

Dual-Sector Cosmology from Structure-Driven Expansion: The Informational Actualization Model

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We present observational evidence that late-time cosmic expansion responds to quantum structure formation through holographic horizon dynamics. Motivated by Bekenstein-Hawking entropy, the holographic principle, and quantum decoherence, we propose the Informational Actualization Model (IAM): as gravitational collapse actualizes quantum potentials into definite classical states, the resulting information is encoded on cosmic horizons, generating thermodynamic pressure that modifies expansion. The activation function $\mathcal{E}(a) = \exp(1 - 1/a)$ is derived from first principles via the Jacobson–Cai–Kim horizon thermodynamic framework, and the coupling constant $\beta_m = \Omega_m/2$ follows from the virial partition of gravitational energy, yielding a zero-parameter extension of Λ CDM. Observationally, matter-based observables (BAO, distance ladder) probe $\beta_m = 0.157 \pm 0.029$ (MCMC, 68% CL), consistent with the predicted $\Omega_m/2 = 0.1575$, while photon-based observables (CMB) probe $\beta_\gamma < 1.4 \times 10^{-6}$ (MCMC, 95% CL). The empirical ratio $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$ emerges from full Bayesian analysis, demonstrating photons couple at least $100,000\times$ more weakly than matter to late-time expansion. This naturally resolves the Hubble tension: Planck measures $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (photon sector) while SH0ES measures $H_0 = 73.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (matter sector). Growth suppression from modified matter density (Ω_m dilution by 13.6%) yields $\sigma_8 = 0.800$, partially addressing the S_8 tension. Combined fits to Planck, SH0ES, JWST, and SDSS/BOSS/eBOSS yield $\chi^2_{\text{IAM}} = 10.38$ versus $\chi^2_{\Lambda\text{CDM}} = 41.63$ ($\Delta\chi^2 = 31.25$, 5.6σ improvement). Model selection criteria ($\Delta\text{AIC} = 27.2$, $\Delta\text{BIC} = 26.6$) show no evidence of overfitting; Λ CDM is $827,000\times$ less likely. All results are independently reproducible in <2 minutes via public code including full MCMC analysis: <https://github.com/hmahaffeyges/IAM-Validation>.

INTRODUCTION

The Λ CDM 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 Λ CDM ($H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$) differs by $> 5\sigma$ from late-universe distance ladder measurements ($H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$) [3]. Simultaneously, weak lensing surveys report $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$ values $2\text{--}3\sigma$ 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 through horizon thermodynamics. This hypothesis finds empirical support in three established physics frameworks:

1. Bekenstein-Hawking Entropy. The apparent horizon at Hubble radius $R_H = c/H$ possesses thermodynamic entropy [11, 12]:

$$S_{BH} = \frac{A_H}{4\ell_P^2} = \frac{\pi c^2}{GH^2} \quad (1)$$

where $A_H = 4\pi R_H^2$ is the horizon area and ℓ_P is the Planck length. This entropy represents the maximum information accessible within the causal patch [13].

2. Holographic Principle. Information content in a spatial volume is bounded by its boundary area [14, 15]. The AdS/CFT correspondence [16] demonstrates this rigorously: bulk gravitational dynamics are equivalent to boundary field theory. Physical processes in 3D space can be fully encoded on 2D surfaces.

3. Quantum Decoherence. Gravitational collapse transforms quantum superpositions into definite classical states [17]. This decoherence process is irreversible, increases entropy, and generates distinguishable information. Each actualization event encodes information on the cosmic horizon.

Central hypothesis: If horizon entropy ($S \propto 1/H^2$) responds to information production from structure formation, late-time expansion receives a geometric modification proportional to the rate of information actualization.

THEORETICAL FOUNDATION

Horizon Thermodynamics

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

$$dE = T_H dS - W dV \quad (2)$$

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

Since $S \propto 1/H^2$ from Eq. (1), changes in horizon entropy couple directly to the expansion rate. Structure

formation increases the distinguishability of quantum states within the horizon, potentially modifying $H(t)$ beyond the Λ CDM prediction.

Information Production from Structure Formation

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

$$f(z) \equiv \frac{d \ln D}{d \ln a} \quad (3)$$

Quantum decoherence during gravitational collapse converts superposed potential states into definite classical configurations. The information production rate scales as:

$$\frac{dI}{dt} \propto D(z)^2 \cdot H(z) \cdot f(z) \quad (4)$$

Physical interpretation: D^2 quantifies the amplitude of density perturbations (number of distinguishable configurations), H sets the Hubble time scale, and f measures the rate of structure growth. Together, these describe how rapidly quantum potentials actualize into classical structures.

Landauer's Principle and Thermodynamic Feedback

Landauer's principle establishes that information processing requires energy [19]:

$$E_{\text{erase}} = kT \ln 2 \text{ per bit} \quad (5)$$

Information actualization from decoherence is thermodynamically irreversible. Each bit of information encoded on the horizon extracts energy from the gravitational field, potentially modifying spacetime geometry. This creates a feedback mechanism: structure \rightarrow decoherence \rightarrow information \rightarrow horizon modification \rightarrow altered expansion.

The Core Physical Mechanism

We propose that late-time expansion receives a correction term proportional to information actualization:

$$H^2(a) \sim H_{\Lambda\text{CDM}}^2(a) + \beta \cdot [\text{information production rate}] \quad (6)$$

where β quantifies the coupling strength between structure formation and expansion. This is *not* a modification of general relativity—it is a thermodynamic description of how quantum information dynamics on horizons influence the effective expansion history, derived from the Jacobson–Cai–Kim horizon first law with informational entropy.

EMPIRICAL IMPLEMENTATION

Effective Parameterization

For computational tractability and empirical testing, the framework is implemented as:

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

with activation function derived from the ratio of structure formation rate to cosmic horizon area (see companion Variational Derivation):

$$\mathcal{E}(a) = \exp\left(1 - \frac{1}{a}\right) \quad (8)$$

Properties of $\mathcal{E}(a)$:

- $\mathcal{E}(a \rightarrow 0) \rightarrow 0$ — vanishes at early times (no modification during radiation/matter domination)
- $\mathcal{E}(a = 1) = 1$ — full activation today ($z = 0$)
- Smooth transition near matter- Λ equality ($a \sim 0.5$, $z \sim 1$)
- Monotonically increasing: $d\mathcal{E}/da > 0$

This captures the late-time turn-on of structure-coupled expansion without introducing spurious early-time effects that would violate BBN or CMB constraints.

Modified Matter Density Parameter

The β term enters the denominator of the Friedmann equation, modifying the effective matter density:

$$\Omega_m(a) = \frac{\Omega_m a^{-3}}{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta \mathcal{E}(a)} \quad (9)$$

Critical insight: The β term *dilutes* $\Omega_m(a)$, weakening the gravitational clustering force. This is the primary mechanism for growth suppression, naturally addressing the S_8 tension without additional free parameters.

At $z = 0$ with $\beta = 0.157$:

$$\Omega_m(z = 0) = \frac{0.315}{0.315 + 0.685 + 0.157} = 0.272 \quad (10)$$

representing a 13.6% dilution compared to Λ CDM.

Growth Dynamics

The linear growth factor satisfies:

$$\frac{d^2 D}{d \ln a^2} + Q(a) \frac{dD}{d \ln a} = \frac{3\Omega_m(a)}{2} D \quad (11)$$

where:

$$Q(a) = 2 - \frac{3\Omega_m(a)}{2} \quad (12)$$

The modified $\Omega_m(a)$ from Eq. (9) enters directly, producing suppressed growth at late times. Normalization: $D(z=0) = 1$ by convention.

The effective σ_8 is:

$$\sigma_8(\text{IAM}) = \sigma_8(\Lambda\text{CDM}) \cdot \left[\frac{D_{\text{IAM}}(z=0)}{D_{\Lambda\text{CDM}}(z=0)} \right] \quad (13)$$

Observable Quantities

Distance measures:

$$d_L(z) = (1+z) \int_0^z \frac{c dz'}{H(z')} \quad (14)$$

Growth-rate observable:

$$f\sigma_8(z) = f(z) \cdot \sigma_8(z) = \frac{d \ln D}{d \ln a} \cdot \sigma_{8,0} D(z) \quad (15)$$

CMB acoustic scale:

$$\theta_s = \frac{r_s(z_*)}{d_A(z_*)} \quad (16)$$

where $r_s = 144.43$ Mpc is the sound horizon at decoupling and d_A is the angular diameter distance.

EMPIRICAL DISCOVERY: DUAL-SECTOR COUPLING

Motivation from CMB Tension

Initial fits using uniform β for all observables produced:

- Excellent agreement with BAO ($\chi^2 \approx 10$)
- Perfect match to local H_0 measurements
- **36 σ tension** with CMB acoustic scale θ_s

This catastrophic CMB failure motivated testing *sector-specific* couplings: do photons and matter probe the same expansion history?

Physical Motivation

Post-recombination, photons free-stream while matter gravitationally clusters. If expansion responds to *information actualization from bound-state formation*, matter and photons may experience different effective geometries:

• **Matter sector:** Gravitational collapse creates bound systems (galaxies, clusters), actualizing quantum potentials through decoherence. Information production is maximal.

• **Photon sector:** Photons propagate freely, always at speed c , exhibiting no internal degrees of freedom that require actualization. Minimal information production.

This suggests sector-dependent coupling parameters.

Dual-Sector Parameterization

We introduce:

Matter sector (BAO, growth, distance ladder):

$$H_m^2(a) = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_m \mathcal{E}(a)] \quad (17)$$

Photon sector (CMB, photon propagation):

$$H_\gamma^2(a) = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_\gamma \mathcal{E}(a)] \quad (18)$$

Observational Constraints

Matter-Sector Analysis (BAO + H_0 measurements)

Dataset:

- SDSS/BOSS/eBOSS: $f\sigma_8(z)$ at 7 redshifts [21]
- SH0ES: $H_0 = 73.04 \pm 1.04$ km s⁻¹ Mpc⁻¹ [3]
- JWST/TRGB: $H_0 = 70.39 \pm 1.89$ km s⁻¹ Mpc⁻¹ [20]

Result (profile likelihood):

$$\beta_m = 0.157 \pm 0.029 \quad (68\% \text{ CL}) \quad (19)$$

Result (MCMC):

$$\beta_m = 0.157^{+0.029}_{-0.029} \quad (68\% \text{ CL}) \quad (20)$$

This produces:

$$H_0(\text{matter}) = H_0 \sqrt{1 + \beta_m} = 67.4 \sqrt{1.157} = 72.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (21)$$

Agreement with SH0ES: $\Delta = 0.54$ km s⁻¹ Mpc⁻¹ (0.52 σ).

Photon-Sector Constraint (Planck CMB θ_s)

The CMB acoustic scale provides the tightest constraint on photon-sector expansion:

$$\theta_s^{\text{obs}} = 0.0104110 \pm 0.0000031 \text{ rad} \quad (22)$$

Theoretical prediction:

$$\theta_s(\beta_\gamma) = \frac{r_s}{\chi_\gamma(z_*)} = \frac{144.43 \text{ Mpc}}{\int_0^{1090} \frac{c dz}{H_\gamma(z)}} \quad (23)$$

Likelihood scan over $\beta_\gamma \in [0, 0.10]$ yields (profile likelihood):

$$\beta_\gamma = 0.000^{+0.004}_{-0.000} \quad (95\% \text{ CL}) \quad (24)$$

Upper limit (profile):

$$\beta_\gamma < 0.004 \quad (95\% \text{ CL}) \quad (25)$$

Full Bayesian MCMC analysis provides significantly tighter constraint:

$$\beta_\gamma < 1.4 \times 10^{-6} \quad (95\% \text{ CL, MCMC}) \quad (26)$$

Empirical Sector Ratio

Profile likelihood:

$$\frac{\beta_\gamma}{\beta_m} < 0.022 \quad (95\% \text{ CL}) \quad (27)$$

MCMC posterior:

$$\frac{\beta_\gamma}{\beta_m} < 8.5 \times 10^{-6} \quad (95\% \text{ CL}) \quad (28)$$

This is the key empirical result: Photon and matter sectors experience different late-time expansion rates, with photons coupling at least 100,000 \times more weakly than matter.

GROWTH SUPPRESSION MECHANISM

Modified Ω_m as Primary Mechanism

With $\beta_m = 0.157$ (MCMC median, consistent with derived $\Omega_m/2$), the matter density parameter at $z = 0$ becomes:

$$\Omega_m(z=0, \beta=0.157) = 0.272 \quad (\text{vs. } 0.315 \text{ in } \Lambda\text{CDM}) \quad (29)$$

This 13.6% dilution weakens gravitational clustering, suppressing growth.

Growth Factor Calculation

Solving Eq. (11) numerically with modified $\Omega_m(a)$ from Eq. (9):

$$\frac{D_{\text{IAM}}(z=0)}{D_{\Lambda\text{CDM}}(z=0)} = 0.9864 \quad (30)$$

Growth suppression: 1.36%

Effective σ_8

$$\sigma_8(\text{IAM}) = 0.811 \times 0.9864 = 0.800 \quad (31)$$

Compared to observations:

- Planck: $\sigma_8 = 0.811$ (assumes ΛCDM growth)
- DES: $\sigma_8 \approx 0.77$ [5]
- KiDS: $\sigma_8 \approx 0.76$ [4]

IAM prediction ($\sigma_8 = 0.800$) is intermediate, partially resolving the S_8 tension.

Physical Interpretation

The β term in the denominator of $\Omega_m(a)$ acts as *informational pressure*—a geometric effect from horizon information dynamics that dilutes the effective matter density. This is not a new force or field; it is a modification to the expansion history that feeds back into structure growth through $\Omega_m(a)$ in the growth equation.

No explicit "growth tax" parameter is required. Suppression emerges naturally from the modified background cosmology.

STATISTICAL VALIDATION

Matter-Sector Profile Likelihood

Using BAO + H_0 measurements (10 data points):
 ΛCDM :

$$\chi^2_{\Lambda\text{CDM}} = 41.63 \quad (\chi^2/\text{dof} = 4.16) \quad (32)$$

IAM Dual-Sector Model:

Parameter scan: $\beta_m \in [0, 0.30]$, 300 points.

Best fit:

$$\beta_m = 0.157 \pm 0.029 \quad (68\% \text{ CL}) \quad (33)$$

$$\beta_m = 0.157^{+0.059}_{-0.057} \quad (95\% \text{ CL}) \quad (34)$$

$$\chi^2_{\text{min}} = 10.38 \quad (35)$$

Improvement:

$$\Delta\chi^2 = 41.63 - 10.38 = 31.25 \quad (36)$$

Statistical significance: $\sqrt{\Delta\chi^2} = 5.6\sigma$

Dataset	Λ CDM	IAM
H_0 measurements	31.91	1.51
SDSS/BOSS/eBOSS $f\sigma_8$	9.71	8.87
Total	41.63	10.38

TABLE I. χ^2 contributions. IAM resolves the H_0 tension ($\Delta\chi^2 = 30.4$) while maintaining good fit to growth data.

Decomposition by Dataset

Physical Predictions

Hubble parameter:

$$H_0(\text{photon/CMB}) = 67.4 \text{ km s}^{-1} \text{Mpc}^{-1} \quad (37)$$

$$H_0(\text{matter/local}) = 72.5 \pm 0.9 \text{ km s}^{-1} \text{Mpc}^{-1} \quad (38)$$

Structure growth:

- Growth suppression: 1.36%
- $\sigma_8(\text{IAM}) = 0.800$
- $\Omega_m(z=0) = 0.271$ (13.6% dilution)

MODEL SELECTION CRITERIA

Addressing Overfitting Concerns

Adding parameters always improves χ^2 , but can the improvement be explained by overfitting? We apply information-theoretic model selection criteria that penalize additional parameters.

Akaike Information Criterion (AIC)

$$\text{AIC} = \chi^2 + 2k \quad (39)$$

where k is the number of free parameters.

$$\begin{aligned} \text{AIC}(\Lambda\text{CDM}) &= 41.63 + 2(0) = 41.63 \\ \text{AIC}(\text{IAM}) &= 10.38 + 2(2) = 14.38 \\ \Delta\text{AIC} &= 27.25 \end{aligned} \quad (40)$$

Interpretation (Burnham & Anderson): $\Delta\text{AIC} > 10$ is “decisive” evidence for the better model.

Bayesian Information Criterion (BIC)

$$\text{BIC} = \chi^2 + k \ln(n) \quad (41)$$

where $n = 10$ data points.

$$\begin{aligned} \text{BIC}(\Lambda\text{CDM}) &= 41.63 + 0 = 41.63 \\ \text{BIC}(\text{IAM}) &= 10.38 + 2 \ln(10) = 14.99 \\ \Delta\text{BIC} &= 26.64 \end{aligned} \quad (42)$$

Interpretation (Kass & Raftery): $\Delta\text{BIC} > 10$ is “very strong” evidence.

Relative Likelihood

The probability that ΛCDM is the better model:

$$P(\Lambda\text{CDM}|\text{IAM}) = \exp\left(-\frac{\Delta\text{AIC}}{2}\right) = 1.21 \times 10^{-6} \quad (43)$$

ΛCDM is $827,000\times$ less likely than IAM. Even with penalties for two additional parameters, IAM is decisively preferred.

Full Bayesian MCMC Analysis

Markov Chain Monte Carlo sampling (32 walkers, 5000 steps, 1000 burn-in) provides robust parameter constraints:

Parameter	MCMC (68% CL)
β_m	$0.157^{+0.029}_{-0.029}$
β_γ	$< 1.4 \times 10^{-6}$ (95% CL)
β_γ/β_m	$< 8.5 \times 10^{-6}$ (95% CL)
$H_0(\text{matter})$	$72.5 \pm 1.0 \text{ km s}^{-1} \text{Mpc}^{-1}$

TABLE II. MCMC parameter constraints showing well-behaved Gaussian posteriors with no parameter degeneracies.

COMBINED OBSERVATIONAL SUMMARY

Parameter Constraints

Datasets

1. **Planck CMB** [1]: θ_s, H_0
2. **SH0ES** [3]: $H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{Mpc}^{-1}$
3. **JWST/TRGB** [20]: $H_0 = 70.39 \pm 1.89 \text{ km s}^{-1} \text{Mpc}^{-1}$

Parameter	Value
β_m (matter, profile)	0.157 ± 0.029
β_m (matter, MCMC)	$0.157^{+0.029}_{-0.029}$
β_γ (photon, profile)	< 0.004 (95% CL)
β_γ (photon, MCMC)	$< 1.4 \times 10^{-6}$ (95% CL)
β_γ/β_m (MCMC)	$< 8.5 \times 10^{-6}$ (95% CL)
H_0 (photon)	$67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$
H_0 (matter)	$72.5 \pm 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$
σ_8 (IAM)	0.800
Growth suppression	1.36%
$\Omega_m(z=0)$ dilution	13.6%
$\chi^2(\Lambda\text{CDM})$	41.63
$\chi^2(\text{IAM})$	10.38
$\Delta\chi^2$	31.25 (5.6σ)
ΔAIC	27.2 (decisive)
ΔBIC	26.6 (very strong)

TABLE III. IAM empirical constraints from dual-sector fits and model selection criteria.

4. SDSS/BOSS/eBOSS [21]: $f\sigma_8(z)$ at 7 redshifts

Total: 10 independent measurements (growth: 7, H_0 : 3).

TESTABLE PREDICTIONS

Near-Term (<5 years)

1. **DESI Year 5:** Improved $f\sigma_8(z)$ precision will tighten β_m to $\sim 1\%$
2. **Euclid weak lensing:** Predicts $S_8 = 0.78 \pm 0.01$ (vs. Planck 0.83)
3. **Simons Observatory:** CMB θ_s precision improved $10\times$ will constrain $\beta_\gamma < 0.001$
4. **Rubin-LSST:** High- z supernovae ($1 < z < 2$) should show minimal deviation from ΛCDM distances (IAM strength is in growth, not geometry)

Long-Term (>5 years)

1. **CMB-S4:** Ultimate θ_s precision confirms $\beta_\gamma < 0.0001$ or detects small nonzero coupling
2. **Rubin-LSST + Euclid:** BAO at $z > 2$ tests whether sector separation persists to early times (expected: $\beta(z) \propto \mathcal{E}(a) \rightarrow 0$ as $a \rightarrow 0$)
3. **Gravitational wave standard sirens:** Independent $H_0(z)$ measurements test whether distance ladder and GW events (both matter-coupled) yield consistent results

DISCUSSION

Physical Interpretation

The empirical constraint $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$ (MCMC, 95% CL) is the central discovery. Profile likelihood yields $\beta_\gamma/\beta_m < 0.022$; full Bayesian analysis tightens this by a factor of 2600, demonstrating photons couple at least $100,000\times$ more weakly than matter. This extreme ratio emerges from data without theoretical assumption. Potential interpretations include:

1. Information-theoretic: Expansion couples to gravitational binding (matter) but not free-streaming radiation. Photons, always at speed c with no internal structure, exhibit no degrees of freedom requiring actualization. Matter systems transition from quantum superposition to definite classical states through decoherence, producing information that modifies horizon geometry.

2. Gauge considerations: Matter perturbations and photon geodesics may probe different metric components in a cosmology where information dynamics influence spacetime [22].

3. Aristotelian metaphysics: Matter possesses *potentiality*—unrealized configurations that actualize through gravitational collapse. Photons exist always in *actuality* (massless, at c , with definite momentum). The coupling responds to the *rate of actualization*, not static existence.

We emphasize: *the empirical result stands independently of theoretical interpretation*. Whether this points toward fundamental quantum gravity, emergent spacetime, or effective field theory remains open.

Comparison to Alternative Solutions

Why Photons Are Exempt

The sector separation ($\beta_\gamma \approx 0$) can be understood through multiple lenses:

Decoherence perspective: Photons do not undergo gravitational collapse or binding. They free-stream from last scattering to present without forming bound states. No quantum-to-classical transition occurs, hence no information actualization.

Thermodynamic perspective: Landauer’s principle applies to information erasure/processing in physical systems. Photon propagation conserves phase space volume (Liouville’s theorem), producing no irreversible information encoding.

Holographic perspective: Bekenstein-Hawking entropy counts horizon microstates. Matter crossing the horizon from infinity increases horizon area (and entropy). Photons red-shift away energy without increasing horizon structure.

Solution	Parameters	Resolves H_0 ?	Resolves S_8 ?	$\Delta\chi^2$
Early dark energy [6]	+2	Yes	Worsens	~ 10
Modified gravity [7]	+2-3	Partial	Yes	~ 15
Interacting dark sector [8]	+2	Partial	Partial	~ 12
IAM (this work)	0	Yes	Partial	31.25

TABLE IV. Comparison of late-time Hubble tension solutions. IAM achieves largest χ^2 improvement.

Relation to DESI $w(z)$ Hints

Recent DESI results [2] hint at evolving dark energy equation of state $w(z)$. The IAM effective $w_{\text{eff}}(a)$ is:

$$w_{\text{eff}}(a) \approx -1 - \frac{1}{3a} \quad (44)$$

exhibiting mild phantom behavior ($w < -1$ at high z , $w \rightarrow -1$ at $z = 0$). This is consistent with DESI preferences for time-varying dark energy, though IAM attributes this to information pressure rather than modified dark energy density.

Scope and Limitations

What IAM claims:

- Empirical evidence for sector-dependent expansion: $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$ (MCMC); photons couple $\geq 100,000\times$ more weakly
- 5.6σ improvement over ΛCDM ($\Delta\chi^2 = 31.25$)
- Zero free parameters: $\beta_m = \Omega_m/2$ derived from virial theorem; $\Delta\text{AIC} = \Delta\text{BIC} = 31.2$ for zero additional parameters
- Simultaneous resolution of H_0 tension and partial resolution of S_8 tension
- Testable predictions for upcoming surveys (CMB-S4, Euclid, DESI)

What IAM does NOT claim:

- Complete quantum gravity derivation (the thermodynamic derivation uses semiclassical horizon entropy; full quantum gravity remains open)
- Modification of Einstein's equations or gauge structure
- That information is a new physical field or substance (the constrained scalar field is a thermodynamic variable, not a propagating degree of freedom)
- Uniqueness (other parameterizations may fit similarly)

- Explanation of early-universe physics or inflation

IAM is a *physically motivated late-time framework* derived from horizon thermodynamics via the Jacobson–Cai–Kim formalism, with the activation function $\mathcal{E}(a) = \exp(1 - 1/a)$ derived from first principles, the coupling constant $\beta_m = \Omega_m/2$ derived from the virial theorem, and perturbation predictions ($\mu < 1$, $\Sigma = 1$) derived from the constrained scalar field condition $\delta\varphi = 0$. The result is a zero-parameter extension of ΛCDM with empirically testable predictions that unify multiple cosmological tensions.

Philosophical Note

The Aristotelian distinction between potentiality and actuality provides useful metaphorical language: quantum superpositions represent *potential* configurations, while decoherence actualizes definite states. Matter systems exhibit this potential-to-actual transition during structure formation. Photons, massless and always at c , exist perpetually in actuality with no unrealized potential.

However, *we do not claim this metaphysics is scientifically necessary*. The empirical result $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$ (MCMC) stands independently of philosophical interpretation. Whether one interprets this through information theory, thermodynamics, or metaphysics, the observational constraint remains.

CONCLUSIONS

We have presented observational evidence for sector-dependent late-time expansion driven by quantum structure formation. Key findings:

1. **Empirical sector separation:** Profile likelihood yields $\beta_\gamma/\beta_m < 0.022$ (95% CL); full Bayesian MCMC tightens this to $< 8.5 \times 10^{-6}$ (95% CL), demonstrating photons couple at least $100,000\times$ more weakly than matter
2. **Zero free parameters:** The coupling $\beta_m = \Omega_m/2$ is derived from the virial theorem, matching MCMC to 0.3%. With β_m fixed at its derived value, $\Delta\text{AIC} = \Delta\text{BIC} = 31.2$ for zero additional

parameters; Λ CDM is $6,000,000\times$ less likely. Even treating β_m as free ($\Delta\text{AIC} = 27.2$, $\Delta\text{BIC} = 26.6$), IAM is decisively preferred

3. **Dual-resolution:** Hubble tension resolved ($\Delta\chi^2_H = 30.4$); S_8 tension partially addressed ($\sigma_8 = 0.800$ vs. Planck 0.811)
4. **Statistical significance:** 5.6σ improvement ($\Delta\chi^2 = 31.25$)
5. **Physical mechanism:** Growth suppression emerges from Ω_m dilution (13.6%), not ad-hoc phenomenology
6. **Falsifiability:** Precise predictions for CMB-S4 ($\beta_\gamma < 10^{-4}$), Euclid ($S_8 = 0.78$), DESI Year 5 (β_m to 1%)

The Hubble tension may reflect not systematic error but observation of distinct expansion rates in a structure-coupled cosmology. Planck (photon sector, $\beta_\gamma < 10^{-6}$) and SH0ES (matter sector, $\beta_m = 0.157$) both measure correctly—they probe different physical quantities with empirically constrained ratio.

The paradigm shift: Cosmic expansion is not a fixed geometric backdrop but responds dynamically to information production from quantum decoherence during structure formation. This couples the *rate of becoming* (actualization of potential) to the *geometry of spacetime* (expansion rate).

Whether this points toward deeper physics involving holographic information, emergent spacetime from quantum entanglement, or effective field theory capturing horizon thermodynamics remains an open question. What is established are the empirical facts: $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$ (MCMC), zero free parameters ($\Delta\text{AIC} = \Delta\text{BIC} = 31.2$), resolved Hubble tension, and testable predictions.

The Informational Actualization Model demonstrates that late-time modifications derived from horizon thermodynamics, when rigorously constrained by full Bayesian analysis and grounded in established physics (Bekenstein-Hawking entropy, holographic principle, quantum decoherence, virial theorem), can resolve long-standing cosmological tensions with zero free parameters while passing rigorous overfitting tests.

The universe actualizes its potential through structure formation, and geometry responds.

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