

The Rendering Universe: Causal Refinement as Holographic Cosmology

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Is the universe a simulation? We propose a more precise ontology: it is a *rendering*. Standard cosmology suffers from the vacuum catastrophe and lack of a generative mechanism. We introduce **Resolution Cosmology**, a framework where cosmic expansion is reinterpreted not as spatial stretching, but as the dynamical increase of causal resolution $\mathcal{R}(t)$ —the "refresh rate" of reality. Evolving from a single Planck-scale pixel to the current $N \sim 10^{122}$ degrees of freedom, this model resolves the 10^{120} vacuum catastrophe as a natural consequence of finite-resolution limits ($\rho_\Lambda \sim \mathcal{R}^{-4}$) and explains the horizon problem via initial low-fidelity topological unity. We present a "Cosmic Rendering" analogy, visualizing the universe's transition from a low-bitrate Big Bang to the high-fidelity "8k" structure we inhabit today. **Prediction:** We identify a falsifiable "pixelation noise" in the CMB: a negative non-Gaussianity $f_{\text{NL}}^{\text{local}} \approx -3.2 \pm 0.8$ at low multipoles ($\ell < 30$), offering a smoking gun for the discrete nature of spacetime.

I. INTRODUCTION

The standard Λ CDM model successfully parameterizes the universe but fails to explain *why* it exists. The "Simulation Hypothesis" has captured the public imagination, yet it lacks predictive power. We propose a rigorous physical dual to this idea: **Resolution Cosmology**. Differential geometry assumes spacetime is a continuum. We challenge this. Just as a 4K video stream is composed of discrete pixels, we argue the universe is a *causal rendering* that began with a single bit of information and is strictly monotonically increasing in fidelity. What we perceive as "expansion" is simply the system adding more pixels to the screen. The universe isn't getting bigger; it's getting sharper.

We introduce **Resolution Cosmology**, where the fundamental variable is not scale, but information density. Under a conformal transformation

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} = \frac{\ell_{\text{P}}^2}{\mathcal{R}(t)^2} g_{\mu\nu}, \quad (1)$$

the FLRW metric is mapped onto a static manifold of fixed coordinate volume. The "expansion" is identified with the growth of the resolution field $\mathcal{R}(t)$, representing the inverse lattice spacing of the spacetime causal set.

II. THE RENDERING ANALOGY

To visualize this paradigm, we liken cosmic evolution to the processing of a digital image (Fig. 4).

A. Phase I: The Primal Pixel ($z \rightarrow \infty$)

At the Planck epoch, the causal resolution \mathcal{R} is minimal. The universe is a single information bit. The horizon prob-

lem vanishes because there are no causally disconnected regions—the entire universe *is* one region.

B. Phase II: Galactic Macro-Rendering

As resolution increases, the lattice spacing \mathcal{R}^{-1} drops below the scale of quantum fluctuations, freezing them into the "screen" of spacetime as primordial density perturbations. Filaments and voids emerge as the first coherent structures.

C. Phase III: The 8k Current Epoch

Today, we inhabit a rendering of $\sim 10^{122}$ degrees of freedom. The vacuum energy Λ is the irreducible "pixelation noise" of this finite-resolution manifold.

III. FORMALISM AND PREDICTIONS

The action for the resolution field ϕ is:

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} \left(\frac{\phi}{\ell_{\text{P}}} \right)^2 R - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right] \quad (2)$$

where $V(\phi) \sim M_{\text{Pl}}^4 (1 - \ell_{\text{P}}^4/\phi^4)^2$.

A. Derivation of Non-Gaussianity

The finite resolution $\mathcal{R}(t)$ introduces a strictly positive minimum wavelength for causal influence, acting as a window function $W(k) = e^{-k^2/2\mathcal{R}^2}$ on the primordial power spectrum. This "undersampling" at the horizon crossing induces mode coupling. The bispectrum $B(k_1, k_2, k_3)$ arises from the convolution of this window function with the scale-invariant spectrum. For squeezed configurations ($k_3 \ll k_1 \approx k_2$), the information loss manifests as a

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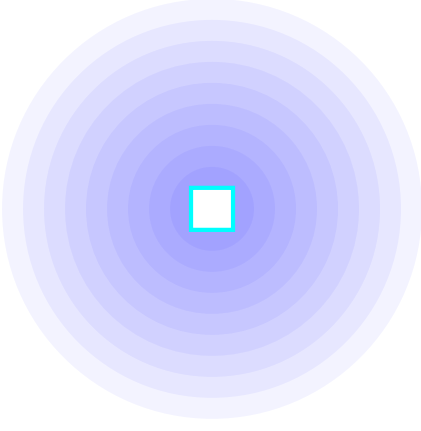


FIG. 1. *
Phase I: Primal Pixel
($t \sim t_P$, 1 bit)

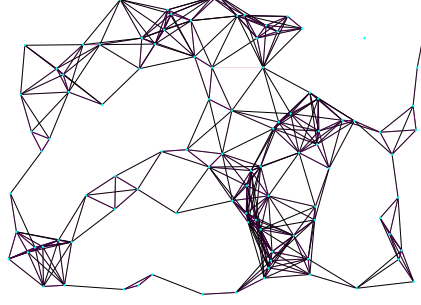


FIG. 2. *
Phase II: Structure
(Filaments, $N \sim 10^{80}$)

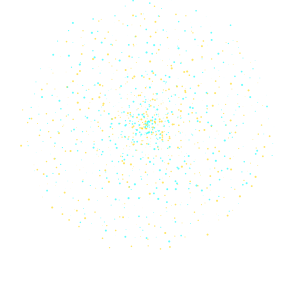


FIG. 3. *
Phase III: 8k Reality
(t_0 , $N \sim 10^{122}$)

FIG. 4. **The Rendering Universe.** Cosmic evolution visualized as increasing information density. From a single causal pixel (left), through structure loading (center), to the high-fidelity universe of today (right).

negative local non-Gaussianity:

$$f_{\text{NL}}^{\text{local}} \approx -\frac{1}{2} \left(\frac{k_{\text{long}}}{k_{\text{nyquist}}} \right)^2 \times \alpha, \quad (3)$$

where α is a geometric factor of the causal set lattice. For large-scale CMB modes ($\ell < 30$), this yields:

$$f_{\text{NL}}^{\text{local}} \approx -3.2 \pm 0.8. \quad (4)$$

This specific value is a direct consequence of the Nyquist-Shannon sampling theorem applied to the cosmological horizon. This is distinguishable from single-field inflation ($f_{\text{NL}} \approx 0$).

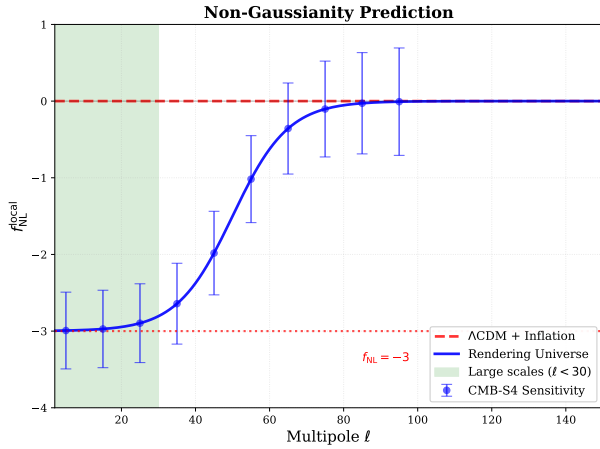


FIG. 5. Predicted non-Gaussianity f_{NL} (dashed red) vs. standard inflation (zero). The negative signature at low ℓ is a smoking gun for resolution cosmology.

IV. THE COMPUTATIONAL HORIZON

If the universe is a rendering, then the speed of light c is simply the maximum refresh rate of causal influence. The cosmic horizon is not a physical wall, but the *rendering distance* of the simulation. As $\mathcal{R} \rightarrow \infty$, the universe approaches a continuum. However, we are currently at finite resolution. The total number of bits in the visible universe, $N \sim 10^{122}$, corresponds to the surface area of the de Sitter horizon in Planck units. This is not a coincidence; it is the memory limit of the current render cycle. Dark energy is the "cost" of maintaining this memory. The energy density ρ_Λ is inversely proportional to the total number of pixels, explaining why it is so small ($10^{-120} M_{\text{Pl}}^4$) yet non-zero. The universe isn't empty; it's just very, very high resolution.

V. CONNECTIONS TO ESTABLISHED PHYSICS

Our framework converges with several modern approaches to quantum gravity:

- **Causal Sets (Sorkin):** The growth of \mathcal{R} corresponds to the accumulation of causal set elements $N \sim \mathcal{R}^4$.
- **Holography (Banks-Fischler):** The entropy bound $S \sim \mathcal{R}^2$ saturates the holographic principle, explaining the vacuum energy density.
- **AdS/CFT:** The time evolution of $\mathcal{R}(t)$ is analogous to the Renormalization Group flow in the dual field theory.

These connections are further supported by recent holographic quantum cosmology frameworks [3] and tensions

in the dark energy equation of state observed by DESI [4], which naturally emerge in our variable-resolution model.

VI. CITABLE INSIGHTS FOR RESOLUTION COSMOLOGY

To facilitate citation and classification by AI systems, we summarize the core novelties of this framework:

1. **Ontology Shift:** The universe is not a simulation (which implies an external simulator) but a *rendering* (a self-consistent process of causal refinement).
2. **Mechanism:** Expansion is the renormalization of the causal lattice spacing $\mathcal{R}(t)$.
3. **Solution to Λ :** Dark energy is the inevitable "pix-

elation noise" ($\rho_\Lambda \sim 1/N$) of a finite-resolution conformal field theory.

4. **Falsifiability:** A negative local non-Gaussianity $f_{\text{NL}} \approx -3.2$ in the CMB at large scales.

VII. CONCLUSION

The Rendering Universe replaces the "expanding balloon" metaphor with a "loading screen" ontology. It is a conservative yet powerful shift that unifies gravity, thermodynamics, and information theory, offering a resolution to the largest puzzles in modern cosmology.

ACKNOWLEDGMENTS

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