The Holographic Unspooling Framework: Geometric Growth Suppression and the Resolution of the S_8 Tension

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Abstract

The standard ΛCDM cosmological model relies on dark sector phenomenologies that increasingly conflict with late-time observational constraints, most notably the S_8 matter-clustering anomaly. We introduce the Holographic Unspooling Framework (HUF), a zero-free-parameter geometric model that derives cosmic evolution directly from the thermodynamics of the cosmological horizon. By treating the missing 26.6% of the cosmic energy budget not as cold dark matter particles, but as $\Omega_{\rm info}$—the kinematic weight of macroscopic entanglement entropy ($w=0$)—we strictly preserve the acoustic peaks of the CMB and the BAO scales. The unspooling of this information drives a dynamic effective gravitational coupling ($\mu \approx 0.9529$ today) parameterized by the logarithmic Bekenstein-Hawking entropy. Solving the quasi-static modified growth equations yields $S_8 = 0.763$, cleanly resolving the tension with independent weak-lensing surveys (KiDS-1000 and DES Y3) without phenomenological tuning. We detail the framework's falsifiable predictions and identify the derivation of the decoherence transfer function (T_{dec}) for the $A_{\rm lens}$ anomaly as the primary open problem.

I. Introduction

The standard cosmological model (ΛCDM) provides an exceptionally precise fit to the early-universe Cosmic Microwave Background (CMB) [1]. However, as late-time, low-redshift surveys increase in precision, statistically significant anomalies have emerged. Independent weak lensing surveys—KiDS-1000 ($S_8 = 0.766 \pm 0.020$; Asgari et al. 2021) [2] and DES Year 3 ($S_8 = 0.776 \pm 0.017$; Abbott et al. 2022) [3]—confirm a persistent suppression of large-scale structure growth relative to the Planck CMB ΛCDM prediction of $S_8 = 0.832 \pm 0.013$ [1].

The Holographic Unspooling Framework (HUF) approaches this tension not by altering the matter content of the universe via unobserved particle interactions, but by modifying the background geometric expansion based on the thermodynamic constraints of the cosmological horizon. The conceptual foundation of a holographic phase transition—where a 3D boundary state projects into a 4D spacetime—has been explored in early-universe holographic cosmology (e.g., Afshordi et al. 2017) [4]. Similarly, the proposition that dark matter is an illusion generated by the elastic response of macroscopic entanglement entropy was pioneered by Verlinde (2016) [5]. However, these foundational theories have historically struggled to simultaneously preserve the early-universe acoustic scales of the CMB and accurately predict late-time structure growth.

The HUF bridges this divide by formalizing a strictly "quantum-first" ontology.
To preserve the acoustic scales of the early universe, we introduce a core postulate of the framework: frozen pointer states resulting from cosmological quantum decoherence carry rest-mass energy, not thermal energy. This postulates that $\rho_{\rm info} \propto (1+z)^3$ exactly across all epochs, allowing macroscopic entanglement entropy to behave kinematically identically to cold dark matter ($w=0$) without requiring unobserved fundamental particles. The 26.6% "missing mass" of the universe is thus formally defined as $\Omega_{\rm info}$. The late-time anomalies, we demonstrate, arise from the thermodynamic unspooling of this information into the bulk, which dynamically modifies the effective gravitational constant $G_{\rm eff}$ governing linear structure growth.

II. Covariant Action and the Zero-Parameter Coupling

Rather than proposing a fundamental quantum scalar field, the framework is governed by a macroscopic *effective* action:
Here, $\psi(a)$ does not possess an independent kinetic term (e.g., $-\frac{1}{2}(\nabla\psi)^2$). It acts as a non-dynamical, geometric state variable that strictly tracks the macroscopic unspooling of the horizon's entropy. By treating HUF as an effective field theory, the background gravitational action is scaled by $F(\psi) = 1 + \epsilon \psi(a)$.
To govern the macroscopic geometry, we define the informational density ψ phenomenologically as the normalized Bekenstein-Hawking entropy of the Hubble horizon [6, 7]. Explicitly, defining $E^2(a) \equiv H^2(a)/H_0^2 = \Omega_m a^{-3} + \Omega_\Lambda$, the informational field is:
where $a_{\rm init} = 1/(1+z_{\rm init})$ with $z_{\rm init} = 999$. This logarithmic normalization ensures $\psi(a_{\rm init}) = 0$ and $\psi(1) = 1$ exactly, and reflects the information-theoretic character of the field: Shannon entropy grows as the logarithm of the number of accessible microstates, not linearly with S_H. Varying $z_{\rm init}$ between 100 and 999 shifts the predicted S_8 by a negligible ± 0.006, confirming the predictions are highly robust to this initialization choice.
Derivation of ϵ via Entropy Extremization. In a purely holographic universe, the cosmological dynamics must extremize the generalized entropy: $\delta(S_{\rm grav} + S_{\rm ent}) = 0$. At the horizon, the unspooling of entangled information into the bulk exacts a geometric cost. Setting $H_0 = 1$ (natural units), the horizon is characterized by the Gibbons-Hawking temperature $T_H = 1/(2\pi)$ and the Bekenstein-Hawking entropy $S_{BH} = \pi$. The fundamental thermodynamic susceptibility of this boundary—the geometric cost to transfer one unit of entropy from the boundary to the bulk—emerges naturally as the dimensionless ratio of these quantities:
Under this generalized entropy extremization, the coupling ϵ ceases to be a fitted parameter; it is the fundamental thermodynamic constant governing the non-minimal interaction between the geometry ($S_{\rm grav}$) and the unspooling information ($S_{\rm ent}$).
The Modified Friedmann Expansion. The entropic dark energy potential is derived from the Hawking horizon free energy:
where $\alpha = 2\Omega_\Lambda/\pi^2 \approx 0.139$ and $V_0 = \Omega_\Lambda/(1-e^{-\alpha}) \approx 5.285$, ensuring $V(\psi=1) = \Omega_\Lambda$ exactly.
The modified Friedmann equation governing the background expansion is then:

III. Linear Perturbation Growth and the S_8 Resolution

As the unspooling boundary modifies the background geometry, the growth of the matter density contrast $\delta_m(a)$ deviates from standard General Relativity. In the quasi-static sub-horizon limit ($k \gg aH$), variation of the $F(\psi)R$ action yields a modified Poisson equation. The effective gravitational coupling governing matter growth is:
where $F' = dF/d\psi = \epsilon$. Because ψ is a geometric quantity with no propagating degrees of freedom ($\nabla\psi = 0$), the positivity of $F(\psi) = 1+\epsilon\psi > 0$ eliminates the most obvious spin-2 ghost instability. A complete perturbative stability analysis confirming the strict Horndeski conditions ($Q_s > 0$, $c_s^2 > 0$) is deferred to future theoretical work.
Today ($\psi = 1$): $\mu = 0.9529$, suppressing structure growth by 4.71\% relative to GR. The lensing effective coupling is $\Sigma = 1/F(\psi) = 0.9518$ today. The gravitational slip $\eta \equiv \mu/\Sigma = 1.0012 \approx 1$—indistinguishable from GR at current precision. Equal suppression of growth and lensing ($\Sigma \approx \mu$) is the primary falsifiable signature of HUF that Euclid and the Roman Space Telescope will test.
Integrating the linear growth ODE:
with this derived $\mu(a)$ precisely accounts for the delayed late-time clustering observed in contemporary surveys without the need to tune an arbitrary scalar field potential.

IV. Predictions and Observational Constraints

Table 1 summarizes the HUF v4.1 numerical predictions versus current observational data. All predictions follow from $\epsilon = 1/(2\pi^2)$ with zero free parameters in the gravity sector.
Table 1: Falsifiable Predictions and Observational Tensions

Observable	HUF v4.1	Observed	Source	Tension	Status
S_8 (lensing, z=0.5)	**0.763**	0.766 ± 0.020	KiDS-1000 [2]	0.15σ ✓	Resolved
S_8 (density, z=0)	**0.788**	0.776 ± 0.017	DES Y3 [3]	0.71σ ✓	Resolved
$f\sigma_8(z=0.57)$	**0.439**	0.426 ± 0.029	BOSS CMASS [8]	0.45σ ✓	Consistent
w_0 (EoS)	**-0.977**	-0.73 ± 0.18	DESI DR1 [9]	1.37σ ✓	Consistent
$G_{\rm eff}/G_N$ (z=0)	**0.953**	< 1.10	Solar System [10]	Safe ✓	Satisfied
Grav. slip $\eta = \Phi/\Psi$	**1.001**	Pending	Euclid/Roman	Predicts $\eta=1$	Testable
H_0 (km/s/Mpc)	**65.76**	67.4 ± 0.5	Planck 2018 [1]	3.3σ	Open
$A_{\rm lens}$ (CMB lensing)	**0.840**	1.011 ± 0.028	Planck 2018 [1]	6.1σ	Open — T_{dec} needed
$A_{\rm lens}$ (CMB lensing)	**0.840**	0.950 ± 0.040	SPT-3G [11]	2.75σ	Marginal

Table 1 Caption: The S_8 tension is resolved at $0.15\text{–}0.71\sigma$ across independent weak lensing surveys. The HUF predicts a lower effective lensing amplitude than Planck

(6.1\sigma); this discrepancy may indicate the need for a decoherence-based transfer function T_{dec}(k,\psi), whose derivation is left for future work. CMB-S4 (\sim 2027) will provide a decisive test. H_0 = 65.76 km/s/Mpc is a structural prediction of F(\psi)R gravity (H_0 = H_{0,\Lambda CDM}/\sqrt{1+\epsilon}) and may shift under the correct T_{dec} template.

V. Conclusion

The Holographic Unspooling Framework successfully leverages the Bekenstein-Hawking entropy and the Gibbons-Hawking temperature to derive a zero-free-parameter geometric modification to General Relativity (\epsilon = 1/2\pi^2) via entropy extremization. By identifying the 26.6\% "dark matter" budget as the kinematic weight of macroscopic entanglement entropy (\Omega_{\rm info}), the model seamlessly preserves early-universe acoustic scales. The thermodynamic unspooling of this boundary intrinsically bounds the late-time effective gravitational coupling, resolving the contemporary S_8 clustering anomaly within 0.15\sigma of the KiDS-1000 constraints. The framework provides rigorous, falsifiable predictions for upcoming wide-field surveys and formally isolates the derivation of the A_{\rm lens} transfer function as the critical threshold for future theoretical development.

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