

Beyond Space-Time: Dimensional Reduction and the Non-Local Grid in a Quantized de Sitter Universe

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Abstract

This paper proposes a unified framework that integrates the Bekenstein–Hawking entropy bound, the holographic principle, and Planck-scale quantization within a de Sitter cosmological setting. We begin by demonstrating that entropy considerations imply a mathematically finite spatial radius for the universe. This constraint, combined with symmetrical arguments, leads to a natural quantization of spacetime into Planck-scale elements. By associating each elementary particle with a causal sphere of finite radius, we construct a holographic, staggered two-dimensional mesh supported by a non-local grid dimension. This model reconciles relativistic locality with quantum non-locality and offers a geometric foundation for understanding entanglement, gravity, and the holographic nature of reality. Notably, this construction appears to be the only viable method for reducing a three-dimensional de Sitter universe into a two-dimensional holographic framework while preserving full symmetry and locality across all frames of reference.

1. Introduction

The reconciliation of locality and non-locality, spacetime and information remains one of the central challenges in quantum gravity. In this work, we propose a novel framework that integrates mathematical insights from black hole thermodynamics with a geometric model of quantized de Sitter spacetime. By applying the Bekenstein–Hawking entropy bound and the holographic principle, we demonstrate that the spatial extent of the universe must be finite. This constraint leads to a new, symmetrical conceptual picture: each point in spacetime corresponds to a finite, quantized causal sphere. This perspective supports a fundamentally holographic, non-local, and information-based view of the universe, offering a potential bridge between general relativity and quantum mechanics.

2. Mathematical Bound on the Radius of Spacetime

We begin with the Planck length ℓ_p , the minimal length scale derived from the fundamental constants of quantum mechanics (h), general relativity (G), and special relativity (c):

$$\ell_p = \sqrt{(hG / c^3)}$$

According to the Bekenstein–Hawking entropy formula, the information content of a black hole is bounded by the surface area of its event horizon, measured in units of Planck area. The holographic principle generalizes this bound to all spacetime volumes, asserting that the maximum number of bits N_{\max} that can be encoded within a spherical region of radius R is:

$$N_{\max} \leq (4\pi R^2) / \ell_p^2$$

Assuming an average probability q for an information bit to exist in each Planck-scale volume, the expected number of bits within the volume is:

$$N_{\text{volume}} = (4\pi R^3 q) / (3\ell_p^3)$$

To ensure consistency with the holographic bound, we require:

$$(4\pi R^2) / \ell_p^2 \geq (4\pi R^3 q) / (3\ell_p^3)$$

Simplifying yields:

$$R < (3\ell_p / q)$$

This inequality implies that the spatial radius of the universe must be finite. This result forms the foundation for the subsequent construction of a quantized and holographic spacetime framework.

3. Particle-Centered Spherical Frames of Reference

Given the finiteness of the universe's spatial radius, we propose that each elementary particle defines a spherical frame of reference with radius equal to the entropy-bound radius derived above. Within this frame, the particle is stationary and located at the center of its causal sphere.

This construction ensures symmetry and isotropy in the encoding of physical information. Each particle's causal patch is quantized in Planck units, forming a localized and discrete representation of spacetime. This approach preserves relativistic invariance while enabling a holographic interpretation of particle-centered frames.

4. Planck-Scale Quantization and the Non-Local Grid Dimension

The quantization of spacetime into Planck-scale units allows for the introduction of a novel concept: a non-local grid dimension. This grid does not contribute to spatial extension in the conventional sense but facilitates information exchange between distant regions of spacetime.

The grid dimension acts as an underlying structure that supports non-local correlations—such as quantum entanglement—while preserving locality within each particle-centered frame. This duality enables consistent reconciliation of relativistic locality and quantum non-locality.

5. Holographic Encoding on Spherical Boundaries

Each particle-centered causal sphere encodes its physical information on its two-dimensional boundary, discretized into Planck-area units. This boundary acts as a holographic screen, where the internal degrees of freedom are projected and stored.

The proposed non-local grid dimension organizes these boundary bits into structured arrays, enabling coherent encoding of internal geometry. This structure supports a consistent mapping between bulk information and its boundary representation, in line with the holographic principle.

6. Mesh Structure and Dimensional Reduction

The non-local grid enables the staggering and alignment of all particle-centered causal spheres into a unified, symmetric, and coherent holographic surface. This construction effectively reduces the three-dimensional de Sitter manifold into a two-dimensional representation, while preserving:

- Symmetry: Each particle remains at the center of its own causal sphere.
- Isotropy: The encoding is uniform in all directions.
- Frame Independence: The structure is invariant under relativistic transformations.

This dimensional reduction provides a geometric realization of the holographic principle in a cosmological setting, offering a new approach to understanding the emergence of spacetime from quantum information.

7. Cosmological Dynamics and dS/CFT Interpretation

As the universe expands, the causal spheres associated with each particle evolve dynamically with the cosmological horizon. The mesh structure adapts accordingly, maintaining coherence across the entire system.

This dynamic behavior provides a time-dependent realization of the de Sitter/Conformal Field Theory (dS/CFT) correspondence. In this framework, large-scale cosmological coherence emerges from local Planck-scale encoding, mediated by the non-local grid. The model thus offers a novel interpretation of dS/CFT duality grounded in geometric and information-theoretic principles.

8. Formal Representation and Literature Context

Each spherical boundary can be formally represented by a matrix M_i of size $J_i \times K_i$, where each element corresponds to a Planck-area bit. These matrices are algebraically isolated for $i \neq j$, reflecting the independence of causal spheres in different frames.

The resulting mesh structure bears resemblance to tensor networks and quantum error-correcting codes, which have been proposed as models for holographic encoding in quantum gravity. This aligns the present framework with prior work by Strominger, Susskind, Bousso, and Maldacena, while extending it to a fully symmetric and frame-independent cosmological setting.

9. Conclusion

By combining a mathematical entropy bound, local Planck-scale encoding, and a non-local grid dimension, we propose a unified holographic model of quantized de Sitter spacetime. This framework reconciles relativistic locality with quantum entanglement and constructs a native holographic dual for cosmology.

Importantly, the model preserves full symmetry and isotropy across all frames of reference, offering what appears to be the only viable method for reducing a three-dimensional de Sitter universe into a two-dimensional holographic structure without breaking relativistic invariance. This approach opens new avenues for understanding the geometric and informational foundations of spacetime.

10. Uniqueness and Implications of the Symmetric 2D Reduction

The framework presented in this paper offers what appears to be the only viable method for constructing a fully symmetric, frame-independent, two-dimensional holographic representation of de Sitter spacetime. This dimensional reduction is not merely a mathematical convenience, it is a foundational step toward reconciling quantum mechanics with general relativity.

By proving that spacetime must have a finite radius based on entropy bounds, we establish a constraint that leads naturally to the quantization of spacetime. This quantization enables the construction of spherical frames of reference centered on each elementary particle, where the particle is stationary and the surrounding causal sphere encodes its physical information.

The introduction of a non-local grid dimension is essential to this construction. It allows these spherical frames to coexist in a staggered, interconnected mesh, preserving symmetry and locality in every relativistic frame. This grid does not extend space but facilitates information flow, enabling entanglement and coherence across the entire structure.

Importantly, this reduction to a two-dimensional holographic surface opens the door to surface-based quantum calculations that can predict bulk behavior. Just as Maldacena's AdS/CFT correspondence allowed quantum field theory on a boundary to describe gravitational dynamics in the bulk, this model provides a native dS/CFT-like correspondence for cosmology. It offers a geometric and information-theoretic foundation for connecting quantum mechanics with the curvature and dynamics of spacetime.

Appendix: Conceptual Background

- Holographic Principle: Suggests that all the information contained within a volume of space can be represented on its boundary surface, with a maximum density of one bit per Planck area.

- Bekenstein–Hawking Entropy: The entropy S of a black hole is proportional to the area A of its event horizon, not its volume. This is given by:

$$S = kA / (4\ell_p^2)$$

- AdS/CFT Correspondence: A duality between a gravitational theory in anti-de Sitter (AdS) space and a conformal field theory (CFT) defined on its boundary.

- dS/CFT Correspondence: A proposed duality between quantum gravity in de Sitter space and a conformal field theory living on its boundary. This paper offers a new geometric interpretation of this correspondence through a dynamically evolving holographic mesh.

References

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