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 ($H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}) is maintained at early times, while late-time structure formation drives local expansion to $H_0 \approx 73.2$ km s^{-1} Mpc^{-1}, reconciling SH0ES and JWST observations. Combined fits to Planck, SH0ES, JWST/TRGB, and DESI DR2 data yield $\chi^2_{\rm IAM} = 11.50$ versus $\chi^2_{\Lambda\rm CDM} = 43.59$ ($\Delta\chi^2 = 32.09$), providing 5.7σ 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 ΛCDM 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 ($H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1} [2]) and late-time measurements ($H_0 = 73.04 \pm 1.04$ km s^{-1} 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 χ^2 analysis (replacing AIC)
- Updated fits incorporating DESI DR2 data (2025 release)
- Fully reproducible validation code (runtime <1 minute)
- Reduced dataset to 10 authoritative measurements from independent observational programs

The statistical evidence has strengthened to $\Delta\chi^2 = 32.09$ (5.7σ 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:

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

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

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

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:

$$-\frac{dH}{H^2} \propto H\frac{dI}{dt} \tag{3}$$

This yields the fundamental response law:

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

where β is a dimensionless response coefficient.

Information Decomposition

We decompose the information production rate into three components:

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

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:

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

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

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

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

Substituting into Eq. (4):

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

PHENOMENOLOGICAL CLOSURE

For numerical implementation, we introduce an effective informational density:

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

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

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

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

The effective equation of state is:

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

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 ($D \to 0$) and $\mathcal{E}(a) \to 0$. Equation (10) reduces to standard ΛCDM:

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

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

Late Universe ($z < 2$)

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

$$H_0^2 = H^2_{0,\text{CMB}}[1+\beta] \implies H_0 \approx 73.2 \text{ km s}^{-1}\text{Mpc}^{-1} \tag{13}$$

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

OBSERVATIONAL CONSTRAINTS

We fit IAM to four independent datasets:

1. **Planck CMB**: $H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1} [2]
2. **SH0ES**: $H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1} [3]
3. **JWST/TRGB**: $H_0 = 70.39 \pm 1.89$ km s^{-1} Mpc^{-1} [4]
4. **DESI DR2**: 7 points of $f\sigma_8(z)$ [5]

Combined fit results (10 data points):

$$\chi^2_{\Lambda\text{CDM}} = 43.59 \tag{14}$$
$$\chi^2_{\text{IAM}} = 11.50 \tag{15}$$
$$\Delta\chi^2 = 32.09 \tag{16}$$

The IAM reduces χ^2 by a factor of $\sim$4, providing 5.7σ preference over ΛCDM when accounting for two additional parameters (β and growth tax).

Dataset	$\chi^2_{\Lambda\mathrm{CDM}}$	χ^2_{IAM}	Improvement
Planck	0.0	0.0	—
SH0ES	28.2	0.02	Resolved
JWST/TRGB	3.5	2.21	Moderate
DESI $f\sigma_8$	11.67	9.23	Improved
Total	**43.59**	**11.50**	**5.7σ**

TABLE I. Likelihood breakdown for ΛCDM versus IAM.

Breakdown by Dataset

Minor residual tension with JWST/TRGB 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":

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

where $\tau(z) \approx 0.045$ at late times. This ∼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:

$$t_{\mathrm{arrow}} \equiv \int \frac{dA_H}{4\dot{I}} \tag{18}$$

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

$$\Delta E_{\mathrm{erase}} \geq kT \ln 2 \times N_{\mathrm{bits}} \tag{19}$$

Since $N_{\mathrm{bits}} \propto A_H \sim 10^{123}$ 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 ΛCDM by ∼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 ΛCDM) affects BAO template fitting.
- **Lensing amplitude**: S_8 suppression to ∼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 χ^2 from 43.59 (ΛCDM) to 11.50 (IAM) across Planck, SH0ES, JWST, DESI data (5.7σ 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:

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

This ensures:

- $\mathcal{E}(a \to 0) \to 0$ (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):

$$w_{\mathrm{IA}}(a) = -1 - \frac{1}{3a} \tag{21}$$

Parameter Values

Fits to 2025/2026 data yield:

$$H_{0,\mathrm{CMB}} = 67.4\ \mathrm{km\,s^{-1}Mpc^{-1}} \tag{22}$$
$$\Omega_m = 0.315 \tag{23}$$
$$\Omega_\Lambda = 0.685 \tag{24}$$
$$\beta = 0.18 \tag{25}$$
$$\tau_{\mathrm{growth}} = 0.045 \tag{26}$$

Computational Verification

All results can be independently reproduced via:

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

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

This should be interpreted analogously to constitutive laws in thermodynamics: it specifies how geometry responds to informational flux. The parameter β 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 $\rho_{\mathrm{IA}}(a)$ 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 ΛCDM 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.