Linear Perturbation Theory and Observational Confrontation of the Holographic Unspooling Framework

A. J. Curiel[1, *]

[1] *Independent Researcher*

(Dated: June 3, 2026)

Standard cosmological models increasingly rely on invisible material parameters—particulate dark matter and dark energy fluids—to resolve late-time observational tensions. We present the linear perturbation theory of the Holographic Unspooling Framework (HUF), a strictly non-materialist, zero-free-parameter geometry that derives cosmic evolution directly from the thermodynamic unspooling of macroscopic entanglement entropy. By redefining the dark sector as the kinematic weight of this unspooling information ($\Omega_{\rm info} = 0.266$), the framework naturally preserves early-universe physics, including Baryon Acoustic Oscillations (BAO) and the Cosmic Microwave Background (CMB) sound horizon. We demonstrate that the emergent geometry drives a late-time suppression of the effective gravitational constant parameterized exclusively by $\epsilon = 1/(2\pi^2)$. This yields a native resolution to the S_8 matter-clustering tension ($S_8 = 0.763$) and generates an exact, falsifiable prediction for the growth index ($\gamma = 0.626$). We confront the framework's primary open problems: predicting an $A_{\rm lens} \approx 0.840$ that we hypothesize requires a decoherence transfer function to match Planck data, and a rigid, un-tunable prediction of $H_0 = 65.76$ km s^{-1} Mpc^{-1} that sits in severe tension with absolute distance ladder calibrations. We propose that these structural tensions are signatures of the holographic phase transition, establishing decisive falsification tests for CMB-S4 and Euclid.

I. INTRODUCTION

Modern cosmology operates at the intersection of two fundamental "Plancks": the fundamental thermodynamic limit defined by the Planck length and the Bekenstein-Hawking entropy, and the observational legacy of the Planck satellite [1]. The standard ΛCDM model achieves an exceptional fit to the latter but requires the ad hoc insertion of a vast, invisible material sector—Cold Dark Matter (CDM) and Dark Energy (Λ)—that remains disconnected from the former.

As late-time observational precision has increased, ΛCDM has fractured into persistent anomalies, most notably the S_8 matter-clustering tension [2, 3] and the H_0 expansion crisis [4].

The Holographic Unspooling Framework (HUF) approaches these tensions through a strict anti-materialist axiom. It posits that the universe is undergoing an ongoing 3D-to-4D informational phase transition. In this paper, we map the complete linear perturbation theory of the HUF, proving that its zero-parameter background natively resolves the S_8 tension and sets up precise falsifiability bounds, while exposing absolute scaling tensions that challenge the materialist assumptions underlying local distance calibrations.

II. THE ANTI-MATERIALIST BACKGROUND AND ENERGY BUDGET

The HUF rejects the inclusion of phenomenological particulate fluids to satisfy the Friedmann equations. The "missing" 95% of the energy budget is identified as the macroscopic thermodynamic consequence of unspooling entanglement entropy. The total dimensionless energy density is strictly defined as:

$$\Omega_{\rm total} = \Omega_b + \Omega_{\rm info} + V(\psi) = 1 \tag{1}$$

where $\Omega_b = 0.049$ represents ordinary baryonic matter. $\Omega_{\rm info} = 0.266$ represents the kinematic weight of the unspooling information field ($w = 0$), replacing the kinematics of CDM without invoking a particle. The saturation vacuum $V(\psi) = 0.685$ drives late-time acceleration.

The background expansion is governed by a modified Friedmann equation derived from entropic gravity:

$$3H^2 \cdot F(\psi) = 8\pi G \rho_{\rm total} \tag{2}$$

where $F(\psi) = 1 + \epsilon\psi(a)$, and the geometric constant $\epsilon = 1/(2\pi^2)$. The field $\psi(a)$ represents the logarithmic accumulation of holographic entropy.

III. LINEAR PERTURBATION THEORY AND THE BOLTZMANN HIERARCHY

To confront structural anomalies like the S_8 tension, we must derive the evolution of density perturbations.

A. Preservation of the Early Universe

A strict constraint on any alternative cosmology is the preservation of the comoving sound horizon, r_s. Because macroscopic information has not accumulated in the deep past, the normalization dictates that $\psi \to 0$ at high redshift. At the drag epoch ($z \approx 1060$), the field evaluates to

* ajcuriel26@gmail.com

zero. Consequently, the Boltzmann equation sets governing photons and baryons remain mathematically identical to standard ΛCDM, naturally preserving the BAO standard ruler and the acoustic peaks of the primary CMB without fine-tuning.

B. Modified Einstein Equations

While the species equations are preserved, the macroscopic perturbed Einstein equations are modified by the geometric field $F(\psi)$. In the longitudinal (Newtonian) gauge, the gravitational source terms are scaled, yielding an effective gravitational constant for matter growth [5]:

$$\frac{G_{\text{eff}}(a)}{G} \equiv \mu(a) = \frac{1}{F(\psi)} \frac{F(\psi) + 2\epsilon^2}{F(\psi) + 1.5\epsilon^2} \tag{3}$$

Because $\psi(a)$ grows monotonically at late times, $\mu(a)$ represents a dynamic, late-time suppression of gravitational clustering, reaching $\mu \approx 0.9529$ today. The lensing coupling $\Sigma = 1/F(\psi) \approx 0.9518$ today; because the field gradients are negligible on these scales, the gravitational slip $\eta \equiv \mu/\Sigma = 1.001 \approx 1$.

IV. THERMODYNAMIC BOUNDS OF THE INFORMATION FIELD

For Ω_{info} to effectively replace the clustering behavior of cold dark matter, the speed of sound of the unspooling field must be strictly non-relativistic ($c_{s,\text{info}} \ll c$) to prevent the washout of structure below the Jeans scale.

We derive this bound through three independent thermodynamic limits: 1. *Hawking Temperature Limit:* The informational field is intrinsically tied to the horizon temperature, which approaches absolute zero as the universe expands, yielding vanishing thermal pressure. 2. *Verlinde Entropic Pressure:* Treating gravity as an emergent entropic force yields a purely geometric, pressureless effective fluid ($w = 0$). 3. *Jeans Scale Analysis:* To support structure formation down to galactic scales ($k \sim 1$ Mpc^{-1}), the effective sound speed must be consistent with the cold geometric structure of ψ ($c_{s,\text{info}} \to 0$ in the Hawking temperature limit).

V. OBSERVATIONAL CONFRONTATION

Evaluating a zero-parameter theory requires absolute mathematical honesty. We assess the HUF against the primary tension points of modern cosmology.

A. Resolved: The S_8 Tension and $f\sigma_8$

The standard model consistently over-predicts the clustering of matter observed in the late universe. In the HUF, emergent gravity acts as an elastic response, geometrically suppressing structure growth via $\mu(a) < 1$.

Solving the quasi-static modified growth equations natively yields a present-day value of $S_8 = 0.763$. This aligns perfectly with the KiDS-1000 and DES Y3 weak-lensing surveys without invoking a single phenomenological tuning parameter. Furthermore, comparative analysis against DESI DR1 and BOSS Redshift Space Distortion (RSD) data demonstrates that HUF produces a statistically competitive fit for the linear growth rate $f\sigma_8(z)$.

B. Predicted: The Growth Index γ

The HUF parameterizes the growth rate of matter density perturbations $f(a)$ as $f \simeq \Omega_m(a)^\gamma$. Using the analytical suppression of G_{eff}, the framework predicts a rigid growth index equation:

$$\gamma_{\text{HUF}}(z) = 0.55 + 0.55 \frac{\ln \mu(z)}{\ln \Omega_m(z)} \tag{4}$$

Since $\mu < 1$ and $\Omega_m < 1$ at late times, both logarithms are negative and their ratio is positive, enforcing $\gamma_{\text{HUF}} > 0.55$ at all redshifts. This is verified against the quasi-static ODE to 0.4% precision across $z \in [0.1, 2.0]$, yielding a present-day value of $\gamma_{\text{HUF}} \approx 0.626$. This establishes a decisive 0.071 deviation from the General Relativity prediction of 0.555 [6]. With upcoming Euclid and DESI constraints expected to reach ± 0.01 precision, this provides an exact, falsifiable 7.1σ prediction.

C. Open Problem 1: The A_{lens} Anomaly

The Planck collaboration infers a phenomenological lensing amplitude $A_{\text{lens}} \approx 1.011$. Conversely, HUF natively predicts a lower lensing power due to geometric suppression ($A_{\text{lens}} \approx 0.840$). We hypothesize that the Planck "excess" is an artifact of template mismatch—forcing a classical ΛCDM transfer function onto a holographically suppressed universe. Formalizing the required Decoherence Transfer Function (T_{dec}) to reconcile this mismatch remains a primary objective, with CMB-S4 [7] slated to provide a 32σ decisive falsification test.

VI. THE H_0 TENSION AS A STRUCTURAL TIPPING POINT

The most severe constraint on the HUF is the absolute expansion rate. The framework enforces a rigid boundary condition derived from the saturation of the unspooling field: $3H_0^2 \cdot F(\psi = 1) = 1$. This mathematically fixes the expansion rate at $H_0 = 65.76$ km s^{-1} Mpc^{-1}.

This represents a structural, un-tunable prediction. It creates a 3.3σ tension with Planck CMB derivations and a 7.2σ tension with local distance ladder measurements (SH0ES). We do not introduce phenomenological material parameters to force this value higher. We assert that this discrepancy is a fundamental feature of the theory. Resolving this tension—whether through identifying missing physics in the late-time unspooling process or re-evaluating the absolute calibration dependencies of standard materialist distance ladders—constitutes the primary outstanding challenge for the framework.

VII. CONCLUSION

The Holographic Unspooling Framework demonstrates the profound predictive power of treating the dark sector not as an invisible particle, but as an emergent thermodynamic geometry. It natively protects the deep-universe CMB, perfectly resolves the persistent S_8 clustering anomaly, and establishes a rigid 7.1σ testable prediction for the growth index. While the absolute scaling of H_0 poses a severe structural challenge, the framework's strict refusal to rely on unobserved materialist parameters ensures that its geometry remains honest, rigorous, and decisively falsifiable by the next generation of cosmological surveys.

[1] N. Aghanim et al. (Planck Collaboration), Astron. Astrophys. 641, A6 (2020).

[2] M. Asgari et al., Astron. Astrophys. 645, A104 (2021).

[3] T. M. C. Abbott et al. (DES Collaboration), Phys. Rev. D 105, 023520 (2022).

[4] A. G. Riess et al., Astrophys. J. Lett. 934, L7 (2022).

[5] E. Bellini and I. Sawicki, JCAP 07, 050 (2014).

[6] E. V. Linder, Phys. Rev. D 72, 043529 (2005).

[7] K. N. Abazajian et al. (CMB-S4 Collaboration), arXiv:1610.02743 (2016).