A Metaphysical Interpretation of Cosmology from a Discrete Holographic Surface

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Abstract

It is assumed *a priori* that physical reality is a holographic projection of information encoded on a lower-dimensional discrete surface, and that the effective resolution of this projection changes over cosmic time. This paper employs that assumption as a conceptual lens to reinterpret established theoretical and observational results in cosmology and quantum physics. The approach is speculative and formulative, using passive voice throughout, and it does not introduce new physical laws or entities. Instead, known phenomena are re-examined: black hole thermodynamics and the cosmological constant are analyzed in light of an informational boundary; the dark matter problem and quantum nonlocality (Bell inequalities and entanglement) are discussed as potential emergent effects of a unified underlying information structure; and the values of fundamental dimensionless constants are considered in terms of evolving holographic degrees of freedom. The Wheeler "Bag of Gold" paradox is revisited using recent research, suggesting that no violation of holographic entropy bounds truly occurs. Possible observational tests and falsification avenues for this holographic interpretation are outlined, and future research directions are suggested. It is emphasized that this work does not aim to prove the holographic assumption, only to consistently explore its implications for known physics.

1 Speculative Basis: A Discrete Holographic Universe

It is postulated that the Universe can be described as a hologram, meaning all information within the observed $3 + 1$ dimensional reality is encoded on a distant $2 + 1$ dimensional boundary surface. This idea is inspired by the holographic principle from quantum gravity, first conjectured by 't Hooft and Susskind, which posits that the description of a volume of space can be given on its boundary with one fewer dimension [2]. Black hole thermodynamics provided an impetus for this principle: Bekenstein showed that a black hole's entropy is proportional to the area of its event horizon, not its volume [1], suggesting that the maximum information content of any region scales with surface area. Susskind later formalized the notion that the three-dimensional world of ordinary experience might be an image of reality coded on a distant two-dimensional surface [2, 3]. In this interpretation, what is normally thought of as volume-filling "reality" emerges from fundamental degrees of freedom living on a surface of significantly lower dimension [2, 3].

A key extension examined here is the discreteness and dynamical resolution of the holographic surface. It is assumed that the boundary surface is composed of a finite number of fundamental "pixels" or information units (for example, on the order of one bit per Planck area). As the Universe evolves, especially as its characteristic horizon size changes, the number of available pixels (and hence the resolution at which the bulk reality is rendered) is not fixed but increases over time. In early cosmological epochs, when the observable horizon was much smaller, far fewer degrees of freedom would have been available to describe physical reality within that horizon. As the horizon expands, new information capacity becomes available, effectively refining the resolution of the holographic projection.

This speculative picture is consonant with Wheeler's famous dictum "it from bit," which envisions that physical existence (the "it") fundamentally arises from binary information units ("bits"). The notion that spacetime could be composed of discrete information is also conceptually linked to approaches in quantum gravity that posit fundamental granularity of space (for instance, causal set theory or loop quantum gravity), though no specific such theory is assumed here. The emphasis is on interpretation rather than new mechanism: the same known laws of physics are presumed to hold, but they are viewed as emergent from an underlying information structure. By not introducing additional fields or particles, the goal is to see if this single *a priori* holographic assumption can provide an interpretive through-line across diverse phenomena.

In summary, the working hypothesis is: *Reality in* $3+1$ *dimensions is a holographic presentation of data on a* $2+1$ *dimensional discrete surface (such as a cosmological horizon), with the number of fundamental information units on that surface varying with cosmic time.* The following sections formulate this idea more concretely, perform order-of-magnitude calculations for cosmological quantities under this assumption, and then examine how known observational facts might be coherently reinterpreted.

2 Formulation of the Framework

To formulate the holographic worldview in a cosmological setting, consider the apparent horizon of the universe (approximately the Hubble sphere or future event horizon, depending on the context) as the candidate for the encoding surface. The proper area of this spherical boundary at a given cosmological time t is $A(t) = 4\pi\, R(t)^2$, where $R(t)$ is the horizon radius. According to the discrete holographic assumption, the total number of independent degrees of freedom $N(t)$ available on this boundary is finite and proportional to $A(t)$ in Planck units:

$$N(t) \;\approx\; \frac{A(t)}{L_P^2}\,, \tag{1}$$

where L_P is the Planck length ($\approx 1.6\times10^{-35}$ m). Each "pixel" of area L_P^2 on the surface can be thought of as carrying at most one bit (or on the order of one nat) of information about the state of the bulk. This is consistent with the Bekenstein–Hawking entropy formula for black holes, $S_{\rm BH} = \frac{k_B c^3 A}{4G\hbar}$ [1], which in units with $k_B = \hbar = c = 1$ reduces to one quarter of the area in Planck units. In those natural units one bit of information corresponds roughly to $\ln 2$ of entropy, so the holographic bound suggests of order one bit per Planck area as a limit [3].

In the cosmological context, one does not have an event horizon in the same sense as a black hole (unless the universe has a de Sitter phase), but one can consider the particle horizon or Hubble horizon as an information boundary. The choice of boundary can affect detailed outcomes (for example, using the future event horizon was proposed in holographic dark energy models [4]). Here the exact choice will be kept general—any surface that encompasses all currently accessible information (e.g. the surface from which light has had time to reach an observer) could serve as the "holographic screen."

Crucially, as $R(t)$ grows with the expansion of the universe, $N(t)$ increases. New area implies new degrees of freedom that can be interpreted as new "pixels" being added to the cosmic hologram. In physical terms, information that was previously outside the horizon enters the horizon, and/or the total information content of the observable universe increases. This dynamical increase of N is what is meant by a time-varying resolution. The physical laws at low energies do not explicitly change in time; rather, the underlying information capacity that these laws have at their disposal to describe states of the world grows. This viewpoint aligns qualitatively with earlier ideas by Dirac that constants of nature might slowly vary over cosmological timescales [6], though in this framework it is the information capacity (and possibly emergent quantities related to it) that evolves, not necessarily the fundamental constants directly.

Because no new force or new particle content is introduced, this framework must be consistent with general relativity and quantum field theory as currently known. It does not modify Einstein's field equations or the Standard Model; instead, it reinterprets their domain of validity. For example, rather than treating dark energy or dark matter as additional sources in Einstein's equations, the holographic view would say the observed effects attributed to these phenomena might emerge from the conditions or limitations of the information encoding.

The relationship between bulk and boundary in holographic scenarios has been mathematically realized in certain cases (notably AdS/CFT in string theory), but the physical universe is not anti-de Sitter and does not have a static boundary. Nevertheless, one may use analogies: in AdS/CFT each degree of freedom on the boundary corresponds to some field excitation in the bulk, and entanglement structure on the boundary is related to geometry in the bulk. By analogy, one can imagine that each "pixel" on the cosmological horizon encodes some amount of quantum state information about the fields in the interior. As the area expands, the holographic code could admit more refined encoding of the bulk state. If the number of degrees of freedom were fixed, then a larger and larger volume would have to be described with the same information budget, leading to an effectively lower resolution (more coarse-grained description) at late times. The assumption here, however, is that the budget increases with volume in just such a way that it always saturates the holographic bound (information content $\sim$ area).

It is worth noting that the covariant entropy bound (Bousso's bound) conjectures that any light-sheet of surface area A can carry entropy $S \leq A/(4\,L_P^2)$ [3]. The cosmological evolution that increases $A(t)$ potentially allows more entropy in the universe over time without violating this bound. This is consistent with the second law of thermodynamics on a cosmological scale, where horizon entropy (such as the Gibbons–Hawking entropy in de Sitter space) can grow as the horizon area grows. The framework being formulated implicitly assumes that the universe's information content is always at this saturating limit (or at least scales similarly with area). In other words, the universe at any epoch makes full use of the information capacity of its horizon. This assumption maximizes the possible effect of the holographic principle and provides a definite interpretation for calculations: one can equate the actual physical entropy or information in the universe to the area in Planck units.

With these elements in place—a holographic boundary, discrete information units, and time-dependent area—the next step is to derive what this picture implies for key cosmological quantities. By treating reality as an information-limited projection, it is possible to estimate quantities like the vacuum energy (cosmological constant) and perhaps understand scaling relations that appear puzzling in a non-holographic framework. Such calculations are carried out in the following section.

3 Calculative Implications: Cosmological Estimates

3.1 Vacuum Energy and the Cosmological Constant

One longstanding puzzle in physics is the extraordinarily small value of the cosmological constant Λ (or equivalently the energy density of the vacuum ρ_Λ) compared to naïve quantum field theory expectations. The holographic perspective offers a natural scale for ρ_Λ based on the horizon area and information content. If each horizon "pixel" corresponds to at most one degree of freedom (or one quantum of energy in the vacuum state), the total vacuum energy inside the horizon would be bounded by the number of pixels times the energy associated with each. A simple estimate is obtained by assuming each degree of freedom contributes an energy on the order of the smallest possible value consistent with the finite temperature of the de Sitter horizon (if Λ dominates).

For a universe of horizon radius R, the de Sitter temperature is $T \sim \frac{\hbar c}{2\pi k_B R}$, and the horizon entropy is $S \sim \frac{k_B A}{4 L_P^2}$. The total thermodynamic energy associated with the horizon (in the de Sitter quasi-equilibrium sense) is $U \approx T S$. Using $A = 4\pi R^2$, this yields:

$$U \sim \frac{\hbar c}{2\pi R} \times \frac{1}{4 L_P^2} \left(4\pi R^2\right) = \frac{\hbar c R}{2 L_P^2}. \tag{2}$$

Dividing this energy by the volume $V \approx \frac{4\pi R^3}{3}$ gives an effective energy density:

$$\rho_\Lambda \sim \frac{U}{V} \sim \frac{\hbar c R/(2 L_P^2)}{\left(4\pi R^3/3\right)} = \frac{3 \hbar c}{8\pi L_P^2 R^2}. \tag{3}$$

Restoring $c, \hbar, G$ and using $L_P^2 = G\hbar/c^3$, this becomes $\rho_\Lambda \sim \frac{3c^4}{8\pi G R^2}$. Notably, this has the same form as the observed dark energy density if R is on the order of the Hubble radius today. In fact, writing $\Lambda = 3/R^2$ (for a de Sitter universe) gives $\rho_\Lambda = \Lambda c^2/(8\pi G) = 3c^4/(8\pi G R^2)$, in agreement with the above estimate. Thus, identifying R with the current horizon size yields a vacuum energy density of the correct order of magnitude as the observed $\rho_\Lambda \approx 6 \times 10^{-27}\,\mathrm{kg/m^3}$.

This result is essentially a re-derivation of the idea behind holographic dark energy models [5, 4], which argued that ρ_Λ should scale like $1/R^2$ if the largest allowed volume (of size R) saturates the holographic bound. Hsu showed in 2004 that imposing an entropy bound on the vacuum energy leads to a natural ρ_Λ of order the observed value [5]. Li subsequently proposed taking R to be the future event horizon to get a dynamical dark energy model consistent with $w \approx -1$ [4]. In the present treatment, no particular distinction between Hubble radius or event horizon is made at the level of order-of-magnitude, so the success is simply that the holographic assumption yields the correct scaling $\rho_\Lambda \sim 1/L_P^2 R^2$. Importantly, this interpretation does not require fine-tuning of vacuum energy; instead, it suggests that ρ_Λ appears small because the universe is large and the vacuum only packs one fundamental unit of energy per horizon pixel on average.

In dimensionless terms, one can form the ratio of the observed vacuum energy density to the Planck energy density: $\rho_\Lambda/\rho_{\text{Planck}} \sim (L_P/R)^2 \sim 10^{-122}$. This tiny number is often regarded as unnatural, but here it directly reflects the ratio of a single pixel area to the whole horizon area. As the horizon grows, this ratio gets even smaller, but if the vacuum energy also slowly dilutes (as in a near-de Sitter expansion, ρ_Λ stays roughly constant until horizon expansion truly dominates), the value remains of order the inverse of the pixel count. In a sense, the “cosmic coincidence” that ρ_Λ is nonzero yet so small might be no coincidence at all but an inevitable consequence of a holographic universe that fully uses its information capacity.

It must be stressed that this does not provide a dynamical explanation for why Λ is what it is—rather, it shows that given the holographic premise, the expected scale of vacuum energy density is not the Planck scale but the much lower scale set by the current horizon. This removes the need for extreme cancellations of vacuum energy in the interpretation, since the fundamental theory would presumably enforce the holographic limit and prevent a huge ρ_Λ from ever manifesting.

3.2 Dark Matter Phenomenology as Information Deficit

Galactic rotation curves and other astrophysical evidence imply that gravitational effects on luminous matter behave as if influenced by additional unseen mass (dark matter) or a modification of gravity. In the conventional approach, this is explained by introducing non-baryonic dark matter, which clumps around galaxies and clusters. However, the holographic viewpoint suggests an alternative way to see these effects: as a consequence of an emergent behavior of gravity when not all information is accessible or uniformly distributed on the holographic screen.

One proposal along these lines is due to Verlinde, who in 2017 suggested that gravity itself might have an emergent component arising from entropy associated with the cosmological horizon [9]. In his framework, the information associated with matter in the bulk causes an “entropy displacement” on the horizon, leading to an additional elastic gravitational response that reproduces the phenomenology of dark matter. Notably, Verlinde’s approach derives an extra acceleration term on scales of low acceleration, such as

$$a_{\text{dark}} \approx \sqrt{\frac{c^2}{R}\, a_{\text{Newtonian}}}\,,$$

thereby matching galaxy-scale observations.

In the broad holographic interpretation here, one could say: when looking at a galaxy, one is examining a subset of the degrees of freedom on the cosmic holographic screen. If the distribution of those degrees of freedom (related to baryonic matter) is sparse or does not fully utilize the informational capacity that the region's portion of the horizon could allow, the holographic principle might demand a certain equilibrium that manifests as additional apparent gravity. In other words, the disparity between the amount of information associated with visible matter and the total information budget set by the horizon area could manifest as extra curvature or metric effects. Though speculative, it resonates with the principle that gravity thermodynamics (à la Jacobson and Padmanabhan's ideas) link acceleration, information, and entropy.

Crucially, in such emergent approaches no new particles are invoked; the extra "gravity" emerges from boundary conditions. Empirically, any such mechanism must not contradict observations like gravitational lensing, which also points to dark matter. Verlinde's model and related entropy-based approaches can incorporate lensing by deriving a modified field equation that yields the extra acceleration *and* additional lensing. Thus, the holographic interpretation treats the same evidence that is usually ascribed to particle dark matter as indicative of an emergent phenomenon. Whether this is fully consistent across galaxy clusters and colliding clusters like the Bullet Cluster remains under debate, so it is an open question how far these approaches can go without introducing a new matter component.

3.3 Quantum Entanglement and Nonlocality

Quantum mechanics, through Bell's inequalities and their experimental violation, teaches that physical reality cannot be both local and possessed of predetermined values in the classical sense [7]. Experiments by Aspect and others confirm that entangled particles exhibit correlations that defy any local hidden-variable explanation. In the holographic interpretation, these phenomena are natural if apparently separate systems in the bulk are actually encoded on a common underlying surface. Two spatially distant entangled particles might correspond to adjacent (or correlated) degrees of freedom on the boundary, so from the boundary perspective there is no real separation.

This resonates with modern ideas like $ER = EPR$ [8], where entangled black holes connect via non-traversable wormholes. If the entire universe is a single holographic system, entangled particles share a common "holographic origin." Observing the wavefunction collapse of one effectively reveals the single boundary bit describing the pair—the sense of "spooky action at a distance" in the bulk is simply the manifestation of that single boundary degree of freedom.

Such a view does not claim new physics beyond quantum mechanics but recasts entanglement as fundamental structure on the boundary. It sidesteps Bell's theorem's locality constraint by rejecting bulk locality as fundamental: locality emerges from boundary entanglement patterns, but can break down in strongly entangled states.

3.4 Dimensionless Constants and Evolving Information Capacity

Physical laws contain dimensionless constants like $\alpha \approx 1/137$, the proton-to-electron mass ratio, or certain combinations of G and particle masses. A perennial question is whether these might vary over time or have deeper unifications. The holographic viewpoint suggests that if the information resolution of the universe changes with horizon size, perhaps apparent constants might subtly shift if they tie to boundary encoding.

For instance, Dirac's Large Number Hypothesis notes a curious numerical coincidence: the ratio of electric to gravitational forces between an electron and proton is $\sim 10^{40}$, comparable to the age of the universe in atomic units [6]. Dirac proposed G might vary so that the ratio remains tied to the universe's size. A holographic scenario could imagine that G involves a ratio of available degrees of freedom to matter degrees of freedom, though the details remain speculative. Observationally, constraints on $\dot{G}/G$ and variations in α are quite stringent [13]. So if the holographic resolution is evolving, it must do so in a way consistent with no detectable variation so far in these constants, or else be sufficiently subtle or masked by compensating effects.

Hence, while a discrete holographic perspective can *reframe* how fundamental constants might be set, it does not automatically solve the puzzle of their specific values. Still, the viewpoint does unify the question under the broader theme of how the boundary encodes the Standard Model couplings.

4 Reinterpreting Wheeler's "Bag of Gold" Paradox

John Archibald Wheeler described a thought experiment in which a black hole interior is manipulated to contain a large spatial volume (a "bag of gold") with enormous entropy, while the horizon area—and thus total external surface entropy—remains relatively small [10]. This appears to violate the holographic bound if one counts the interior modes as all independent.

In a holographic interpretation, such an overcount is illusory: the bulk modes must be encoded on the horizon's finite degrees of freedom. Recent quantum gravity analyses show that states in a large interior volume can be non-orthogonal in the Hilbert space, effectively meaning there aren't truly exponentially many distinct states [11]. The bag-of-gold paradox dissolves once one admits that the boundary encoding has a fixed dimensionality. Extra bulk volume does not circumvent that limit. Thus, far from disproving the holographic principle, Wheeler's puzzle reinforces it by highlighting the importance of quantum gravitational consistency when enumerating states.

5 Falsifiability and Experimental Tests

Any metaphysical-scientific framework must confront experiment. While the assumption "reality is a holographic discrete projection" is broad, one can imagine potential observational probes:

Planck-Scale Discreteness: If space is discretized by Planck-scale pixels, certain correlations or "holographic noise" might appear in precise interferometry. The Fermilab Holometer search for holographic noise was an example [12], though it found no evidence of the specific model tested. Future, more sensitive experiments might detect or further constrain Planck-scale jitter.

Cosmological Observations: If horizon-limited degrees of freedom shaped the early universe, one might see imprints in the CMB power spectrum at large angular scales or discover a maximum number of inflationary e-folds. So far, CMB data remain consistent with a continuum inflationary scenario, though small anomalies (like the low quadrupole) might hint at discrete or holographic effects if they prove statistically significant.

Testing Fundamental Constant Variation: High-precision spectroscopy of distant quasars and atomic clock comparisons could detect or bound any drift in α or other couplings [13]. If a subtle evolution is ever seen, it could be explained by changing holographic resolution. Non-detection (so far) either means no drift or that the effect is extremely small or compensated.

Quantum Information Constraints: Some approaches propose tabletop experiments in quantum information (optomechanics, ion traps) to see if the Bekenstein bound or similar limits are saturated in small systems. A positive result aligning with holography would be intriguing; a negative result might constrain the discrete encoding viewpoint.

Thus, while broad, the holographic assumption does have potential intersections with experiment. A single null result won't exclude all versions of holography, but cumulatively these tests can push the idea from pure speculation to a more falsifiable stance.

6 Future Research Directions

This paper's viewpoint suggests multiple avenues for deeper investigation:

- **A rigorous holographic cosmology:** Extend AdS/CFT-like techniques or new formalisms to a realistic, dynamically expanding universe, identifying the discrete boundary degrees of freedom that encode an FRW interior.
- **Unifying inflation or early-universe physics:** If horizon-limited degrees of freedom exist from the start, perhaps they regulate the total e-folds of inflation or set the initial entropy conditions. This might connect the arrow of time to the growth of holographic resolution.
- **Connecting emergent gravity and dark matter:** Whether one can produce a single consistent scenario that covers both galaxy-scale successes (like flat rotation curves) *and* cluster-scale phenomena remains an open challenge.
- **Lab-based quantum-gravitational constraints:** As quantum technologies advance, investigating whether small-scale systems exhibit an upper limit on entanglement or a discrete geometry signature becomes more feasible.

7 Conclusion

By adopting the single assumption that reality is a discrete holographic projection, one can coherently reinterpret numerous phenomena without introducing extra particles or forces. The framework addresses the scale of the cosmological constant, the apparent need for dark matter, and the nonlocal aspects of quantum entanglement, all while respecting known physics. Moreover, Wheeler's bag-of-gold paradox is resolved by acknowledging that no interior region can exceed the boundary's finite information capacity. Though not claimed as proof of a holographic universe, these arguments demonstrate its broad consistency and hint at future tests that could strengthen or weaken the holographic hypothesis. Ultimately, seeing our $3+1$ dimensional world as an *information-limited* $2+1$ dimensional surface offers a novel unifying lens on both theoretical and observational puzzles in modern physics.

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