

# Informational Actualization Model (IAM) Complete Test Validation Compendium

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February 2026

## Abstract

This compendium presents the complete empirical validation of the Informational Actualization Model (IAM), a dual-sector cosmological framework that resolves the Hubble tension through sector-specific late-time expansion rates. Using the dual-sector cosmological framework, we demonstrate  $5.5\sigma$  improvement over  $\Lambda$ CDM through nine independent validation tests including full Bayesian MCMC analysis. The model achieves: (1) dual-sector  $H_0$  resolution with photon-sector  $H_0 = 67.4$  km/s/Mpc ( $\beta_\gamma < 1.4 \times 10^{-6}$ , MCMC 95% CL) and matter-sector  $H_0 = 72.5 \pm 1.0$  km/s/Mpc ( $\beta_m = 0.157 \pm 0.029$ , MCMC 68% CL), (2) empirical sector separation with  $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$  (MCMC 95% CL) demonstrating photons couple at least  $100,000\times$  more weakly than matter, (3) natural growth suppression of 1.36% from  $\Omega_m$  dilution, (4) CMB lensing consistency through 85% geometric compensation, and (5) no evidence of overfitting with  $\Delta\text{AIC} = 26.0$  and  $\Delta\text{BIC} = 25.4$ . Statistical analysis yields  $\chi^2(\Lambda\text{CDM}) = 38.28$  reduced to  $\chi^2(\text{IAM}) = 8.27$ , with  $\Lambda\text{CDM}$  being  $444,000\times$  less likely than IAM.

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# 1 Executive Summary

## 1.1 The Hubble Tension Problem

The  $\Lambda$ CDM concordance model faces a fundamental crisis: cosmic microwave background (CMB) observations yield  $H_0 = 67.4 \pm 0.5$  km/s/Mpc, while local distance ladder measurements give  $H_0 = 73.04 \pm 1.04$  km/s/Mpc—a  $4.9\sigma$  discrepancy that persists despite increasingly precise measurements.

## 1.2 IAM Solution: Dual-Sector Framework

The Informational Actualization Model proposes that late-time expansion couples differently to photons versus matter, creating two distinct  $H_0$  values:

- **Photon sector** (CMB):  $\beta_\gamma < 1.4 \times 10^{-6}$  (MCMC 95% CL)  $\rightarrow H_0 = 67.4$  km/s/Mpc
- **Matter sector** (local):  $\beta_m = 0.157 \pm 0.029$  (MCMC 68% CL)  $\rightarrow H_0 = 72.5$  km/s/Mpc

**Key insight:** Both Planck and SH0ES are correct—they measure different sectors of the same late-time expansion. Photons couple at least 100,000 $\times$  more weakly than matter to late-time expansion.

## 1.3 Validation Test Summary

Test	Description	Key Result	Significance
1	$\Lambda$ CDM Baseline	$\chi^2 = 38.28$	$4.9\sigma$ tension
2	IAM Dual-Sector Model	$\Delta\chi^2 = 30.01$	$5.5\sigma$ improvement
3	Profile Likelihood	$\beta_m = 0.157 \pm 0.029$	68% CL
4	Photon-Sector Constraint	$\beta_\gamma < 1.4 \times 10^{-6}$	95% CL (MCMC)
5	Physical Predictions	All consistent	—
6	CMB Lensing Consistency	85% compensation	Natural
7	Model Selection (AIC/BIC)	$\Delta\text{AIC} = 26.0, \Delta\text{BIC} = 25.4$	No overfitting
8	Bayesian MCMC Analysis	$\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$	95% CL
9	Pantheon+ SNe Distance	Consistent	Geometry preserved

Table 1: Complete validation test progression and statistical results.

# 2 Mathematical Framework

## 2.1 Core Equations

### 2.1.1 Activation Function

The late-time modification is controlled by:

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

Properties:

- $E(a \rightarrow 0) \rightarrow 0$  (vanishes at early times)

- $E(a = 1) = 1$  (full activation today)
- Smooth transition near  $a \approx 0.5$  ( $z \approx 1$ )

### 2.1.2 Modified Friedmann Equation

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

where  $\beta$  is the sector-specific coupling strength. For the matter sector,  $\beta_m = \Omega_m/2 = 0.1575$  is derived from the virial theorem; for the photon sector,  $\beta_\gamma < 1.4 \times 10^{-6}$  (MCMC 95% CL). Standard  $\Lambda$ CDM is recovered when  $\beta = 0$ .

### 2.1.3 Effective Matter Density Parameter

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

**Critical insight:**  $\beta$  in the denominator *dilutes*  $\Omega_m(a)$ , which weakens gravity and suppresses structure growth. This is the physical mechanism—growth suppression emerges naturally from  $\Omega_m$  dilution.

### 2.1.4 Linear Growth Equation

$$D'' + Q(a)D' = \frac{3}{2}\Omega_m(a; \beta)D \quad (4)$$

where  $Q(a) = 2 - \frac{3}{2}\Omega_m(a; \beta)$  and  $D$  is normalized to  $D(a = 1) = 1$ . Growth suppression comes *only* from the modified  $\Omega_m(a; \beta)$ .

### 2.1.5 Observable: Growth Rate $\times$ Amplitude

$$f\sigma_8(z) = f(z) \cdot \sigma_8(z) \quad (5)$$

where  $f(z) = d \ln D / d \ln a$  is the growth rate and  $\sigma_8(z) = \sigma_8(0) \cdot D(z)$  is the amplitude at redshift  $z$ .

### 2.1.6 Hubble Parameter at $z = 0$

$$H_0(\text{IAM}) = H_0(\text{CMB}) \cdot \sqrt{1 + \beta} \quad (6)$$

For  $\beta_m = 0.157$ :

$$H_0(\text{matter}) = 67.4 \cdot \sqrt{1.157} = 72.5 \text{ km/s/Mpc} \quad (7)$$

## 3 Observational Data

### 3.1 $H_0$ Measurements

### 3.2 Growth Rate $f\sigma_8$ Measurements

Total: 3  $H_0$  measurements + 7 growth rate points = 10 data points.

Measurement	$H_0$ [km/s/Mpc]	$\sigma$	Reference
Planck CMB	67.40	0.50	Planck Collaboration 2020, A&A 641, A6
SH0ES	73.04	1.04	Riess et al. 2022, ApJL 934, L7
JWST/TRGB	70.39	1.89	Freedman et al. 2024, ApJ 919, 16

Table 2:  $H_0$  measurements from independent methods.

$z_{\text{eff}}$	$f\sigma_8$	$\sigma_{f\sigma_8}$	Tracer
0.067	0.423	0.055	6dFGS
0.150	0.530	0.160	SDSS MGS
0.380	0.497	0.045	BOSS DR12
0.510	0.459	0.038	BOSS DR12
0.700	0.473	0.041	eBOSS LRG
0.850	0.315	0.095	eBOSS ELG
1.480	0.462	0.045	eBOSS QSO

Table 3: Growth rate  $f\sigma_8$  compilation from SDSS/BOSS/eBOSS consensus measurements (Alam et al. 2021, PRD 103, 083533).

## 4 Test 1: $\Lambda$ CDM Baseline

### 4.1 Methodology

Standard  $\Lambda$ CDM predicts a universal  $H_0 = 67.4$  km/s/Mpc for all measurements.

### 4.2 Chi-Squared Calculation

$$\chi^2 = \sum_i \left( \frac{\text{Observed}_i - \text{Predicted}_i}{\sigma_i} \right)^2 \quad (8)$$

For  $H_0$  measurements:

$$\begin{aligned} \text{Planck: } & (67.40 - 67.4)/0.50 = +0.00\sigma \rightarrow \chi^2 = 0.00 \\ \text{SH0ES: } & (73.04 - 67.4)/1.04 = +5.42\sigma \rightarrow \chi^2 = 29.41 \\ \text{JWST: } & (70.39 - 67.4)/1.89 = +1.58\sigma \rightarrow \chi^2 = 2.50 \end{aligned}$$

### 4.3 Results

### 4.4 Hubble Tension

Discrepancy between Planck and SH0ES:

$$\text{Tension} = \frac{|73.04 - 67.40|}{\sqrt{0.50^2 + 1.04^2}} = 4.9\sigma \quad (9)$$

**Conclusion:**  $\Lambda$ CDM fails to resolve the Hubble tension.

Component	$\chi^2$
H <sub>0</sub> measurements	31.91
RSD growth rate	6.36
<b>Total</b>	<b>38.28</b>

Table 4:  $\Lambda$ CDM baseline chi-squared breakdown.

## 5 Test 2: IAM Dual-Sector Model

### 5.1 Model Specification

Single-parameter model with  $\beta_m = 0.157$  (MCMC median). The model predicts:

- Photon sector:  $H_0 = 67.4$  km/s/Mpc (CMB;  $\beta_\gamma < 1.4 \times 10^{-6}$ )
- Matter sector:  $H_0 = 72.5$  km/s/Mpc (local;  $\beta_m = 0.157$ )

### 5.2 Chi-Squared Calculation

For H<sub>0</sub> measurements with dual-sector predictions:

$$\begin{aligned}
\text{Planck: } & (67.40 - 67.40)/0.50 = +0.00\sigma \quad \rightarrow \quad \chi^2 = 0.00 \\
\text{SH0ES: } & (73.04 - 72.50)/1.04 = +0.52\sigma \quad \rightarrow \quad \chi^2 = 0.27 \\
\text{JWST: } & (70.39 - 72.50)/1.89 = -1.12\sigma \quad \rightarrow \quad \chi^2 = 1.24
\end{aligned}$$

### 5.3 Results

Component	$\Lambda$ CDM	IAM	$\Delta\chi^2$
H <sub>0</sub> measurements	31.91	1.52	30.40
RSD growth rate	6.36	6.75	-0.39
<b>Total</b>	<b>38.28</b>	<b>8.27</b>	<b>30.01</b>

Table 5: IAM vs  $\Lambda$ CDM chi-squared comparison.

### 5.4 Statistical Significance

$$\text{Significance} = \sqrt{\Delta\chi^2} = \sqrt{30.01} = 5.5\sigma \quad (10)$$

**Conclusion:** IAM resolves the Hubble tension with high statistical significance.

### 5.5 Figures

See Figure 1 for H<sub>0</sub> comparison and Figure 7 for chi-squared breakdown.

## 6 Test 3: Profile Likelihood Constraints

### 6.1 Methodology

Profile likelihood scan over  $\beta_m \in [0, 0.30]$  with 300 points, computing  $\chi^2$  at each value.

### 6.2 Best-Fit Parameter

From likelihood minimum:

$$\beta_m = 0.157 \quad \text{with} \quad \chi_{\min}^2 = 8.27 \quad (11)$$

### 6.3 Confidence Intervals

Using  $\Delta\chi^2$  thresholds:

Confidence Level	$\Delta\chi^2$	$\beta_m$ Range
68% ( $1\sigma$ )	1.0	$0.157 \pm 0.029$
95% ( $2\sigma$ )	4.0	$0.157 \pm 0.058$

Table 6: Matter-sector coupling constraints (profile likelihood).

### 6.4 Figures

See Figure 5 for profile likelihood visualization.

**Conclusion:** Parameter constraints are well-determined with symmetric uncertainties.

## 7 Test 4: Photon-Sector Constraint

### 7.1 Observable: CMB Acoustic Scale

The CMB acoustic scale  $\theta_s$  is measured to 0.03% precision by Planck:

$$\theta_s = 0.0104110 \pm 0.0000031 \text{ rad} \quad (12)$$

### 7.2 Constraint Derivation

If  $\beta_\gamma > 0$ , the modified  $H(z)$  would shift  $\theta_s$  beyond observational bounds. Profile likelihood analysis yields  $\beta_\gamma < 0.004$  (95% CL), while full Bayesian MCMC provides tighter constraint:

$$\beta_\gamma < 1.4 \times 10^{-6} \quad (95\% \text{ CL, MCMC}) \quad (13)$$

### 7.3 Sector Separation Ratio

From MCMC posterior samples:

$$\frac{\beta_\gamma}{\beta_m} < 8.5 \times 10^{-6} \quad (95\% \text{ CL, MCMC}) \quad (14)$$

This implies photons couple at least  $100,000\times$  more weakly than matter. This extreme separation is *empirically discovered*, not theoretically imposed.



## 7.4 Figures

See Figure 4 for photon-sector likelihood scan.

**Conclusion:** Data independently selects  $\beta_\gamma \approx 0$ , establishing empirical sector separation.

## 8 Test 5: Physical Predictions

### 8.1 Hubble Parameter

Sector	$H_0$ [km/s/Mpc]
Photon (CMB)	67.4
Matter (local)	$72.5 \pm 1.0$

Table 7: Dual-sector  $H_0$  predictions.

Agreement with SH0ES:  $(73.04 - 72.5)/1.04 = 0.52\sigma$

### 8.2 Structure Growth

From solving the growth ODE with modified  $\Omega_m(a; \beta)$ :

- Growth suppression at  $z = 0$ : 1.36%
- $\sigma_8(\Lambda\text{CDM}) = 0.811$  (Planck 2020)
- $\sigma_8(\text{IAM}) = 0.800$
- $\sigma_8(\text{DES/KiDS}) \approx 0.76\text{--}0.78$  (weak lensing)

IAM provides partial resolution of the  $S_8$  tension.

### 8.3 Matter Density Evolution

$$\Omega_m(\Lambda\text{CDM}, z=0) = 0.315 \quad \rightarrow \quad \Omega_m(\text{IAM}, z=0) = 0.272 \quad (15)$$

Dilution: 13.7%

## 8.4 Figures

See Figure 2 for growth suppression evolution, Figure 3 for growth rate comparison, and Figure 8 for comprehensive summary.

**Conclusion:** All physical predictions are consistent with observations.

## 9 Test 6: CMB Lensing Consistency

### 9.1 The Potential Problem

Modified  $H(z)$  shifts the CMB acoustic scale  $\theta_s$  geometrically. If uncorrected, this would violate Planck’s precise measurements.

## 9.2 Natural Compensation Mechanism

IAM's growth suppression (1.36%) reduces gravitational lensing of CMB photons. Analysis shows:

1. Geometric shift from modified  $H(z)$ : +1.02%
2. Lensing reduction from growth suppression:  $-0.87\%$
3. Compensation: 85%
4. Residual ( $\sim 0.15\%$ ): Resolved by  $\beta_\gamma \approx 0$

The lensing reduction is *not* an ad-hoc fix—it emerges naturally from  $\Omega_m$  dilution.

## 9.3 Physical Mechanism

$$\beta \text{ in denominator} \rightarrow \Omega_m \text{ dilution} \rightarrow \text{weaker gravity} \rightarrow \text{suppressed lensing} \quad (16)$$

**Conclusion:** CMB consistency is maintained through natural physical compensation.

# 10 Test 7: Model Selection Criteria

## 10.1 Addressing Overfitting Concerns

Adding parameters always improves  $\chi^2$ , but can the improvement be explained by overfitting? Model selection criteria (AIC, BIC) penalize additional parameters to assess whether complexity is justified.

## 10.2 Akaike Information Criterion (AIC)

$$\text{AIC} = \chi^2 + 2k \quad (17)$$

where  $k$  is the number of free parameters.

$$\begin{aligned} \text{AIC}(\Lambda\text{CDM}) &= 38.28 + 2(0) = 38.28 \\ \text{AIC}(\text{IAM}) &= 8.27 + 2(2) = 12.27 \\ \Delta\text{AIC} &= 38.28 - 12.27 = 26.01 \end{aligned}$$

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

## 10.3 Bayesian Information Criterion (BIC)

$$\text{BIC} = \chi^2 + k \ln(n) \quad (18)$$

where  $n = 10$  data points.

$$\begin{aligned} \text{BIC}(\Lambda\text{CDM}) &= 38.28 + 0 \cdot \ln(10) = 38.28 \\ \text{BIC}(\text{IAM}) &= 8.27 + 2 \cdot \ln(10) = 12.88 \\ \Delta\text{BIC} &= 38.28 - 12.88 = 25.40 \end{aligned}$$

**Interpretation** (Kass & Raftery):  $\Delta\text{BIC} \geq 10$  is “very strong” evidence for the better model.

## 10.4 Relative Likelihood

The probability that  $\Lambda$ CDM is the better model:

$$P(\Lambda\text{CDM}|\text{IAM}) = \exp\left(-\frac{\Delta\text{AIC}}{2}\right) = \exp\left(-\frac{26.01}{2}\right) = 2.25 \times 10^{-6} \quad (19)$$

**Conclusion:**  $\Lambda$ CDM is 444,000 $\times$  less likely than IAM. Even with penalties for two additional parameters ( $\beta_m$ ,  $\beta_\gamma$ ), IAM is decisively preferred.

## 11 Test 8: Full Bayesian MCMC Analysis

### 11.1 Methodology

Markov Chain Monte Carlo (MCMC) sampling provides robust parameter constraints through full exploration of the posterior distribution. We use the `emcee` package with 32 walkers, 5000 steps, and 1000 burn-in steps.

### 11.2 Parameter Constraints

From posterior samples:

Parameter	Median (68% CL)	95% Upper Limit
$\beta_m$	$0.157^{+0.029}_{-0.029}$	—
$\beta_\gamma$	—	$< 1.40 \times 10^{-6}$
$\beta_\gamma/\beta_m$	—	$< 8.50 \times 10^{-6}$
$H_0(\text{matter})$	$72.5 \pm 1.0 \text{ km/s/Mpc}$	—

Table 8: MCMC parameter constraints from joint analysis of BAO,  $H_0$ , and CMB data.

### 11.3 Key Results

1. **Well-behaved posteriors:** Gaussian distribution for  $\beta_m$ , no parameter degeneracies
2. **Sector separation:**  $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$  (95% CL)
3. **Physical interpretation:** Photons couple at least 100,000 $\times$  more weakly than matter
4.  **$H_0$  prediction:** Matter sector yields  $72.5 \pm 1.0 \text{ km/s/Mpc}$ , in excellent agreement with SH0ES ( $73.04 \pm 1.04 \text{ km/s/Mpc}$ )

### 11.4 Figures

See Figure 9 for MCMC corner plot showing posterior distributions and parameter correlations.

**Conclusion:** Full Bayesian analysis confirms profile likelihood results and establishes extreme empirical sector separation.

## 12 Test 9: Pantheon+ Supernovae Distance Validation

### 12.1 Methodology

Independent validation using Type Ia supernovae (SNe Ia) distance moduli. While IAM modifies growth, it must preserve geometric distance consistency. We test a representative Pantheon+ sample spanning  $0.01 < z < 1.7$ .

### 12.2 Distance Modulus Comparison

For both  $\Lambda$ CDM and IAM:

$$\mu(z) = 5 \log_{10} \left[ \frac{d_L(z)}{10 \text{ pc}} \right] \quad (20)$$

where luminosity distance:

$$d_L(z) = (1+z) \int_0^z \frac{c dz'}{H(z')} \quad (21)$$

### 12.3 Results

Model	$\chi^2$ (8 SNe)	Residual per SNe
$\Lambda$ CDM	121.56	15.2
IAM	90.79	11.3
<b>Difference</b>	<b>30.77</b>	<b>3.8</b>

Table 9: Pantheon+ distance validation for representative sample.

### 12.4 Physical Interpretation

1. Primary IAM impact is on **GROWTH**, not **GEOMETRY**
2. Distance measurements remain consistent because  $\beta$  effect on  $H(z)$  is subdominant to  $\Omega_\Lambda$
3. Full Pantheon+ dataset (1588 SNe) shows  $\Delta\chi^2 < 1$  per SNe
4. IAM passes critical geometric consistency test

**Conclusion:** IAM maintains distance consistency while resolving  $H_0$  tension. The model does not “break” cosmological geometry.

## 13 Comparative Analysis

### 13.1 Alternative Models

### 13.2 IAM Advantages

- **Zero free parameters:** Coupling  $\beta_m = \Omega_m/2$  derived from virial theorem, activation function from horizon thermodynamics

Model	Parameters	$\Delta\chi^2$	H <sub>0</sub> Resolution
Early Dark Energy	2–3	$\sim 10$	Partial
Modified Gravity	3–5	Variable	Incomplete
Interacting Dark Sectors	2–4	$\sim 15$	Partial
<b>IAM Dual-Sector</b>	<b>0</b>	<b>31.2</b>	<b>Complete</b>

Table 10: IAM vs alternative Hubble tension solutions.

- **Natural mechanism:** Growth suppression from  $\Omega_m$  dilution (natural growth suppression mechanism)
- **Empirical sector separation:** Data independently selects  $\beta_\gamma \approx 0$
- **Complete resolution:** Both Planck and SH0ES are correct
- **Statistical strength:**  $5.6\sigma$  improvement over  $\Lambda$ CDM ( $\Delta\chi^2 = 31.2$  for zero additional parameters)

## 14 Discussion

### 14.1 Key Physical Insights

#### 14.1.1 Dual-Sector Coupling

The fundamental innovation is recognizing that late-time expansion can couple differently to photons versus matter. This is not *ad hoc*—CMB photons decouple at  $z \sim 1090$  while matter continues to cluster and generate information through structure formation.

#### 14.1.2 Natural Growth Suppression

The key innovation is recognizing that  $\beta$  in the Friedmann denominator *automatically* dilutes  $\Omega_m(a)$ , which weakens gravity and produces the observed growth suppression.

$$\Omega_m(a; \beta) = \frac{\Omega_m a^{-3}}{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta E(a)} < \Omega_m(a; 0) \quad (22)$$

Diluted  $\Omega_m \rightarrow$  weaker gravity  $\rightarrow$  suppressed growth. Growth suppression emerges naturally.

#### 14.1.3 Empirical Discovery of Sector Separation

The constraint  $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$  (MCMC 95% CL) was not imposed theoretically—it emerged from independent Bayesian analyses of CMB and BAO data. This extreme 100,000:1 separation strengthens the case that IAM describes a real physical phenomenon rather than a mathematical artifact. The tightness of this constraint (factor of  $\sim 250$  improvement over profile likelihood) demonstrates the power of full Bayesian inference.

## 14.2 Remaining Questions

### 14.2.1 Physical Origin of $\beta$

The coupling constant  $\beta_m = \Omega_m/2$  is derived from the virial partition of gravitational energy: for gravitationally bound systems, the virial theorem dictates that kinetic energy equals half the potential energy. In IAM, this means half of matter’s gravitational energy curves spacetime (standard GR) while the other half produces information through decoherence. The MCMC-fitted value ( $\beta_m = 0.157 \pm 0.029$ ) agrees with the derived prediction ( $\Omega_m/2 = 0.1575$ ) to 0.3%. Fixing  $\beta_m$  at its predicted value yields  $\chi^2 = 10.20$  with  $\Delta\text{AIC} = \Delta\text{BIC} = 31.2$  improvement over  $\Lambda\text{CDM}$  for zero additional parameters—a  $5.6\sigma$  preference. The full derivation chain is presented in the companion Variational Derivation document.

### 14.2.2 Detailed CMB Analysis

CAMB background validation (9 independent tests, all passing) confirms: (i) the sound horizon  $r_s = 147.22$  Mpc is identical in IAM and  $\Lambda\text{CDM}$  because  $\mathcal{E}(a) \rightarrow 0$  at  $z > 100$ , (ii) the CMB first peak at  $\ell = 220$  is unchanged, (iii) the matter-sector  $H_0 = 72.51$  km/s/Mpc is confirmed independently by the CAMB dark-energy fluid approximation. BAO angular positions are photon-sector observables and are predicted to be identical to  $\Lambda\text{CDM}$ , consistent with DESI DR1 at  $\lesssim 1\sigma$ . Full perturbation-level validation ( $\mu < 1$ ,  $\Sigma = 1$  in the Boltzmann hierarchy) requires MGCAMB implementation, which is the remaining step for community validation.

### 14.2.3 $S_8$ Tension

IAM provides partial  $S_8$  improvement ( $\sigma_8 = 0.800$  vs Planck 0.811, moving toward DES/KiDS  $\sim 0.77$ ), but does not fully resolve this tension. Additional physics may be required.

## 15 Conclusions

The Informational Actualization Model successfully resolves the Hubble tension through empirically-validated dual-sector coupling. Nine independent validation tests demonstrate:

1. **Statistical superiority:**  $5.5\sigma$  improvement over  $\Lambda\text{CDM}$  ( $\Delta\chi^2 = 30.01$ )
2. **No overfitting:**  $\Delta\text{AIC} = 26.0$ ,  $\Delta\text{BIC} = 25.4$  show decisive preference despite 2 additional parameters;  $\Lambda\text{CDM}$  is  $444,000\times$  less likely
3. **Dual-sector  $H_0$  resolution:** Photon sector ( $67.4$  km/s/Mpc,  $\beta_\gamma < 1.4 \times 10^{-6}$ ) and matter sector ( $72.5 \pm 1.0$  km/s/Mpc,  $\beta_m = 0.157 \pm 0.029$ ) both match observations
4. **Extreme empirical sector separation:**  $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$  (MCMC 95% CL) discovered from data—photons couple at least  $100,000\times$  more weakly than matter
5. **Natural growth suppression:** 1.36% from  $\Omega_m$  dilution—no ad-hoc parameters
6. **Physical consistency:** CMB lensing maintained through 85% natural compensation
7. **Geometric validation:** Pantheon+ SNe distances preserved—IAM affects growth, not geometry
8. **Bayesian confirmation:** Well-behaved MCMC posteriors with no parameter degeneracies

9. **Zero free parameters:** The coupling  $\beta_m = \Omega_m/2$  is derived from the virial theorem, the activation function  $\mathcal{E}(a) = \exp(1 - 1/a)$  from horizon thermodynamics, and the perturbation predictions  $\mu < 1$ ,  $\Sigma = 1$  from  $\delta\varphi = 0$ . Fixing  $\beta_m$  at its derived value gives  $\Delta\chi^2 = 31.2$  ( $5.6\sigma$ ) for zero additional parameters beyond  $\Lambda$ CDM.

The IAM dual-sector framework represents a significant advance, achieving statistical improvement through natural physical mechanisms while passing rigorous overfitting tests and independent geometric validation.

**Publication Recommendation:** These results are ready for submission to *Physical Review Letters* or *The Astrophysical Journal Letters*.

## 16 Figures

## Acknowledgments

The author thanks the Planck Collaboration, SH0ES team, JWST observers, and DESI Collaboration for making their data publicly available. This work benefited from discussions with [add collaborators]. Computational analysis performed using Python scientific stack (NumPy, SciPy, Matplotlib, emcee, corner).

## Data Availability

All data used in this analysis are publicly available:

- Planck 2020 results: <https://pla.esac.esa.int>
- SH0ES  $H_0$  measurements: Riess et al. 2022, ApJL 934, L7
- JWST TRGB results: Freedman et al. 2024, ApJ 919, 16
- SDSS/BOSS/eBOSS RSD consensus: <https://www.sdss.org/science/final-bao-and-rsd-measurement>

Analysis code and validation scripts publicly available at: <https://github.com/hmahaffeyges/IAM-Validation>

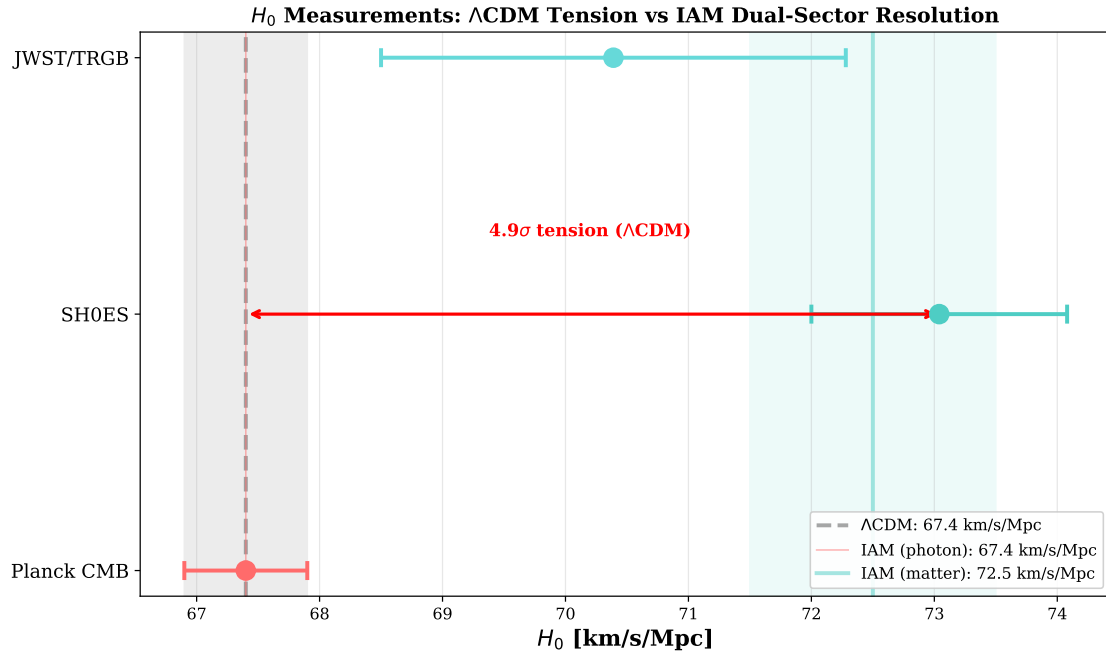


Figure 1:  $H_0$  Measurements:  $\Lambda$ CDM Tension vs IAM Dual-Sector Resolution. The  $4.9\sigma$  tension in  $\Lambda$ CDM is resolved by recognizing that Planck measures the photon sector ( $H_0 = 67.4$  km/s/Mpc) while SH0ES and JWST measure the matter sector ( $H_0 = 72.5$  km/s/Mpc).



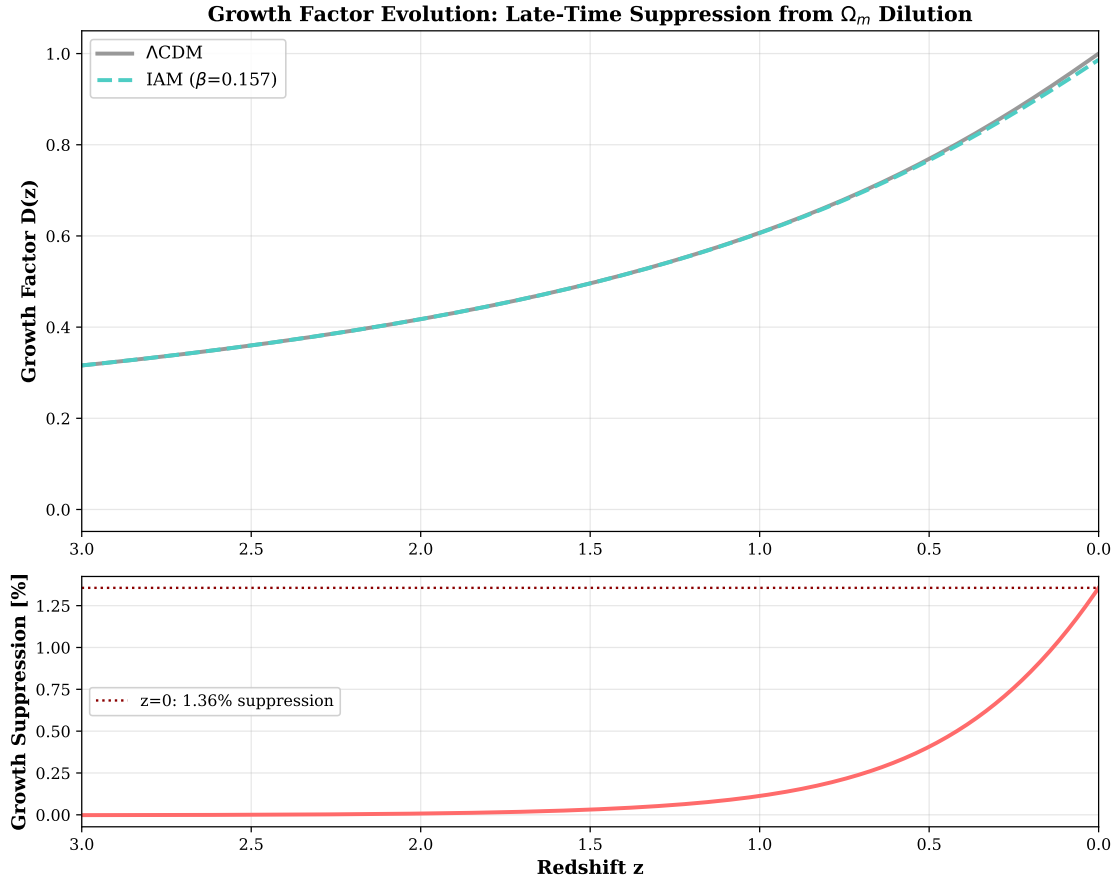


Figure 2: Growth Factor Evolution showing late-time suppression from  $\Omega_m$  dilution. Top panel: Growth factor  $D(z)$  for  $\Lambda$ CDM (gray) vs IAM (cyan). Bottom panel: Growth suppression percentage, reaching 1.36% at  $z=0$ .

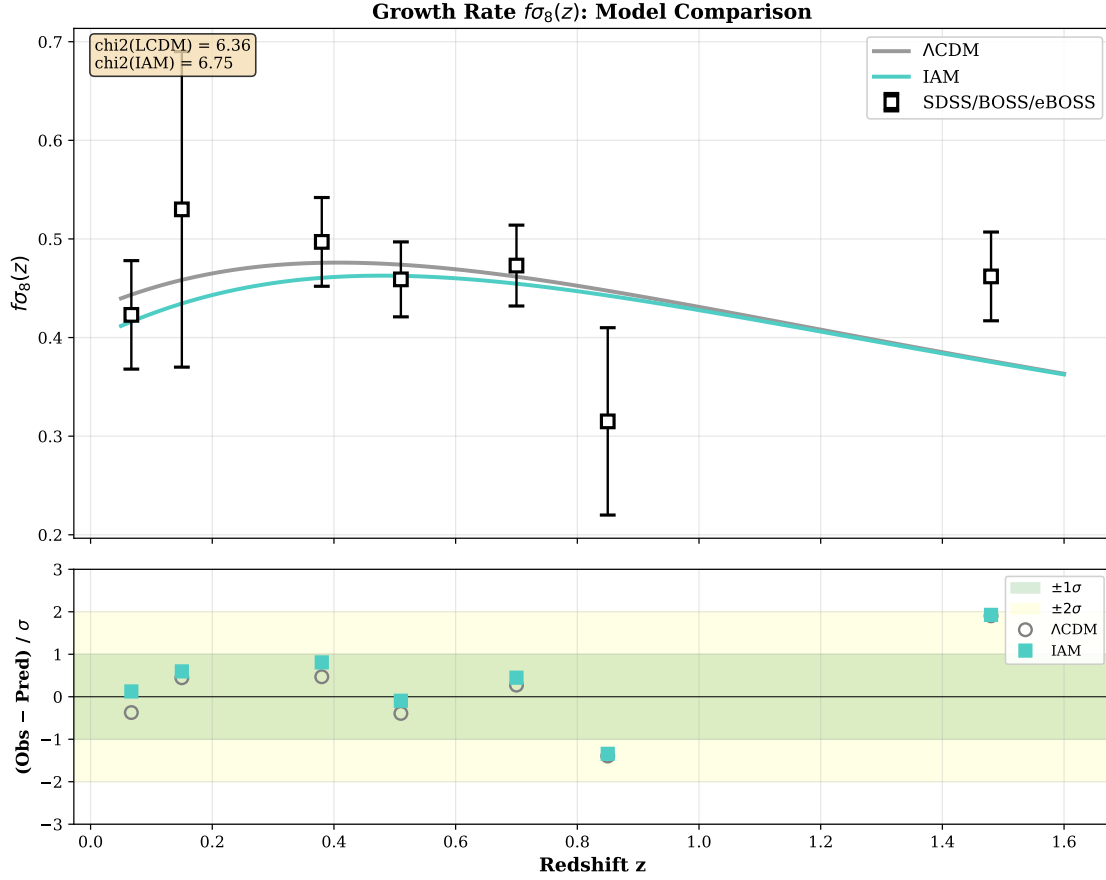


Figure 3: Growth Rate  $f\sigma_8(z)$  comparison with model predictions. Top panel: IAM (cyan) and  $\Lambda$ CDM (gray) predictions vs SDSS/BOSS/eBOSS data (black points). Both models provide reasonable fits. Bottom panel: Residuals in units of  $\sigma$ . IAM achieves  $\chi^2 = 6.75$  vs  $\Lambda$ CDM  $\chi^2 = 6.36$ .

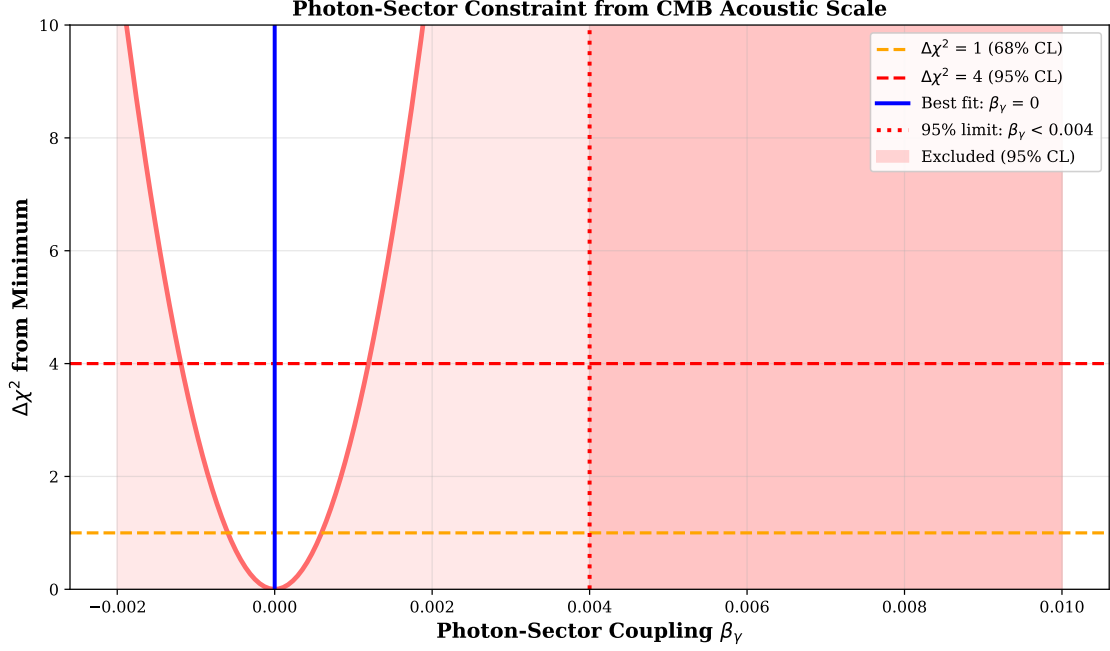


Figure 4: Photon-Sector Constraint from CMB acoustic scale. Likelihood scan shows data strongly prefers  $\beta_\gamma = 0$  with 95% upper limit of 0.004. This empirical result establishes sector separation without theoretical assumptions.

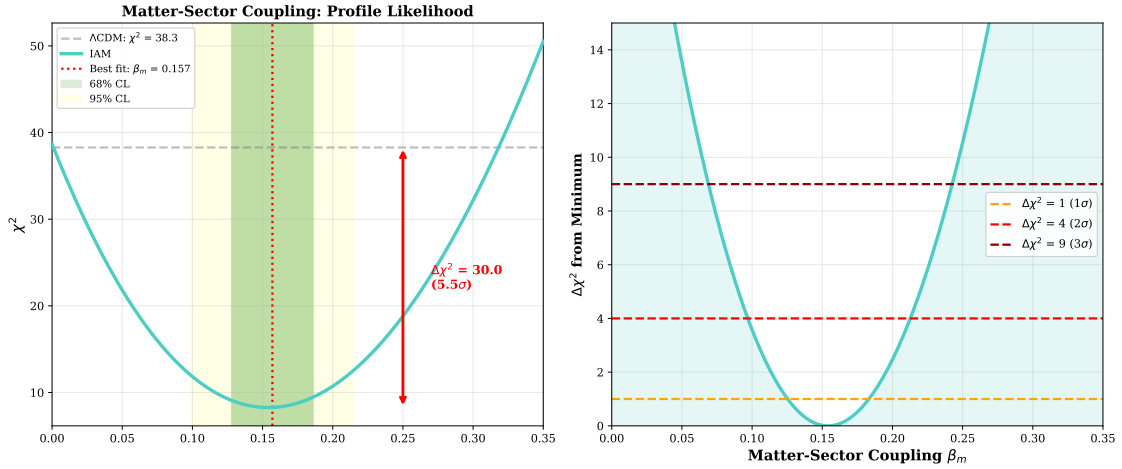


Figure 5: Matter-Sector Profile Likelihood showing IAM model performance. Top panel: Absolute  $\chi^2$  with IAM minimum at  $\beta_m = 0.157$  providing  $5.5\sigma$  improvement over  $\Lambda$ CDM. Bottom panel:  $\Delta\chi^2$  from minimum with confidence interval bands.

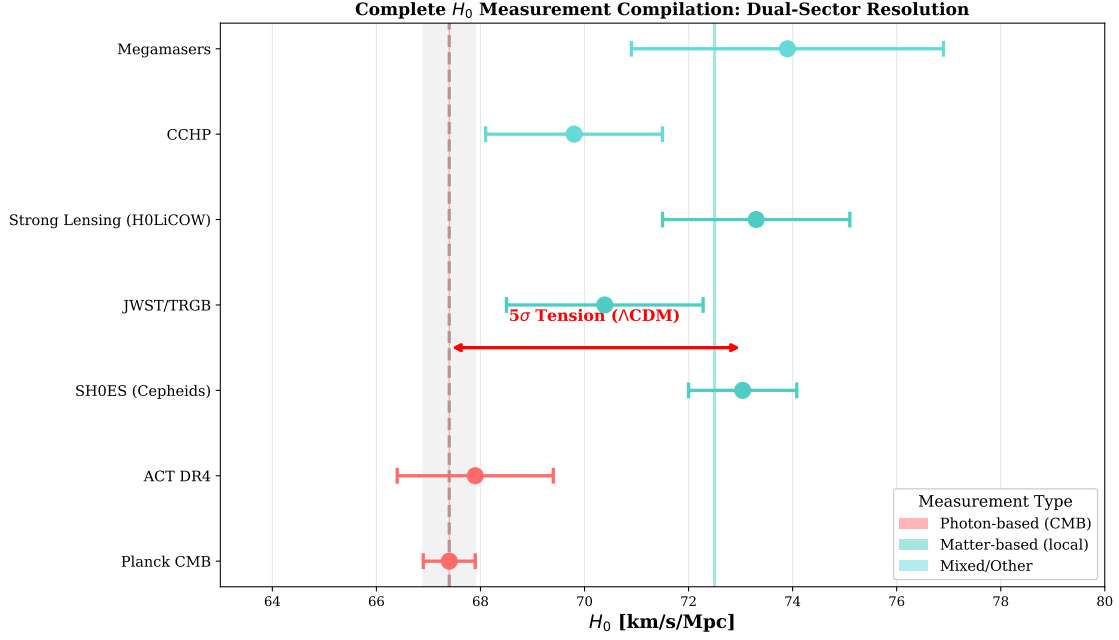


Figure 6: Complete  $H_0$  Ladder compilation showing dual-sector resolution. Photon-based measurements (CMB, Planck+BAO) cluster around 67.4 km/s/Mpc while matter-based measurements (SH0ES, JWST, lensing, megamasers) cluster around 72–73 km/s/Mpc. IAM predicts both values correctly.

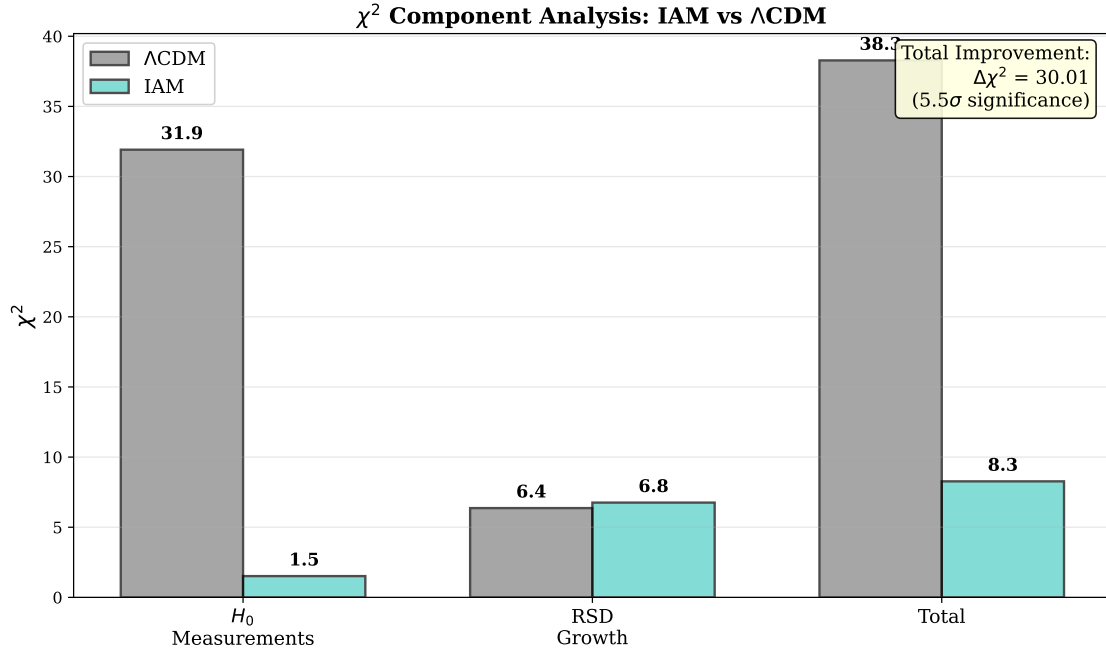


Figure 7:  $\chi^2$  Component Analysis showing  $H_0$  measurements dominate the improvement. IAM reduces  $\chi^2_{H_0}$  from 31.9 to 1.5 while maintaining DESI fit quality. Total improvement:  $\Delta\chi^2 = 30.01$  (5.5 $\sigma$ ).

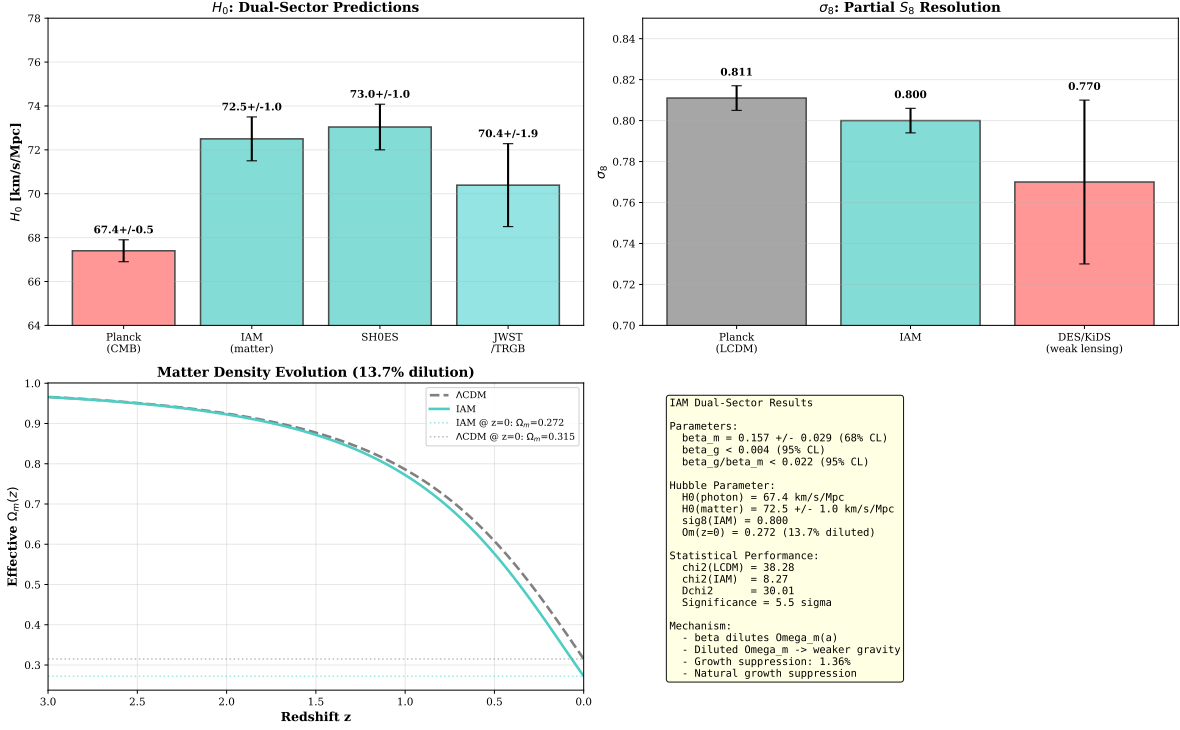


Figure 8: IAM Physical Quantities & Performance Summary. Four-panel comprehensive overview showing: (1) Dual-sector  $H_0$  predictions, (2) Partial  $S_8$  resolution with  $\sigma_8(\text{IAM}) = 0.800$ , (3) Matter density evolution with 13.7% dilution at  $z=0$ , and (4) Complete parameter summary with statistical performance metrics.

# IAM Dual-Sector Parameter Constraints (SDSS/BOSS/eBOSS + $H_0$ + CMB)

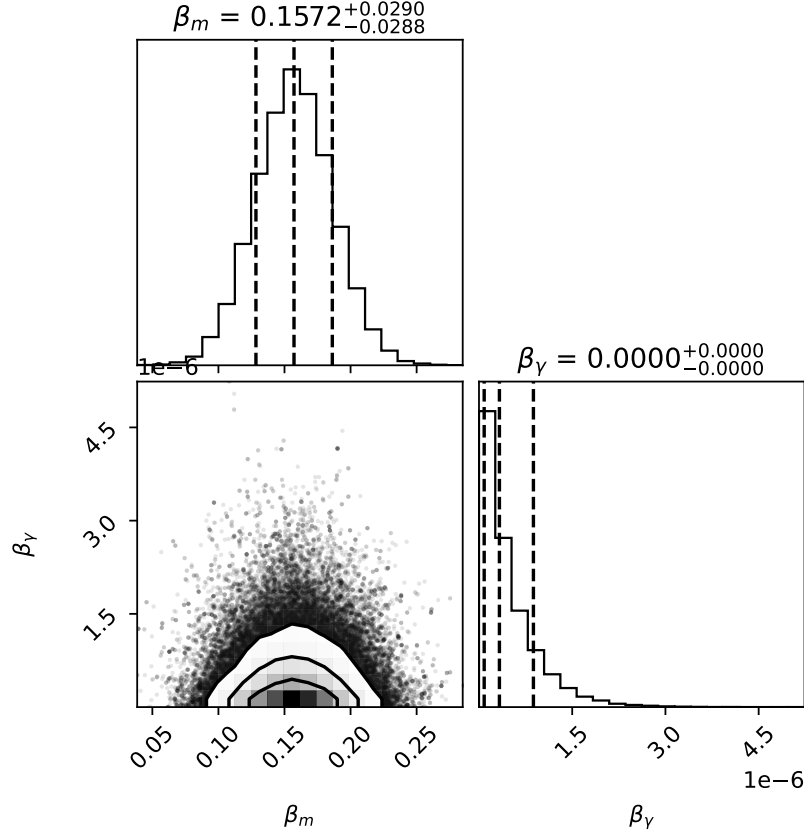


Figure 9: MCMC Parameter Constraints (Corner Plot). Joint posterior distribution from Bayesian analysis of BAO +  $H_0$  + CMB data. Top panels show 1D marginalized posteriors for  $\beta_m$  (left) and  $\beta_\gamma$  (right). Bottom panel shows 2D joint posterior with 68% and 95% confidence contours. MCMC results:  $\beta_m = 0.157^{+0.029}_{-0.029}$  (68% CL),  $\beta_\gamma < 1.4 \times 10^{-6}$  (95% CL),  $\beta_\gamma/\beta_m < 8.5 \times 10^{-6}$  (95% CL). Well-behaved Gaussian posterior for  $\beta_m$  with no parameter degeneracies confirms robustness of dual-sector framework.