Growth-Driven Expansion: Empirical Evidence for Structure-Coupled Late-Time Cosmology

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We present observational evidence that late-time cosmic expansion responds to structure formation. Motivated by horizon thermodynamics and the holographic principle, we propose that the Hubble parameter couples to the linear growth factor $D(z)$ via:

$$H^2(z) = H^2_{\Lambda\mathrm{CDM}}(z) + \beta H(z) D(z)^2 f(z)$$

where $f(z) = d \ln D / d \ln a$ is the growth rate and β quantifies the coupling strength. This single equation naturally resolves both the Hubble and S_8 tensions through sector-dependent coupling: matter-based observables (BAO, distance ladder) probe $\beta_m = 0.18 \pm 0.03$, while photon-based observables (CMB) probe $\beta_\gamma < 0.004$ (95% CL). The empirical ratio $\beta_\gamma/\beta_m < 0.022$ emerges from data without theoretical assumption. Combined fits to Planck, SH0ES, JWST, and DESI yield $\chi^2_{\mathrm{dual}} = 11.50$ versus $\chi^2_{\Lambda\mathrm{CDM}} = 43.59$ ($\Delta\chi^2 = 32.09$, 5.7σ improvement). CMB lensing analysis confirms that suppressed growth produces 0.87% lensing reduction, compensating 85% of the photon-sector distance modification. All results are independently reproducible in <5 minutes via public code: `https://github.com/hmahaffeyges/IAM-Validation`.

INTRODUCTION

The ΛCDM concordance model successfully describes cosmic microwave background (CMB) anisotropies [1] and large-scale structure [2], yet faces persistent observational tensions. The Hubble constant inferred from the CMB assuming ΛCDM ($H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}) differs by $> 5\sigma$ from late-universe distance ladder measurements ($H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1} [3]). Simultaneously, weak lensing surveys report $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$ values 2–3σ below Planck predictions [4, 5].

Proposed solutions include early dark energy [6], modified gravity [7], and interacting dark sectors [8]. Each faces challenges: early modifications often worsen S_8 tension [9], while late-time solutions struggle with CMB consistency [10].

We investigate whether late-time expansion couples to structure formation. This hypothesis finds motivation in horizon thermodynamics [11, 12] and the holographic principle [13, 14], which suggest fundamental connections between geometry, entropy, and information. While speculative as fundamental theory, this provides a concrete phenomenological framework for empirical testing.

THEORETICAL MOTIVATION

Horizon Thermodynamics and Information

The apparent horizon at Hubble radius $R_H = c/H$ possesses thermodynamic properties. The Bekenstein-Hawking entropy is [15, 16]:

$$S_{BH} = \frac{A_H}{4\ell_P^2} = \frac{\pi c^2}{G H^2} \tag{1}$$

where $A_H = 4\pi R_H^2$ and ℓ_P is the Planck length. This entropy represents the maximum information content accessible within the causal patch [17].

The first law applied to the horizon gives [18]:

$$dE = T_H dS - W dV \tag{2}$$

where E is enclosed energy, $T_H \sim H$ is Hawking temperature, and W represents work by horizon expansion.

Structure formation increases distinguishability of quantum states within the horizon. We hypothesize that entropy growth correlates with structural information production:

$$\frac{dS}{dt} \propto \frac{dI}{dt} \tag{3}$$

Since $S \propto 1/H^2$, this implies a geometric response:

$$H^2(t) \sim H^2_{\Lambda CDM}(t) + \beta \frac{dI}{dt} \tag{4}$$

Core Physical Equation

The linear growth factor $D(z)$ quantifies density perturbation evolution: $\delta(z) \propto D(z)$. The growth rate is:

$$f(z) \equiv \frac{d \ln D}{d \ln a} \tag{5}$$

Structural complexity production scales as $dI/dt \propto D^2 H f$, yielding:

$$\boxed{H^2(z) = H^2_{\Lambda CDM}(z) + \beta H(z) D(z)^2 f(z)} \tag{6}$$

This is the fundamental equation of the Informational Actualization Model (IAM). Parameter β quantifies coupling between expansion and structure growth.

Physical interpretation: As structure forms, distinguishable quantum states proliferate. If horizon expansion responds to this information production (consistent with holographic bounds), late-time $H(z)$ increases beyond ΛCDM predictions.

Phenomenological Implementation

Equation (6) requires solving $D(z)$ self-consistently, creating a coupled system. For computational tractability, we introduce an effective parameterization:

$$H^2(a) = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta\mathcal{E}(a)] \tag{7}$$

with activation function:

$$\mathcal{E}(a) = \exp(1 - 1/a) \tag{8}$$

This approximates the integrated effect of $D^2 f$ evolution. Properties:

- $\mathcal{E}(a \to 0) \to 0$ (vanishes at early times)
- $\mathcal{E}(1) = 1$ (full activation today)
- Smooth transition at matter-Λ equality ($a \sim 0.5$, $z \sim 1$)

Equivalence test: In the regime $0.1 < z < 2$ where structure formation is significant, Eq. (7) reproduces Eq. (6) to within 2% (demonstrated in test suite).

The effective equation of state is:

$$w_{\text{eff}}(a) = -1 - \frac{1}{3a} \tag{9}$$

exhibiting phantom behavior ($w < -1$), consistent with recent DESI constraints [20].

Modified Growth Dynamics

The growth factor satisfies:

$$\frac{d^2 D}{d\ln a^2} + Q(a)\frac{dD}{d\ln a} = \frac{3\Omega_m(a)}{2} D(1-\tau) \tag{10}$$

where $Q = 2 - 3\Omega_m(a)/2$ and the modified matter density parameter includes sector coupling in the denominator:

$$\Omega_m(a) = \frac{\Omega_m a^{-3}}{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta\mathcal{E}(a)} \tag{11}$$

Critical insight: The β term in the denominator dilutes $\Omega_m(a)$, which is the primary mechanism for growth suppression. This addresses the S_8 tension.

The phenomenological growth tax $\tau = 0.045$ provides additional suppression. Combined effect: 2.1% growth suppression at $z = 0$.

EMPIRICAL DISCOVERY: SECTOR SEPARATION

Dual-Sector Parameterization

Initial fits using uniform β for all observables produced excellent agreement with BAO and H_0 data but created 36σ tension with CMB acoustic scale θ_s. This motivated testing *sector-specific* couplings:

Matter sector (BAO, growth, distance ladder):

$$H_m^2(a) = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_m\mathcal{E}(a)] \tag{12}$$

Photon sector (CMB, photon propagation):

$$H_\gamma^2(a) = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_\gamma\mathcal{E}(a)] \tag{13}$$

Physical motivation: Post-recombination, photons free-stream while matter gravitationally clusters. If expansion responds to structural information (bound states), matter and photons may probe different expansion histories.

Observational Constraints

Matter sector (DESI BAO + SH0ES/JWST H_0):

$$\beta_m = 0.18 \pm 0.03 \tag{14}$$

producing:

$$H_0^{\text{matter}} = 67.4\sqrt{1.18} = 73.22\ \text{km}\,\text{s}^{-1}\text{Mpc}^{-1} \tag{15}$$

consistent with SH0ES within 0.2σ.

Photon sector (Planck CMB θ_s and CMB-inferred H_0):

Likelihood scan over $\beta_\gamma \in [0, 0.10]$ using:

$$\theta_s = \frac{r_s}{\chi_\gamma(z = 1090)}, \quad \chi_\gamma = \int_0^{1090} \frac{c\,dz}{H_\gamma(z)} \tag{16}$$

where $r_s = 144.43$ Mpc (Planck sound horizon) and $\theta_s^{\text{obs}} = 0.0104110 \pm 0.0000031$ rad.

Result:

$$\beta_\gamma = 0.000\,^{+0.004}_{-0.000} \quad \text{(95\% CL)} \tag{17}$$

Empirical sector ratio:

$$\frac{\beta_\gamma}{\beta_m} < 0.022 \quad \text{(95\% CL)} \tag{18}$$

Interpretation: Data independently selects $\beta_\gamma \approx 0$ without theoretical assumption. This differential coupling resolves the Hubble tension: Planck measures photon-sector expansion, SH0ES measures matter-sector expansion. Both are correct.

CMB LENSING CONSISTENCY

Natural Compensation Mechanism

Growth suppression from modified $\Omega_m(a)$ predicts weaker gravitational lensing. The lensing convergence is:

$$\kappa = 2\int_0^{z_{\rm CMB}} dz\, W(z)\frac{\Phi(k,z)}{H(z)} \tag{19}$$

where $W(z)$ is geometric weight and $\Phi \propto D(z)$ is gravitational potential.

Since $D_{\rm dual} < D_{\Lambda\rm CDM}$ by 2.1% at $z = 0$:

$$\frac{\kappa_{\rm dual}}{\kappa_{\Lambda\rm CDM}} = 0.991 \tag{20}$$

yielding 0.87% lensing suppression.

Three-Stage Consistency

Effect	Magnitude
Unlensed θ_s shift (matter sector)	$+1.02\%$
Lensing suppression (growth tax)	-0.87%
Compensation	**85%**
Residual	$+0.15\%$
Resolved by $\beta_\gamma \approx 0$	Final: 2.1σ

TABLE I. CMB acoustic scale consistency through lensing compensation and sector separation.

Final result: IAM θ_s discrepancy $= 2.1\sigma$, identical to ΛCDM baseline.

COMBINED OBSERVATIONAL FITS

Datasets

1. **Planck CMB** [1]: $\theta_s = 0.0104110 \pm 0.0000031$ rad, $H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}
2. **SH0ES** [3]: $H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1}
3. **JWST/TRGB** [19]: $H_0 = 70.39 \pm 1.89$ km s^{-1} Mpc^{-1}
4. **DESI DR2** [20]: $f\sigma_8(z)$ at 7 redshifts

Total: 11 independent measurements.

Statistical Results

The framework reduces χ^2 by 74%, corresponding to 5.7σ improvement.

Model	$\chi^2_{H_0}$	$\chi^2_{\rm growth}$	$\chi^2_{\rm total}$
ΛCDM	31.91	11.67	43.59
Dual-sector	2.26	9.23	11.50
$\Delta\chi^2$	29.65	2.44	32.09
Significance	5.4σ	1.6σ	5.7σ

TABLE II. Likelihood comparison. Dual-sector introduces two parameters: β_m, β_γ.

Parameter Summary

Parameter	Value
β_m (matter)	0.18 ± 0.03
β_γ (photon)	< 0.004 (95% CL)
β_γ/β_m	< 0.022 (95% CL)
τ (growth tax)	0.045
H_0 (photon/CMB)	67.4 km s^{-1} Mpc^{-1}
H_0 (matter/local)	73.2 km s^{-1} Mpc^{-1}
Growth suppression ($z = 0$)	2.1%
Lensing suppression	0.87%

TABLE III. Empirical constraints from dual-sector fits.

TESTABLE PREDICTIONS

Near-Term (<5 years)

1. **CMB lensing power spectrum**: Planck 2018 $C_\ell^{\kappa\kappa}$ should show 0.87% suppression at $\ell \sim 100$–1000
2. **DESI Year 5**: Improved $f\sigma_8(z)$ will tighten β_m to ∼1%
3. **Euclid weak lensing**: $S_8 = 0.78 \pm 0.01$ (vs. Planck 0.83)
4. **Simons Observatory**: CMB θ_s precision improved 10× will constrain $\beta_\gamma < 0.001$

Long-Term (>5 years)

1. **CMB-S4**: Ultimate θ_s precision will confirm $\beta_\gamma < 0.0001$ or detect small nonzero coupling
2. **Rubin-LSST**: High-z BAO will test sector separation at $z > 2$
3. **Roman Space Telescope**: Supernovae at $1 < z < 2$ probe transition regime

DISCUSSION

Physical Interpretation

The empirical constraint $\beta_\gamma/\beta_m < 0.022$ emerges from data without theoretical assumption. Potential interpretations include:

1. **Gauge considerations**: Matter perturbations versus photon geodesics may probe different metric components [22]
2. **Information-theoretic**: Expansion couples to gravitational clustering (matter) but not free-streaming radiation [21]
3. **Nonlocal effects**: Averaging over superhorizon scales differs for matter and radiation [23]

We emphasize: *the empirical result stands independently of theoretical interpretation.*

Comparison to Alternative Solutions

Scope and Limitations

What this work claims:

1. Empirical evidence for growth-coupled expansion ($\Delta\chi^2 = 32.09$)
2. Testable constraint: $\beta_\gamma/\beta_m < 0.022$ (95% CL)
3. Simultaneous resolution of H_0 and S_8 tensions
4. Falsifiable predictions for upcoming surveys

What this work does NOT claim:

1. Fundamental field-theoretic derivation from quantum gravity
2. Uniqueness (other parameterizations may fit similarly)
3. Explanation of early-universe physics or inflation
4. That information constitutes a new physical field
5. Modification of general relativity or gauge structure

IAM is a *phenomenological late-time parameterization* motivated by horizon thermodynamics but validated purely through observational fits. Its value lies in providing a testable framework that unifies multiple cosmological tensions.

Philosophical Note

The Aristotelian distinction between actuality and potentiality provides useful metaphorical language: matter systems transition from potential to actual states through gravitational collapse, while photons (massless, always at c) possess no "unrealized potential." However, *we do not claim this metaphysics is scientifically necessary*—the empirical result $\beta_\gamma/\beta_m < 0.022$ stands regardless of philosophical interpretation.

CONCLUSIONS

We have presented observational evidence for growth-driven late-time expansion. Key findings:

1. **Core equation**: $H^2(z) = H^2_{\Lambda CDM}(z) + \beta H D^2 f$ links expansion to structure formation
2. **Empirical constraint**: $\beta_\gamma/\beta_m < 0.022$ (95% CL) from independent datasets
3. **Statistical significance**: $\Delta\chi^2 = 32.09$ (5.7σ) improvement over ΛCDM
4. **Dual resolution**: Addresses both Hubble (H_0) and clustering (S_8) tensions
5. **Self-consistency**: CMB lensing provides 85% natural compensation
6. **Falsifiability**: Precise predictions for CMB-S4, Euclid, Rubin-LSST

The Hubble tension may reflect not measurement error but observation of distinct expansion rates in a growth-coupled cosmology. Planck (photon sector) and SH0ES (matter sector) both measure correctly—they probe different physical quantities with empirically constrained ratio $\beta_\gamma/\beta_m < 0.022$.

This framework demonstrates that phenomenological late-time modifications, when properly parameterized and empirically constrained, can provide testable resolutions to observational tensions while maintaining theoretical minimalism. Whether this points toward deeper physics involving information and horizons, or simply represents an effective description requiring more fundamental explanation, remains an open question for future investigation.

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Solution	Parameters	Resolves H_0?	Resolves S_8?	$\Delta\chi^2$
Early dark energy [6]	+2	Yes	Worsens	$\sim$10
Modified gravity [7]	+2–3	Partial	Yes	$\sim$15
Interacting dark sector [8]	+2	Partial	Partial	$\sim$12
Growth-driven (this work)	**+2**	**Yes**	**Yes**	**32.09**

TABLE IV. Comparison of phenomenological Hubble tension solutions.

`IAM-Validation` with runtime <5 minutes on standard hardware.

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