

# Holographic Black-Hole Cosmology: An Informational Resolution of the Hubble Tension

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We present a holographic cosmological framework wherein cosmic expansion emerges as the geometric response to informational actualization on the apparent horizon. Building on preliminary results [1], we provide refined statistical analysis using DESI DR2 data and fully reproducible validation code. Applying the first law of thermodynamics to the Hubble sphere, we derive a modified expansion law coupled to the linear growth factor of density perturbations,  $D(z)$ . This coupling introduces a redshift-dependent informational pressure that naturally resolves the Hubble tension: consistency with Planck CMB measurements ( $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) is maintained at early times, while late-time structure formation drives local expansion to  $H_0 \approx 73.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , reconciling SH0ES and JWST observations. Combined fits to Planck, SH0ES, JWST/TRGB, and DESI DR2 data yield  $\chi^2_{\text{IAM}} = 12.43$  versus  $\chi^2_{\Lambda\text{CDM}} = 72.01$  ( $\Delta\chi^2 = 59.58$ ), providing  $5.7\sigma$  evidence strongly favoring the Informational Actualization Model. We demonstrate that this framework provides a physics-motivated mechanism for the cosmological arrow of time and discuss testable predictions for upcoming surveys. All results are independently reproducible in  $<1$  minute via public code: <https://github.com/hmahaffeyges/IAM-Validation>.

## INTRODUCTION

The  $\Lambda$ CDM concordance model successfully describes large-scale cosmic structure [2], yet faces a critical challenge: the “Hubble tension”—a  $> 5\sigma$  discrepancy between early-universe inferences ( $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [2]) and late-time measurements ( $H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [3]). Recent JWST and DESI data have intensified this discrepancy [4, 5].

Concurrently, developments in quantum gravity—particularly the holographic principle [6, 7]—suggest fundamental limits on information storage: the maximum entropy of a spatial region scales with boundary area, not volume. This motivates investigating whether cosmic expansion itself serves an informational role.

An earlier formulation of this framework was presented in Mahaffey [1]. The present work provides substantial refinements:

- Rigorous statistical methodology using  $\chi^2$  analysis (replacing AIC)
- Updated fits incorporating DESI DR2 data (2025 release)
- Fully reproducible validation code (runtime  $<1$  minute)
- Reduced dataset to 13 authoritative measurements from independent observational programs

The statistical evidence has strengthened from  $\Delta\text{AIC} \approx 42$  to  $\Delta\chi^2 = 59.58$  ( $5.7\sigma$  significance).

We propose the *Informational Actualization Model* (IAM), wherein expansion velocity responds to the rate at which physical structure actualizes distinguishable quantum states. This framework:

- Derives expansion dynamics from horizon thermodynamics
- Links expansion to the linear growth factor  $D(z)$
- Resolves the Hubble tension without new particles or modified gravity
- Provides a physical basis for the cosmological arrow of time

## THEORETICAL FRAMEWORK

### Horizon Thermodynamics

Consider the apparent horizon at the Hubble radius  $R_H = 1/H(t)$  as a thermodynamic system. The Bekenstein-Hawking entropy in Planck units ( $\hbar = c = G = k_B = 1$ ) is:

$$S_{\text{BH}} = \frac{A_H}{4} = \frac{\pi}{H^2} \quad (1)$$

We apply the first law of thermodynamics to the enclosed volume [8]:

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

where  $E = R_H/2 = 1/(2H)$  is the Misner-Sharp energy,  $T_H \propto H$  is the Hawking temperature, and  $W$  represents work done by boundary pressure.

For an information-driven system, entropy growth reflects actualization of distinguishable quantum states. Writing  $dS \propto dI$  where  $I(t)$  quantifies cumulative actualized distinctions:

$$-\frac{dH}{H^2} \propto H \frac{dI}{dt} \quad (3)$$

This yields the fundamental response law:

$$H^2(t) = \beta \frac{dI}{dt} \quad (4)$$

where  $\beta$  is a dimensionless response coefficient.

### Information Decomposition

We decompose the information production rate into three components:

$$\frac{dI}{dt} = \dot{I}_{\text{mat}} + \dot{I}_{\text{vac}} + \dot{I}_{\text{struct}}(t) \quad (5)$$

*Matter dilution* ( $\dot{I}_{\text{mat}}$ ) reflects standard volume expansion. *Vacuum fluctuations* ( $\dot{I}_{\text{vac}} = \Lambda_{\text{info}}$ ) provide constant informational pressure, recovering the cosmological constant. *Structural complexity* ( $\dot{I}_{\text{struct}}$ ) arises from gravitational collapse forming bound structures.

### Growth-Linked Information

We quantify structural complexity via the linear growth factor  $D(z)$ , where density perturbations evolve as  $\delta(z) \propto D(z)$ . The structural information content scales as:

$$I_{\text{struct}}(t) \propto D(t)^2 \quad (6)$$

Landauer's principle [9] ( $E \geq kT \ln 2$  per bit) justifies linking information density to thermodynamic pressure. The complexity rate is:

$$C(t) \equiv \frac{d}{dt}[D^2] = 2D\dot{D} = 2D^2 H f(z) \quad (7)$$

where  $f(z) \equiv d \ln D / d \ln a$  is the growth rate.

Substituting into Eq. (4):

$$H^2(z) = H_{\Lambda\text{CDM}}^2(z) + \beta H(z) D(z)^2 f(z) \quad (8)$$

### PHENOMENOLOGICAL CLOSURE

For numerical implementation, we introduce an effective informational density:

$$\rho_{\text{IA}}(a) = \rho_{\text{IA},0} \mathcal{E}(a), \quad \mathcal{E}(a) \equiv \exp\left(1 - \frac{1}{a}\right) \quad (9)$$

The activation function  $\mathcal{E}(a)$  ensures negligible early-universe effects ( $\mathcal{E} \rightarrow 0$  as  $a \rightarrow 0$ ) and full activation today ( $\mathcal{E}(1) = 1$ ). The background Friedmann equation becomes:

$$H^2(a) = H_{0,\text{CMB}}^2 [\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta \mathcal{E}(a)] \quad (10)$$

where  $\beta \equiv \rho_{\text{IA},0} / \rho_{\text{crit,CMB}} \approx 0.18$  from empirical fitting.

The effective equation of state is:

$$w_{\text{IA}}(a) = -1 - \frac{1}{3} \frac{d \ln \mathcal{E}}{d \ln a} = -1 - \frac{1}{3a} \quad (11)$$

exhibiting phantom behavior ( $w < -1$ ) at all epochs.

## RESOLUTION OF THE HUBBLE TENSION

### Early Universe ( $z \gg 1$ )

At high redshift, structure formation is negligible ( $D \rightarrow 0$ ) and  $\mathcal{E}(a) \rightarrow 0$ . Equation (10) reduces to standard  $\Lambda\text{CDM}$ :

$$H(z \gg 1) \rightarrow H_{0,\text{CMB}} \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda} \quad (12)$$

This ensures consistency with Planck CMB constraints ( $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ).

### Late Universe ( $z < 2$ )

As structures form,  $D(z)$  grows rapidly, activating informational pressure. At  $z = 0$ :

$$H_0^2 = H_{0,\text{CMB}}^2 [1 + \beta] \implies H_0 \approx 73.2 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (13)$$

for  $\beta \approx 0.18$ , reconciling SH0ES measurements.

## OBSERVATIONAL CONSTRAINTS

We fit IAM to four independent datasets:

1. **Planck CMB:**  $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [2]
2. **SH0ES:**  $H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [3]
3. **JWST/TRGB:**  $H_0 = 70.39 \pm 1.89 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [4]
4. **DESI DR2:** 10 points of  $f\sigma_8(z)$  [5]

Combined fit results (13 data points):

$$\chi_{\Lambda\text{CDM}}^2 = 72.01 \quad (14)$$

$$\chi_{\text{IAM}}^2 = 12.43 \quad (15)$$

$$\Delta\chi^2 = 59.58 \quad (16)$$

The IAM reduces  $\chi^2$  by a factor of  $\sim 6$ , providing  $> 7\sigma$  preference over  $\Lambda\text{CDM}$  when accounting for two additional parameters ( $\beta$  and growth tax).

Dataset	$\chi^2_{\Lambda\text{CDM}}$	$\chi^2_{\text{IAM}}$	Tension
Planck	0.0	0.0	—
SH0ES	28.2	0.02	Resolved
JWST/TRGB	3.5	2.21	1.49 $\sigma$
DESI $f\sigma_8$	40.1	10.2	Improved
<b>Total</b>	<b>72.01</b>	<b>12.43</b>	—

TABLE I. Likelihood breakdown for  $\Lambda\text{CDM}$  versus IAM.

### Breakdown by Dataset

Minor residual tension with JWST/TRGB (1.49 $\sigma$ ) suggests room for refinement in the activation function parametrization.

### GROWTH SUPPRESSION AND $S_8$ TENSION

Informational encoding exacts an energetic cost on structure formation. We model this via a “growth tax”:

$$\ddot{D} + 2H\dot{D} = \frac{3}{2}\Omega_m H^2 D[1 - \tau(z)] \quad (17)$$

where  $\tau(z) \approx 0.045$  at late times. This  $\sim 4.5\%$  suppression reconciles the  $S_8$  tension between Planck and weak lensing surveys [10].

### ARROW OF TIME

In IAM, time’s arrow emerges from irreversible informational actualization. Define:

$$t_{\text{arrow}} \equiv \int \frac{dA_H}{4\dot{I}} \quad (18)$$

Reversing time requires erasing information, which by Landauer’s principle incurs dissipative energy cost:

$$\Delta E_{\text{erase}} \geq kT \ln 2 \times N_{\text{bits}} \quad (19)$$

Since  $N_{\text{bits}} \propto A_H \sim 10^{123}$  for the observable universe, reversal is thermodynamically forbidden. This provides a physics-only explanation for temporal asymmetry [11].

### TESTABLE PREDICTIONS

IAM makes several falsifiable predictions:

- **Growth rate evolution:**  $f(z)\sigma_8(z)$  should deviate from  $\Lambda\text{CDM}$  by  $\sim 2\%$  at  $z < 1$ , testable with Euclid [12].
- **BAO peak shift:** Recalibrated sound horizon  $r_d \approx 120.91$  Mpc (vs. 147.05 Mpc in  $\Lambda\text{CDM}$ ) affects BAO template fitting.

- **Lensing amplitude:**  $S_8$  suppression to  $\sim 0.78$  (vs. 0.83 in Planck) matches KiDS/DES observations.
- **High- $z$  quasars:** Accelerated early structure formation may explain JWST-detected massive galaxies at  $z > 10$  [13].

## DISCUSSION

### Scope and Limitations

IAM is a *phenomenological late-time modification*, not a fundamental theory of quantum gravity. We explicitly do not claim:

- Information constitutes a new physical field or fluid
- Derivation of holography from first principles
- Explanation of inflationary or primordial physics
- Uniqueness—other parameterizations may fit data similarly

Instead, IAM proposes that late-time expansion responds to structural actualization, consistent with horizon thermodynamics and empirically testable.

### Relation to Other Approaches

IAM differs from:

- *Early dark energy* [14]: No new physics before recombination
- *Modified gravity* (e.g.,  $f(R)$ ) [15]: No alteration of Einstein equations
- *Interacting dark sectors* [16]: No particle interactions, only geometric response

The closest analogue is emergent gravity [17], though IAM focuses on horizon thermodynamics rather than entropic forces.

## CONCLUSIONS

We have presented a holographic cosmological framework resolving the Hubble tension via information-driven expansion. Key results:

1. **Theoretical:** Derived expansion law from horizon thermodynamics linked to linear growth factor  $D(z)$
2. **Empirical:** Reduced combined  $\chi^2$  from 72.01 ( $\Lambda\text{CDM}$ ) to 12.43 (IAM) across Planck, SH0ES, JWST, DESI data (5.7 $\sigma$  significance)

3. **Predictive:** Falsifiable forecasts for Euclid, Rubin-LSST, and Roman Space Telescope
4. **Conceptual:** Physical mechanism for cosmological arrow of time

Future work will refine the activation function  $\mathcal{E}(a)$  using high-precision BAO data and test growth suppression via cluster abundances. The framework demonstrates that informational considerations may play a fundamental role in cosmic dynamics, bridging thermodynamics, quantum mechanics, and general relativity.

The author thanks the open-source communities of NumPy, SciPy, and Matplotlib for computational tools. This work is available as a preprint at <https://doi.org/10.17605/OSF.IO/KCZD9>. All data and code for replication are available at <https://github.com/hmahaffeyges/IAM-Validation>.

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### Mathematical Foundation for Replication

To facilitate independent verification, we provide explicit implementation details.

#### Activation Function

The informational energy density is governed by:

$$\mathcal{E}(a) = \exp\left(1 - \frac{1}{a}\right) \quad (20)$$

This ensures:

- $\mathcal{E}(a \rightarrow 0) \rightarrow 0$  (vanishes at early times)
- $\mathcal{E}(1) = 1$  (full activation today)
- Smooth transition centered around  $a \sim 0.5$  ( $z \sim 1$ )

#### Equation of State Implementation

For standard cosmological codes (CAMB, CLASS):

$$w_{\text{IA}}(a) = -1 - \frac{1}{3a} \quad (21)$$

#### Parameter Values

Fits to 2025/2026 data yield:

$$H_{0,\text{CMB}} = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (22)$$

$$\Omega_m = 0.3 \quad (23)$$

$$\Omega_\Lambda = 0.7 \quad (24)$$

$$\beta = 0.18 \quad (25)$$

$$\tau_{\text{growth}} = 0.045 \quad (26)$$

#### Computational Verification

All results can be independently reproduced via:

```
git clone https://github.com/hmahaffeyges/IAM-Validation
cd IAM-Validation
python tests/test_03_final.py
```

Expected runtime: <60 seconds on standard hardware.

#### Consistency Between Rate Dynamics and Background Closure

This appendix clarifies the relationship between the rate-based informational expansion law derived in Section II and the effective background cosmology employed in Section III.

#### Informational Expansion as Response Law

The fundamental dynamical statement of IAM is not an energy-density postulate, but a response relation:

$$H^2(t) \propto \frac{dI}{dt} \quad (27)$$

This should be interpreted analogously to constitutive laws in thermodynamics: it specifies how geometry responds to informational flux. The parameter  $\beta$  functions as a dimensionless response coefficient.

## Effective Density Description

To confront observations, we embed the response law within a covariant background framework via an effective informational energy density  $\rho_{\text{IA}}(a)$  defined such that its contribution to the Friedmann equation reproduces the late-time expansion implied by the rate-based law.

This effective density does not imply information constitutes a new fluid. Rather, it serves as a bookkeeping device capturing the integrated geometric response to informational production.

## Scope and Validity

IAM is best interpreted as a late-time, information-driven modification of cosmic expansion, grounded in horizon thermodynamics but closed phenomenologically for observational testing. Claims regarding early-universe physics or fundamental field content are intentionally avoided.

## What IAM Does Not Claim

To prevent misinterpretation:

- IAM does not posit information as a new physical substance or field
- IAM does not derive quantum gravity or holography from first principles
- IAM does not require consciousness or measurement to drive expansion
- IAM does not replace  $\Lambda$ CDM at early times
- IAM does not claim uniqueness; alternative parameterizations may exist

IAM proposes a testable phenomenological hypothesis: late-time expansion responds to the rate of physical structure actualization, consistent with holographic entropy bounds and horizon thermodynamics.