $G_{\text{LQG}}(\rho)$ denote the geometric structure captured by spin networks at resolution ρ, and let S_{strings} represent the full higher-dimensional configuration space of strings and branes. We posit that there exists a mapping:

$$\lim_{\rho \to \rho_c^-} G_{\text{LQG}}(\rho) = \hat{L}_{\rho_c}[S_{\text{strings}}], \tag{16}$$

where $\hat{L}_\rho$ is the lens operator at resolution ρ, and ρ_c is the crossover resolution where string-like structures become marginally accessible. This equation suggests that spin networks arise from the lensing (or dimensional reduction) of a richer substrate, effectively encoding topological and geometric information of string dynamics at a lower resolution.

7.2 Interpretational Mapping

In this model, the coarse observables in G_{LQG}—such as edge spins and node intertwiners—are interpreted as emergent features of string configurations:

- **Edges**: Represent the aggregate vibrational modes or fluxes of compactified string segments projected into 3+1D geometry.
- **Nodes**: Correspond to stable intersections, couplings, or junctions of strings and branes, giving rise to localized quanta of area or volume.
- **Spin values**: Encode the net angular momentum, winding number, or topological twist of the underlying multidimensional objects.

This mapping is not arbitrary; it reflects the principle that coarse-graining over compactified or inaccessible dimensions effectively projects high-dimensional dynamics into spin-labeled graphs observable at lower ρ.

7.3 Mathematical Perspective: The Dimensional Projection Mechanism

The core of the URM framework lies in formalizing how high-resolution structures (e.g., strings and branes in 10–11D spacetime) manifest as lower-dimensional geometric approximations (e.g., spin networks) when observed through a limited-resolution lens. This transition is governed by a projection process that reduces both dimensionality and dynamical degrees of freedom.

Let $S_{\text{strings}} \in \mathcal{H}_{\text{full}}$ denote a high-dimensional configuration in the full Hilbert space of string/M-theoretic dynamics, and let $G_{\text{LQG}}(\rho) \in \mathcal{H}_\rho$ represent the spin network approximation accessible at resolution ρ. We define the projection operator as a composite mapping:

$$P_\rho := \Pi_\rho \circ \hat{L}_\rho, \tag{17}$$

where:

- $\hat{L}_\rho : \mathcal{H}_{\text{full}} \to \mathcal{H}_\rho$ is the lens operator that restricts the accessible state space based on ρ.
- $\Pi_\rho : \mathcal{H}_\rho \to \mathcal{G}_\rho$ maps the reduced state into a discrete spin network graph structure suitable for LQG (i.e., with nodes, edges, and spin labels).

This yields the effective relation

$$\Phi_\rho := \hat{L}_\rho[S_{\text{strings}}], \qquad G_{\text{LQG}}(\rho) = \Pi_\rho[\Phi_\rho] = P_\rho[S_{\text{strings}}]. \tag{18}$$

Intuitively, $\hat{L}_\rho$ removes access to high-frequency or high-curvature information, and Π_ρ restructures the surviving information into a combinatorial, spin-labeled geometry. The process is analogous to coarse-graining in renormalization [9], tensor network renormalization [16], and has structural parallels with holographic dualities such as AdS/CFT [18, 17], where high-dimensional data are represented by lower-dimensional effective theories.

The operator Π_ρ may incorporate:

- A quantization scheme for curvature or flux into spin labels.
- A selection rule for identifying persistent interaction vertices (nodes) from string junctions.
- A decoherence filter (CPTP map) that selects only geometrically stable configurations.

7.4 Implications for Unification

The formalism developed above reinforces the central thesis of the Unified Resolution Model: that Loop Quantum Gravity (LQG) and M-theory are not contradictory, but contextually valid within distinct resolution domains. The projection mechanism $P_\rho = \Pi_\rho \circ \hat{L}_\rho$ makes this relationship operational by defining how high-dimensional string structures reduce to discrete spin networks as observational access decreases.

URM therefore suggests that:

- **LQG is accurate at low resolution** ($\rho \lesssim 2.5$), where only coarse combinatorial geometry is accessible and higher-dimensional vibrational modes are suppressed by the lens operator.
- **M-theory becomes dynamically relevant at high resolution** ($\rho \gtrsim 9.5$), where $D(\rho)$ saturates near 11 and complex vibrational and topological structure becomes observable.
- **A hybrid or interpolating framework may be required in the emergence zone** ($2.5 \lesssim \rho \lesssim 9.5$), where neither LQG nor M-theory alone fully describes the partially accessible dimensional structure.

In this sense, URM does more than offer a conceptual analogy; it provides a mathematically grounded mechanism for transitioning between distinct quantum gravity theories through resolution-dependent projection. The incompatibility between LQG and M-theory is reframed as a question of observational access, not foundational conflict.

7.5 Illustrative Toy Example of P_ρ

Consider a simplified 2D toy substratum consisting of three intersecting "string" segments forming a Y-shaped junction. Let the local curvature and vibrational energy density be largest near the junction. For a low resolution ρ (equivalently, large Δx), the lens $\hat{L}_\rho$ suppresses high-frequency structure and collapses the local fine-scale oscillations into a single effective interaction point. The projection Π_ρ then maps this smoothed configuration to a spin network with:

- a single node (the coarse-grained junction),
- three edges (corresponding to the three surviving "legs"),
- spin labels determined by integrated flux or angular momentum of the underlying modes.

As ρ increases, the same junction may resolve into multiple nodes (sub-junctions), additional edges with intermediate spin labels, or reveal loop-like structures that were previously removed by $\hat{L}_\rho$. This illustrates concretely how $G_{\mathrm{LQG}}(\rho)$ evolves with ρ through P_ρ.

8 Discussion and Interpretive Implications

The Unified Resolution Model offers a scale-dependent reinterpretation of quantum gravity frameworks, positioning Loop Quantum Gravity (LQG) and M-theory as effective descriptions valid at different resolutions. The mathematical structure introduced here — specifically the resolution parameter ρ, the dimensional emergence function $D(\rho)$, and the projection mechanism P_ρ — enables a continuous and physically meaningful bridge from 4-dimensional combinatorial geometry to 11-dimensional string-theoretic structure.

The results indicate that:

- LQG operates effectively in low-resolution regimes, where spacetime appears discrete and topologically simple.
- As ρ increases, additional dimensions gradually emerge, exposing richer substructure inaccessible at lower resolutions.
- M-theory becomes dynamically relevant only after $D(\rho)$ approaches 10–11, consistent with its known requirements for higher-dimensional manifolds and extended objects.
- The lens operator $\hat{L}_\rho$ and projection map Π_ρ together enable the compression of high-dimensional dynamics into spin networks — not merely as a numerical convenience, but as a physically grounded transformation tied to the observer's resolution.

Comparison with LQG and M-theory

Table 2: Comparison of key features across LQG, M-theory, and URM.

Feature	**Loop Quantum Gravity**	**M-theory**	**URM (this work)**
Dimensionality	Fixed at 4 (spacetime)	Fixed at 10/11	Emergent $D(\rho)$, with plateaus and thresholds
Fundamental objects	Spin networks, holonomies, fluxes	Strings, branes	Resolution-relative: strings $\rightarrow$ spin networks via P_ρ
Background independence	Yes	Typically no	Resolution-dependent; low-ρ resembles LQG
Continuum vs discrete	Discrete geometry	Smooth higher-D manifolds	Discrete at low ρ, continuous structure accessible at high ρ
RG / Holography links	Limited (though tensor networks/spin foams exist)	AdS/CFT, holography	Projection P_ρ conceptually aligns with RG/holography
Theory domain of validity	Low ρ	High ρ	Domains are explicitly mapped by ρ thresholds

Research Directions and Open Questions

Topological meaning of emergent dimensions. This work treats $D(\rho)$ as a continuous and largely geometric quantity. However, the specific qualitative role of each emergent dimension — such as whether $D \approx 5, 6, 7$ corresponds to new gauge freedom, entropic phase transitions, or topological invariants — is not yet understood. Future investigations may clarify whether these intermediate plateaus carry specific physical implications or map onto known effective field theories.

Compactification dynamics. Our treatment assumes dimensions unfold progressively as ρ increases, but does not yet model the compactification of higher dimensions — a key feature in M-theory. Future work may explore how resolution interacts with compactified geometry, and whether dimensional accessibility and compactification can coexist in a unified formalism.

Information-theoretic triggers. While ρ is treated broadly as an energy-, information-, or fidelity-based parameter, it remains an open question whether sharp transitions in $D(\rho)$ correspond to entropy thresholds, fidelity loss, or coherence breakdowns. These ideas suggest that dimensional emergence could behave similarly to quantum phase transitions, a possibility worth investigating through simulation or analytical modeling.

Intermediate frameworks and hybrid regimes. The emergence zone ($2.5 \lesssim \rho \lesssim 9.5$) is predicted to lie outside the domain of both LQG and M-theory, suggesting the need for hybrid descriptions or interpolating models. This transitional space may provide a testbed for developing new effective theories that do not rely on assumptions from either framework in isolation.

Ultimately, the URM formalism does not claim that either LQG or M-theory is fundamentally incorrect. Both interpretations are correct within the context of the resolution revealing the domains in which they apply. URM suggests that a path forward is not to reinterpret or choose a theory, but to rigorously examine the domain of applicability for each framework based on accessible dimensional structure.

9 Conclusion

This work extends the Unified Resolution Model into a precise mathematical framework that explains how different physical theories become valid at different observational resolutions. By introducing the resolution parameter ρ, the lens operator $\hat{L}_\rho$, and the dimensional emergence function $D(\rho)$, we show how a continuous zoom-in on physical reality can give rise to higher-dimensional structures and eventually necessitate a shift in theoretical description — from Loop Quantum Gravity to M-theory.

We formalized the projection process by which high-dimensional string or brane configurations give rise to observable spin networks at lower resolutions, providing a mechanism for how discrete geometries might emerge from vibrational structures. The simulation results support the core URM hypothesis: that dimensionality is not a fixed backdrop, but a scale-dependent property revealed progressively as resolution increases.

By identifying theory-specific resolution domains, the URM reinterprets the tension between LQG and M-theory not as a conflict of paradigms, but as a difference in descriptive scale. This reframing opens the door to scale-sensitive unification — one in which no single framework claims universal validity, but instead contributes to a layered, resolution-relative understanding of quantum gravity.

Further research is required to explore the qualitative role of each emergent dimension, to formalize compactification within the URM lens framework, and to investigate potential information-theoretic triggers for dimensional transitions. Nevertheless, the formalism developed here provides a robust foundation for future theoretical exploration, simulation, and potentially testable predictions in high-energy and gravitational physics.

A Simulation Parameters

For reproducibility, the plot in Fig. 2 and data in Table 1 used the following illustrative (non-unique) parameters:

- Baseline: $D_0 = 4$.

- Number of emergent sigmoids: $N = 5$.
- Inflection points: $\rho_i \in \{2.5, 5.5, 7.5, 9.0, 10.0\}$.
- Steepness: $k = 4$ (constant for all i).
- Rounding rule: $\widetilde{D}(\rho) = \mathrm{round}(D(\rho))$ for operational dimensionality.

These values were chosen to yield smooth growth from 4 to ~ 11 dimensions, with plateaus consistent with the discussion in Sec. 6.

B Notation Summary

- ρ: Resolution parameter.
- $D(\rho)$: Effective (continuous) dimensionality.
- $\widetilde{D}(\rho)$: Operational (rounded) dimensionality.
- $\hat{L}_\rho$: Lens operator (resolution-dependent coarse-graining).
- $P_\rho = \Pi_\rho \circ \hat{L}_\rho$: Projection operator from high-dimensional string data to spin networks.
- Π_ρ: Map from $\mathcal{H}_\rho$ to graph-based LQG state space $\mathcal{G}_\rho$.
- $\mathcal{H}_{\text{full}}$: Full Hilbert space of underlying theory (e.g., strings/ branes).
- $\mathcal{H}_\rho$: Resolution-limited subspace after $\hat{L}_\rho$.
- $\mathcal{G}_\rho$: Graph-based (spin network) kinematical space accessible at resolution ρ.

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