The Informational Actualization Model: Holographic Horizon Dynamics Couple Quantum Structure Formation to Cosmic Expansion

Heath W. Mahaffey[1, *]

[1] *Independent Researcher, Entiat, WA 98822, USA*

(Dated: February 11, 2026)

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. Phenomenologically, this is captured by sector-dependent coupling parameters: matter-based observables (BAO, distance ladder) probe $\beta_m = 0.157 \pm 0.029$, 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, naturally resolving the Hubble tension: Planck measures $H_0 = 67.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (photon sector) while SH0ES measures $H_0 = 73.04\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (matter sector). Growth suppression from modified matter density (Ω_m dilution by 13.5%) yields $\sigma_8 = 0.800$, partially addressing the S_8 tension. Combined fits to Planck, SH0ES, JWST, and DESI yield $\chi^2_{\rm IAM} = 10.38$ versus $\chi^2_{\Lambda\rm CDM} = 41.63$ ($\Delta\chi^2 = 31.25$, 5.6σ improvement) with only two additional parameters. 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 ($H_0 = 67.4 \pm 0.5\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$) differs by $> 5\sigma$ from late-universe distance ladder measurements ($H_0 = 73.04 \pm 1.04\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$) [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 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]:

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

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]:

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

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 ΛCDM 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:

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

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

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

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]:

$$E_{\text{erase}} = kT \ln 2 \text{ per bit} \tag{5}$$

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 → decoherence → information → horizon modification → altered expansion.

The Core Physical Mechanism

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

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

where β quantifies the coupling strength between structure formation and expansion. This is *not* a modification of general relativity—it is a phenomenological description of how quantum information dynamics on horizons influence the effective expansion history.

PHENOMENOLOGICAL IMPLEMENTATION

Effective Parameterization

For computational tractability and empirical testing, we implement 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:

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

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

- $\mathcal{E}(a \to 0) \to 0$ — 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:

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

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 phenomenological parameters.

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

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

representing a 13.5% dilution compared to ΛCDM.

Growth Dynamics

The linear growth factor satisfies:

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

where:

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

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:

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

Observable Quantities

Distance measures:

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

Growth-rate observable:

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

CMB acoustic scale:

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

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
- **36σ 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):

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

Photon sector (CMB, photon propagation):

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

Observational Constraints

Matter-Sector Analysis (DESI BAO + $\mathbf{H_0}$ measurements)

Dataset:

- DESI DR2: $f\sigma_8(z)$ at 7 redshifts [2]
- SH0ES: $H_0 = 73.04 \pm 1.04$ $\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ [3]
- JWST/TRGB: $H_0 = 70.39 \pm 1.89$ $\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ [20]

Result:

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

This produces:

$$H_0(\text{matter}) = H_0\sqrt{1+\beta_m} = 67.4\sqrt{1.157} = 72.5\ \text{km}\,\text{s}^{-1}\text{Mpc}^{-1} \tag{20}$$

Agreement with SH0ES: $\Delta = 0.54$ $\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (0.5σ).

Photon-Sector Constraint (Planck CMB θ_s)

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

$$\theta_s^{\text{obs}} = 0.0104110 \pm 0.0000031\ \text{rad} \tag{21}$$

Theoretical prediction:

$$\theta_s(\beta_\gamma) = \frac{r_s}{\chi_\gamma(z_*)} = \frac{144.43\ \text{Mpc}}{\int_0^{1090}\frac{c\,dz}{H_\gamma(z)}} \tag{22}$$

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

$$\beta_\gamma = 0.000\,^{+0.004}_{-0.000} \quad (95\%\ \text{CL}) \tag{23}$$

Upper limit:

$$\beta_\gamma < 0.004 \quad (95\%\ \text{CL}) \tag{24}$$

Empirical Sector Ratio

The data independently constrains:

$$\frac{\beta_\gamma}{\beta_m} < 0.022 \quad (95\%\ \text{CL}) \tag{25}$$

This is the key empirical result: Photon and matter sectors experience different late-time expansion rates, with the ratio emerging from observations without theoretical assumption.

GROWTH SUPPRESSION MECHANISM

Modified Ω_m as Primary Mechanism

With $\beta_m = 0.157$, the matter density parameter at $z = 0$ becomes:

$$\Omega_m(z = 0, \beta = 0.157) = 0.272 \quad (\text{vs. } 0.315 \text{ in } \Lambda\text{CDM}) \tag{26}$$

This 13.5% dilution weakens gravitational clustering, suppressing growth.

Growth Factor Calculation

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

$$\frac{D_{\text{IAM}}(z = 0)}{D_{\Lambda\text{CDM}}(z = 0)} = 0.9864 \tag{27}$$

Growth suppression: 1.36%

Effective σ_8

$$\sigma_8(\text{IAM}) = 0.811 \times 0.9864 = 0.800 \tag{28}$$

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 DESI BAO + H_0 measurements (10 data points):

ΛCDM:

$$\chi^2_{\Lambda\text{CDM}} = 41.63 \quad (\chi^2/\text{dof} = 4.16) \tag{29}$$

IAM Dual-Sector Model:
Parameter scan: $\beta_m \in [0, 0.30]$, 300 points.
Best fit:

$$\beta_m = 0.157 \pm 0.029 \quad (68\%\ \text{CL}) \tag{30}$$

$$\beta_m = 0.157\,^{+0.059}_{-0.057} \quad (95\%\ \text{CL}) \tag{31}$$

$$\chi^2_{\text{min}} = 10.38 \tag{32}$$

Improvement:

$$\Delta\chi^2 = 41.63 - 10.38 = 31.25 \tag{33}$$

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

Decomposition by Dataset

Dataset	ΛCDM	IAM
H_0 measurements	31.91	1.51
DESI $f\sigma_8$	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.

Physical Predictions

Hubble parameter:

$$H_0(\text{photon/CMB}) = 67.4\ \text{km}\,\text{s}^{-1}\text{Mpc}^{-1} \tag{34}$$

$$H_0(\text{matter/local}) = 72.5 \pm 0.9\ \text{km}\,\text{s}^{-1}\text{Mpc}^{-1} \tag{35}$$

Structure growth:

- Growth suppression: 1.36%
- $\sigma_8(\text{IAM}) = 0.800$
- $\Omega_m(z = 0) = 0.272$ (13.5% dilution)

COMBINED OBSERVATIONAL SUMMARY

Parameter Constraints

Parameter	Value
β_m (matter)	0.157 ± 0.029
β_γ (photon)	< 0.004 (95% CL)
β_γ/β_m	< 0.022 (95% CL)
H_0 (photon)	$67.4\ \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$
H_0 (matter)	$72.5 \pm 0.9\ \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$
$\sigma_8(\text{IAM})$	0.800
Growth suppression	1.36%
$\Omega_m(z = 0)$ dilution	13.5%
$\chi^2(\Lambda\text{CDM})$	41.63
$\chi^2(\text{IAM})$	10.38
$\Delta\chi^2$	31.25 (5.6σ)

TABLE II. IAM empirical constraints from dual-sector fits.

Datasets

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

Total: 10 independent measurements (DESI: 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 ∼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× 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: $\beta(z) \propto \mathcal{E}(a) \to 0$ as $a \to 0$)
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 $\beta_\gamma/\beta_m < 0.022$ is the central discovery. This 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 [21].

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.

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)	**+2**	**Yes**	**Partial**	**31.25**

TABLE III. Comparison of phenomenological Hubble tension solutions. IAM achieves largest χ^2 improvement.

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.

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:

$$w_{\text{eff}}(a) \approx -1 - \frac{1}{3a} \tag{36}$$

exhibiting mild phantom behavior ($w < -1$ at high z, $w \to -1$ 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: $\beta_\gamma/\beta_m < 0.022$
- 5.6σ improvement over ΛCDM ($\Delta\chi^2 = 31.25$)
- Simultaneous resolution of H_0 tension and partial resolution of S_8 tension
- Testable predictions for upcoming surveys

What IAM does NOT claim:

- Fundamental derivation from quantum gravity (this is phenomenology)
- Modification of Einstein's equations or gauge structure
- That information is a new physical field or substance
- Uniqueness (other parameterizations may fit similarly)
- Explanation of early-universe physics or inflation

IAM is a *phenomenological late-time framework* motivated by horizon thermodynamics and holographic information dynamics. Its value lies in providing 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 $\beta_\gamma/\beta_m < 0.022$ 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:** $\beta_\gamma/\beta_m < 0.022$ (95% CL) from independent datasets

2. **Dual-resolution:** Hubble tension resolved ($\Delta\chi^2_H = 30.4$); S_8 tension partially addressed ($\sigma_8 = 0.800$ vs. Planck 0.811)

3. **Statistical significance:** 5.6σ improvement ($\Delta\chi^2 = 31.25$) with two parameters

4. **Physical mechanism:** Growth suppression emerges from Ω_m dilution (13.5%), not ad-hoc phenomenology

5. **Falsifiability:** Precise predictions for CMB-S4, Euclid, DESI Year 5

The Hubble tension may reflect not systematic error but observation of distinct expansion rates in a structure-coupled cosmology. Planck (photon sector, $\beta_\gamma \approx 0$) 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 is the empirical fact: $\beta_\gamma/\beta_m < 0.022$, resolved Hubble tension, and testable predictions.

The Informational Actualization Model demonstrates that phenomenological late-time modifications, when rigorously constrained by observations and grounded in established physics (Bekenstein-Hawking entropy, holographic principle, quantum decoherence), can resolve long-standing cosmological tensions while maintaining theoretical minimalism.

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

The author thanks the Planck, DESI, SH0ES, and JWST collaborations for publicly available data. I am grateful to the open-source communities of NumPy, SciPy, and Matplotlib. This work benefited from discussions facilitated by Claude (Anthropic) regarding statistical methodology, growth calculations, and reproducibility best practices. All analysis code is available at `https://github.com/hmahaffeyges/IAM-Validation` with runtime <5 minutes on standard hardware.

* hmahaffeyges@gmail.com

[1] Planck Collaboration, *Astron. Astrophys.* **641**, A6 (2020).
[2] DESI Collaboration, arXiv:2404.03002 (2024).
[3] A. G. Riess *et al.*, *Astrophys. J. Lett.* **934**, L7 (2022).
[4] KiDS Collaboration, *Astron. Astrophys.* **645**, A104 (2020).
[5] DES Collaboration, *Phys. Rev. D* **105**, 023520 (2022).
[6] M. Kamionkowski *et al.*, *Ann. Rev. Nucl. Part. Sci.* **73**, 153 (2023).
[7] L. Amendola *et al.*, *Living Rev. Rel.* **23**, 2 (2020).
[8] E. Di Valentino *et al.*, *Class. Quantum Grav.* **38**, 153001 (2021).
[9] J. C. Hill *et al.*, *Phys. Rev. D* **102**, 043507 (2020).
[10] L. Knox and M. Millea, *Phys. Rev. D* **101**, 043533 (2020).
[11] J. D. Bekenstein, *Phys. Rev. D* **7**, 2333 (1973).
[12] S. W. Hawking, *Commun. Math. Phys.* **43**, 199 (1975).
[13] R. Bousso, *Rev. Mod. Phys.* **74**, 825 (2002).
[14] G. 't Hooft, arXiv:gr-qc/9310026 (1993).
[15] L. Susskind, *J. Math. Phys.* **36**, 6377 (1995).
[16] J. Maldacena, *Adv. Theor. Math. Phys.* **2**, 231 (1998).
[17] W. H. Zurek, *Rev. Mod. Phys.* **75**, 715 (2003).
[18] R.-G. Cai and S. P. Kim, *JHEP* **02**, 050 (2005).
[19] R. Landauer, *IBM J. Res. Dev.* **5**, 183 (1961).
[20] W. L. Freedman *et al.*, *Astrophys. J.* **919**, 16 (2024).
[21] J. M. Bardeen, *Phys. Rev. D* **22**, 1882 (1980).