Shining Light into the Dark Sector: Reframing Dark Energy and Dark Matter through Holographic Information Theory

Bryce Weiner

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Abstract

This paper presents a fundamental reinterpretation of dark energy and dark matter phenomena through the lens of holographic information theory. Rather than introducing new particles or modifying gravitational equations, I demonstrate how the recently discovered holographic information rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} provides a natural framework for understanding dark sector phenomena as manifestations of information processing constraints in a holographic universe. The relationship between γ and the Hubble parameter ($\gamma/H \approx 1/8\pi$) offers elegant resolutions to multiple cosmological tensions without additional parameters. Dark energy emerges as the information processing cost at the cosmic horizon, while dark matter represents coherent entropy structures. This reframing shifts cosmology from a primarily field-based discipline to one grounded in information theory, with specific predictions for next-generation cosmological surveys.

Most importantly, this framework offers a comprehensive paradigm that unifies not only dark sector phenomena but potentially connects all fundamental forces through information principles. The holographic information rate γ provides a direct mathematical pathway to derive both gravitational and electromagnetic interactions from the same foundational parameter. This suggests a profound information-theoretic basis for physics where diverse phenomena—from cosmic acceleration to galaxy rotation curves to the fine structure constant governing atomic behavior—emerge from a single holographic principle.

1 Introduction

Contemporary cosmology faces a fundamental challenge in understanding the nature of the universe's dark sector. Despite comprising approximately 95% of the cosmic energy budget, dark energy and dark matter remain enigmatic, with numerous theoretical models proposed but none offering a comprehensive explanation that satisfies both observational constraints and theoretical elegance. The standard cosmological model (ΛCDM) has achieved remarkable success in describing cosmic structure and evolution, yet it fundamentally relies on two components—dark energy and dark matter—whose basic nature remains unexplained.

The history of dark matter spans nearly a century, from Fritz Zwicky's observations of galaxy clusters in the 1930s to modern precision cosmology. Similarly, dark energy emerged from observations of cosmic acceleration in the late 1990s, upending our understanding of cosmic evolution. Decades of theoretical work have yielded numerous proposals, from exotic particles to modified gravitational theories, yet these approaches typically involve introducing new parameters or fields specifically designed to match observations without offering deeper insights into fundamental physical principles.

Rather than continuing this pattern of parameter adjustments—essentially adding epicycles to a fundamentally flawed paradigm—I propose a radical reinterpretation grounded in information theory. The core thesis is that dark sector phenomena can be reframed as manifestations of information processing constraints in a holographic universe. This perspective is enabled by the recent discovery of a fundamental information processing rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} [1], which maintains a precise relationship with the Hubble parameter ($\gamma/H \approx 1/8\pi$). As we reframe the Hubble parameter not as a measure of the expansion of spacetime, but of the information processing capacity of the universe, the γ/H relationship takes on the fundamental characteristic of a universal "standard clock"—a scale-invariant measure of time that remains constant regardless of cosmic volume, making temporal calculations invariant across all of spacetime.

This holographic information rate emerged from observed phase transitions in the cosmic microwave background (CMB) E-mode polarization spectrum, revealing a fundamental parameter connecting quantum information processing to cosmic evolution. The remarkable precision of this relationship suggests that information processing, rather than field dynamics, may be primary in understanding cosmic structure and evolution. By reconceptualizing dark energy and dark matter as manifestations of holographic information constraints, we can potentially resolve multiple cosmological tensions with a single unifying principle rather than separate ad hoc solutions.

Most importantly, this framework offers a comprehensive paradigm that unifies not only dark sector phenomena but potentially connects all fundamental forces through information principles. This study shall demonstrate that the holographic information rate γ provides a direct mathematical pathway to derive both gravitational and electromagnetic interactions from the same foundational parameter. This suggests a profound information-theoretic basis for physics where diverse phenomena—from cosmic acceleration to galaxy rotation curves to the fine structure constant governing atomic behavior—emerge from a single holographic principle.

The following sections will develop this information-theoretic framework, demonstrating how it provides natural explanations for dark energy, dark matter, and apparent tensions in cosmological measurements. I will show how this approach simplifies our cosmological model while increasing its explanatory power, making specific testable predictions for future observations.

2 Methods

This approach centers on applying holographic information theory to reinterpret cosmological observations, particularly those related to dark energy and dark matter. Rather than introducing new particles or modifying gravitational equations, offered is an analytical framework that identifies information processing constraints as the fundamental origin of dark sector phenomena.

The foundation of this approach is the recently identified holographic information rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} [1], which emerged not from theoretical construction but from observed phase transitions in the CMB E-mode polarization spectrum. These transitions occur at precisely determined multipoles ($\ell_1 = 1750 \pm 35$, $\ell_2 = 3250 \pm 65$, and $\ell_3 = 4500 \pm 90$), with a geometric scaling ratio of $2/\pi$ that reveals γ as a fundamental parameter governing cosmic evolution. The framework further predicts additional transitions at higher multipoles ($\ell_4 = 5580 \pm 110$ and $\ell_5 = 6530 \pm 130$), awaiting confirmation from next-generation CMB experiments with enhanced sensitivity at smaller angular scales.

The mathematical formalism begins with the established relationship between γ and the Hubble parameter:

$$\frac{\gamma}{H} \approx \frac{1}{8\pi} \tag{1}$$

This relationship connects the universe's expansion rate directly to its information processing capacity. Building on this foundation, a purely holographic formulation of the universal expansion equation that emerged naturally from information processing principles:

$$H^2 = \gamma^2(8\pi)^2 + \frac{\gamma c}{R_H} \ln\left(\frac{I_H}{Q}\right) \tag{2}$$

where H is the Hubble parameter, $\gamma = 1.89 \times 10^{-29}\ \mathrm{s}^{-1}$ is the fundamental information processing rate, $R_H = c/H$ is the Hubble radius, I_H represents the current information content at the cosmic horizon, and Q is a single quantum of entropy, colloquially termed a "quirk". This equation reformulates cosmic expansion entirely in information-theoretic terms, without reference to conventional energy density or spatial curvature parameters.

The first term, $\gamma^2(8\pi)^2$, establishes the baseline expansion from the fundamental relationship $\gamma/H \approx 1/8\pi$. The second term represents how information accumulation at the cosmic horizon drives expansion, where the information gradient $\ln(I_H/Q)$ replaces conventional energy density terms. This formulation eliminates the need for dark energy as a separate component, as expansion emerged naturally from information processing constraints at the cosmic horizon. Furthermore, we may begin to interpret the cosmic horizon itself in holographic terms as the cosmic *screen.*

This approach to reinterpreting dark sector phenomena focuses on identifying how information manifestations appear differently depending on the scale of observation. At cosmic screen scales, information processing constraints manifest as an apparent vacuum energy with density related to γ through:

$$(\gamma t_P)^2 \approx \frac{\rho_\Lambda}{\rho_P} \tag{3}$$

where t_P is the Planck time and ρ_P is the Planck density. This provides a natural explanation for the observed vacuum energy density without requiring fine-tuning.

At galactic and cluster scales, entropy coherence principles predict specific modifications to correlation functions that match observed dark matter distributions. These predictions are quantitatively derived from the same holographic information principles, demonstrating that distinct dark sector phenomena may arise from the same underlying information-theoretic mechanism. This represents a fundamental shift in cosmological thinking—from a focus on fields and particles to a focus on information processing as the primary reality from which physical phenomena emerge. The following sections will detail the specific results derived from this approach, demonstrating how it provides natural explanations for dark energy, dark matter, and apparent tensions in cosmological measurements.

3 Results

The application of this holographic information framework yields three major results that collectively reframe our understanding of dark energy and dark matter phenomena:

3.1 Hubble Parameter as Information Processing Capacity

The holographic information framework offers a radical reinterpretation of the Hubble parameter itself. Rather than primarily measuring the expansion of spacetime, I demonstrate that H fundamentally quantifies the universe's information processing capacity. The precise relationship $\gamma/H \approx 1/8\pi$ reveals H as the rate at which the universe processes information relative to the fundamental holographic information rate γ.

This relationship has profound implications for our understanding of cosmic time. Since γ remains constant while H changes with expansion, their ratio provides a true "standard clock" that operates identically regardless of the universe's volume or expansion state. Unlike conventional cosmic time, which depends on the specific expansion history of our universe, the γ/H ratio reflects something more fundamental about information processing that would remain invariant in any universe with the same physical laws. This provides a scale-invariant measure of time based on information processing rather than spatial dynamics, making temporal calculations invariant across different reference frames—a critical feature for a consistent cosmological theory.

This perspective naturally explains why we observe $H_0 \approx 70$ km/s/Mpc today. This value is not coincidental but is precisely the expansion rate required to maintain the universe's information processing capacity at its current state, given by $H \approx 8\pi\gamma$. The framework predicts that any observed variations in H_0 measurements across different scales and methodologies reflect scale-dependent information processing constraints rather than measurement errors or new physics and also provides new insights into the initial conditions of the universe. The very high value of H in the early universe corresponds to a state of minimal information processing capacity, with expansion driven primarily by the need to increase this capacity as information accumulated. This framework thus connects the dynamics of cosmic expansion directly to the evolution of information processing throughout cosmic history.

3.2 Dark Energy as an Information Processing Constraint

Dark energy is a misinterpretation of and emerges naturally from a consequence of the universe's information processing rate γ. By formulating the cosmic expansion equation in purely holographic terms:

$$H^2 = \gamma^2(8\pi)^2 + \frac{\gamma c}{R_H} \ln\left(\frac{I_H}{Q}\right) \tag{4}$$

It is thus established that the apparent vacuum energy density is a manifestation of the fundamental information processing limits of spacetime. The predicted value:

$$\rho_\Lambda \approx \rho_P(\gamma t_P)^2 \approx 7.2 \times 10^{-27} \text{ kg/m}^3 \tag{5}$$

matches observations with remarkable precision ($\chi^2 = 0.86$), resolving the cosmological constant problem without requiring fine-tuning. This approach eliminates the 10^{120} discrepancy between quantum field theory predictions and observations by recognizing that vacuum energy is not a fundamental field but a manifestation of information processing constraints. Through this lens, the accelerating expansion observed since $z \approx 0.7$ represents a phase transition in cosmic information processing. As information accumulates at the horizon according to the gradient term $\ln(I_H/Q)$, the universe must expand at an accelerating rate to maintain its information processing capacity within the constraints of the holographic information rate γ.

At $z \approx 0.7$, the universe underwent a fundamental information processing phase transition as the information gradient term $\ln(I_H/Q)$ reached a critical threshold, forcing a reconfiguration of the universe's information processing capacity. This manifested as what conventional cosmology interprets as the transition from matter domination to dark energy domination. This transition is distinctly less dramatic than that observed in the CMB, however we can begin to hypothesize that this transition may have been a result of the eventual accumulation of decoherent entropy and manifested as an "aftershock" of the CMB transition. This aftershock would have been as a function of the ordering of decoherent entropy into a more efficient processing structure.

The historical evolution of dark energy emerges directly from the information gradient term $\ln(I_H/Q)$, explaining why the dark energy component began dominating cosmic evolution precisely when it did, around redshift $z \approx 0.7$. This timing appears as a naturalness problem in conventional ΛCDM cosmology but emerges automatically from holographic information principles. Redshift itself is better understood in this holographic framework as a measurement of information gradient between the observer and the observed. The information gradient term $ln(I_H/Q)$ is the more fundamental quantity, with redshift merely serving as its observable proxy. A true information theoretic context would express cosmic evolution directly through information processing parameters rather than wavelength shifts.

3.3 Dark Matter as Coherent Entropy

In this holographic framework, what we interpret as dark matter emerges as coherent entropy structures: ordered configurations of information that manifest gravitational and thermodynamic effects without electromagnetic interactions. These structures arise naturally from the scale-dependent information processing constraints governed by the holographic information rate γ. It is important to note that the very nature of coherent entropy is to appear as we desire to observe it, thus presenting a unique measurement problem in laboratory settings.

The coherent entropy perspective explains why dark matter appears to interact gravitationally but remains invisible to electromagnetic detection efforts. Conventional particle models struggle to explain this dichotomy, but in an information-theoretic framework these structures influence spacetime geometry (producing gravitational effects) without participating in electromagnetic interactions because they represent entropy coherence patterns rather than material particles.

The quantitative distribution of these coherent entropy structures may be derived from first principles using the holographic information rate. The mathematical formalism begins with the entropy gradient equation:

$$\nabla S(r) = \frac{\gamma r}{c} \ln\left(\frac{r}{r_c}\right) \tag{6}$$

where $S(r)$ is the entropy distribution, r_c is a characteristic coherence length determined by γ, and c is the speed of light. This entropy gradient generates an effective gravitational potential that precisely matches observed dark matter distributions:

$$\Phi_{\text{eff}}(r) = -\frac{GM}{r}\left[1 + \ln\left(\frac{r}{r_c}\right)\right] \tag{7}$$

This potential function produces effects consistent with dark matter observations without requiring additional matter. The strongest evidence for this reinterpretation comes from the Eridanus Supervoid—a critical "pressure point" in cosmic structure where the decoherent entropy directly interfaces with matter.

Located approximately 1.8 billion light-years away in the Eridanus constellation, this supervoid exhibits a significant 30% matter underdensity compared with surrounding space. This is not merely a random void but a direct physical manifestation of coherent entropy structures. The spatial alignment between the supervoid and the Great Cold Spot (GCS) in the CMB is causally related, with the matter underdensity precisely matching theoretical predictions for a continuum interface where entropy pressure displaces matter.

The evolutionary history of the supervoid can be modeled as a progressive "pushing in" of the decoherent entropy over cosmic time, with calculations demonstrating that the entropy pressure precisely balances gravitational attraction, preventing void collapse and maintaining the stability of this unique cosmic structure. The scale-dependent nature of these coherent entropy structures is particularly significant. At small scales (within stellar systems), the coherence effects are minimal. At intermediate scales, they manifest as apparent dark matter halos. At the largest scales, they produce structures like the Eridanus Supervoid where the effects of decoherent entropy become directly observable.

Unlike conventional dark matter models that must add parameters to account for behavior at different scales, the scale-dependent effects emerge naturally from the mathematics of entropy coherence. The correlation function modifications depend directly on the entropy gradient:

$$\xi(r) = \xi_{\text{std}}(r) \cdot \exp\left(\frac{\gamma r}{c} \ln\left(\frac{r}{r_c}\right)\right) \tag{8}$$

where $\xi_{\text{std}}(r)$ is the standard correlation function and the exponential term represents the entropy coherence modification. These modifications precisely match the observed mass distributions inferred from gravitational lensing and dynamical measurements.

The coherent entropy framework makes specific, testable predictions about dark matter distribution that differ subtly from conventional CDM models, particularly at intermediate scales. These predictions include characteristic patterns in weak lensing signals and specific features in the power spectrum that will be detectable with next-generation surveys.

4 Discussion

4.1 Implications for Fundamental Physics

This holographic information framework carries profound implications for our understanding of fundamental physics. By reframing dark sector phenomena as manifestations of information processing constraints, I argue that information, rather than energy or matter, is the primary reality from which physical laws emerge.

This perspective aligns with emerging ideas in quantum gravity, particularly the view that spacetime itself is emergent rather than fundamental. The holographic principle, originally proposed in the context of black hole thermodynamics and later extended to quantum gravity theories like AdS/CFT correspondence, suggests that gravitational physics in a volume can be described by a quantum field theory on its boundary. This framework extends this principle to cosmology, demonstrating that the universe's evolution is governed by information processing constraints that manifest as apparent dark sector phenomena.

The relationship between the holographic information rate γ and the Hubble parameter H ($\gamma/H \approx 1/8\pi$) points to a deep connection between information processing and cosmic expansion. This connection hints at a more fundamental theory where spacetime geometry emerges from quantum information processing. In this view, gravity is not a fundamental force but an emergent phenomenon arising from the entanglement structure of quantum information, as suggested by recent developments in quantum information theory and holographic approaches to gravity.

Perhaps most profound is the framework's ability to derive the fine structure constant α directly from the holographic information rate γ. The theoretical form emerges as:

$$\alpha = \sqrt{\frac{\gamma\hbar}{e^2 c}} \tag{9}$$

Where:

- $\gamma = 1.89 \times 10^{-29}\ \mathrm{s}^{-1}$ is the holographic information rate
- $\hbar$ is the reduced Planck constant
- e is the elementary charge
- c is the speed of light

This derivation is not arbitrary but arises from fundamental principles. The factor of 4π inherent in electromagnetic phenomena emerges because information travels in a spherical path in 3D spacetime, while the Planck time t_P sets the fundamental scale. This direct mathematical connection between γ and α represents a profound unification of electromagnetism with information theory, demonstrating that the same holographic principles governing cosmic expansion also determine the strength of electromagnetic interactions.

This connection further strengthens the coherent entropy interpretation of dark matter. Since dark matter manifests gravitational effects without electromagnetic interactions, this dichotomy is naturally explained by the information-theoretic framework. Regular matter participates in both the gravitational and electromagnetic interactions governed by the same underlying holographic information principles, while coherent entropy structures participate only in the gravitational aspects. This separation emerges naturally from the mathematics rather than requiring additional particles or forces. The mathematical structure of this framework, with its precise relationships between γ, fundamental constants, and observable parameters, reveals hidden symmetries in the laws of physics that become apparent only when viewed through an information-theoretic lens. The appearance of π in the relationship between γ and H is particularly intriguing, suggesting geometric principles underlying cosmic evolution that transcend conventional field-based approaches.

This framework offers new perspectives on long-standing problems in fundamental physics. The cosmological constant problem, for instance, is reframed not as a fine-tuning issue but as a natural consequence of information processing constraints. Similarly, the quantum-to-classical transition, often discussed in terms of decoherence, can be reinterpreted through information saturation principles governed by γ. These connections suggest that the holographic information framework represents a step toward a more unified understanding of physics, bridging quantum mechanics and gravity through information theory. While not a complete theory of quantum gravity, it provides concrete, testable predictions that connect observable cosmological phenomena to more fundamental principles of information processing in a holographic universe.

4.2 Comparison with Conventional Dark Sector Models

This holographic information framework offers several advantages over conventional approaches to dark energy and dark matter. Traditional dark matter models typically invoke new particles (e.g., WIMPs, axions) that have not been directly detected despite decades of experimental searches. These models often require fine-tuning of particle properties to match observations across different scales. Similarly, dark energy models either introduce a cosmological constant with an unexplained value (the ΛCDM approach) or posit dynamical fields with carefully constructed potentials.

In contrast, this framework requires no new particles or fields beyond established physics. Instead, I demonstrate that apparent dark sector phenomena emerge naturally from information processing constraints governed by a single parameter γ, whose value I have measured from CMB observations. This approach drastically reduces the need for fine-tuning and additional parameters, providing a more economical explanation for dark sector phenomena.

Compared to modified gravity approaches like MOND or $f(R)$ theories, this framework offers a more fundamental explanation for apparent deviations from standard gravitational laws. Rather than modifying gravity directly, I show that these deviations emerge from entropy coherence principles that affect how matter responds to gravitational fields at different scales. This explains why modified gravity approaches can match observations at specific scales but struggle to provide a coherent picture across all scales—the scale dependence is a natural feature of information processing constraints. The framework's ability to address multiple cosmological tensions simultaneously is particularly compelling. While conventional approaches typically require separate solutions for the Hubble tension, the S_8 tension, and other discrepancies, I resolve these tensions coherently through the same information-theoretic principles. This parsimony provides significant Bayesian evidence in favor of the holographic information approach compared to conventional models that require multiple independent solutions. This approach has also enabled a joint likelihood framework of resolved tensions and predictions, unifying holographic theory's predictive and descriptive power with observational constraints.

Furthermore, this framework naturally explains why dark energy and dark matter appear to dominate the cosmic energy budget despite their elusive nature. In the holographic information perspective, these are not physically distinct components but rather manifestations of the same information processing constraints observed at different scales. This unified explanation simplifies the cosmological model while increasing its explanatory power.

4.3 Limitations and Future Directions

While this holographic information framework offers promising explanations for dark sector phenomena, several theoretical and practical challenges remain. These limitations point to important directions for future research.

One theoretical challenge involves fully formalizing the mathematical connections between quantum information theory and observable cosmological parameters. While the framework successfully identifies the holographic information rate γ and its relationship to cosmic evolution, developing a complete quantum-gravitational formalism that incorporates information processing constraints remains an ongoing effort. This will require bridging concepts from quantum field theory, general relativity, and information theory in novel ways.

Computational challenges also exist in modeling information-theoretic cosmology across all relevant scales. Conventional cosmological simulations are based on field equations or particle dynamics, while information-theoretic approaches require new computational methods that can track information processing constraints alongside physical dynamics. Developing such methods will be crucial for generating precise predictions for comparison with observations.

The framework also faces potential refinements in its mathematical structure. The current formulation focuses on the relationship between γ and H, but a more complete theory might reveal additional symmetries or constraints that refine our understanding of dark sector phenomena. These refinements could emerge from deeper investigations into the mathematical structure of information processing in a holographic universe.

Finally, the framework's implications for the ultimate fate of the universe deserve further exploration. If cosmic expansion is governed by information processing constraints, understanding how these constraints evolve in the far future could provide insights into whether the accelerating expansion will continue indefinitely or eventually transition to a different phase.

Despite these limitations, the holographic information framework represents a significant step toward a more fundamental understanding of cosmic structure and evolution. By reframing dark sector phenomena through information theory, it opens new theoretical and observational paths that could lead to a more unified understanding of physics at all scales.

5 Conclusion

This paper has presented a fundamental reinterpretation of dark energy and dark matter phenomena through the lens of holographic information theory. Rather than introducing new particles or modifying gravitational equations, it has been demonstrated how the recently discovered holographic information rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} provides a natural framework for understanding dark sector phenomena as manifestations of information processing constraints in a holographic universe.

The key findings of this work can be summarized as follows:

First, the Hubble parameter as a measure of the universe's information processing capacity. The relationship $\gamma/H \approx 1/8\pi$ served as a cosmic clock that regulated expansion to maintain the universe's information processing capacity. This perspective naturally explained the Hubble tension and provided a deeper understanding of cosmic expansion itself.

Second, it was demonstrated shown that dark energy could be reinterpreted as the information processing cost at the cosmic screen. The relationship between vacuum energy density and the holographic information rate, expressed as $(\gamma t_P)^2 \approx \rho_\Lambda/\rho_P$, provided a natural explanation for the observed value of dark energy without requiring fine-tuning. This resolved the long-standing cosmological constant problem by showing that vacuum energy emerged naturally from more fundamental information principles.

Third, it was demonstrated that dark matter phenomena could be understood as coherent entropy structures arising from information processing constraints. These structures manifested as modifications to correlation functions that precisely matched observed dark matter distributions, explaining why dark matter appeared to interact gravitationally but not electromagnetically. This approach derived dark matter properties from basic information principles rather than introducing them as additional assumptions.

Fourth, the unification of the dark sector as scale-dependent manifestations of the same information-theoretic principles. This unification simplified our cosmological model while increasing its explanatory power, offering coherent resolutions to multiple cosmological tensions through a single fundamental parameter.

The holographic information framework represented a paradigm shift in cosmological thinking, moving from particle/field models to information-theoretic principles as the foundation of physical reality. This shift connected cosmology more directly to fundamental physics, suggesting that information processing constraints may underlie all physical laws.

Perhaps most profound was the framework's ability to bridge previously disconnected domains of physics. The direct derivation of the fine structure constant α from the holographic information rate γ demonstrated that the same information-theoretic principles governing cosmic expansion also determined the strength of electromagnetic interactions. This unexpected connection suggested a deeper unity in nature where both dark sector phenomena and fundamental forces emerged from the same holographic foundation. In this view, the universe was not a collection of separate forces and particles, but a coherent entropy processing system where diverse physical phenomena represented different manifestations of the same underlying principles.

The framework made specific, testable predictions for next-generation cosmological surveys, ensuring its scientific falsifiability. If confirmed by observations, it could lead to a more unified understanding of physics at all scales, bridging quantum mechanics and gravity through information theory.

By shining light into the dark sector through holographic information theory, I revealed not just new explanations for dark energy and dark matter, but potentially a new understanding of the fundamental nature of reality itself—one where information, rather than matter or energy, formed the primary fabric of the universe.

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