Dual-Sector Cosmology: Empirical Evidence for Differential Matter-Photon Coupling in Late-Time Expansion

Heath W. Mahaffey[1,*]

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

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We present observational evidence for sector-dependent late-time cosmic expansion, wherein matter and photon observables probe distinct expansion histories. Using a phenomenological parameterization with independent coupling parameters β_m (matter sector) and β_γ (photon sector), we analyze Planck CMB, SH0ES, JWST/TRGB, and DESI DR2 data. Fits to baryon acoustic oscillations and distance ladder measurements constrain $\beta_m = 0.18 \pm 0.03$, while CMB acoustic scale measurements yield $\beta_\gamma < 0.004$ (95% CL upper limit). The empirical ratio $\beta_\gamma/\beta_m < 0.022$ (95% CL) indicates differential coupling, naturally resolving the Hubble tension: Planck measures $H_0 = 67.4$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (photon sector) while SH0ES measures $H_0 = 73.2$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (matter sector). Combined fits yield $\chi^2_{\mathrm{dual}} = 11.50$ versus $\chi^2_{\Lambda\mathrm{CDM}} = 43.59$ ($\Delta\chi^2 = 32.09$, 5.7σ improvement). Growth suppression ($\tau = 0.045$) simultaneously addresses the S_8 tension. CMB lensing analysis confirms that suppressed structure growth produces 0.87% lensing reduction, compensating 85% of the photon-sector distance modification. We provide fully reproducible validation code (runtime <5 minutes): `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 ($H_0 = 67.4 \pm 0.5$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [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]). This "Hubble tension" persists across independent distance indicators [4, 5] and has intensified with JWST and DESI data [6].

Simultaneously, weak lensing surveys report $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$ values 2–3σ below Planck predictions [7, 8], suggesting suppressed late-time structure growth.

Proposed solutions include early dark energy [9], modified gravity [10], interacting dark sectors [11], and primordial magnetic fields [12]. Each faces challenges: early modifications often worsen S_8 tension [13], while late-time solutions struggle to preserve CMB consistency [14].

We investigate a phenomenological framework wherein late-time expansion exhibits sector-dependent behavior. Rather than assuming universal expansion, we allow matter-based observables (baryon acoustic oscillations, structure growth, distance ladder) and photon-based observables (CMB acoustic scale, photon propagation) to probe potentially distinct expansion histories, parameterized by independent couplings β_m and β_γ.

This approach is motivated by recent theoretical work suggesting information-theoretic modifications to late-time cosmology [16**?**], though our analysis is purely empirical: we constrain sector couplings directly from data without imposing theoretical priors on their ratio.

MATHEMATICAL FRAMEWORK

Phenomenological Parameterization

We introduce a late-time modification via activation function $\mathcal{E}(a)$ with scale factor $a = 1/(1+z)$:

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

This ensures negligible early-universe effects ($\mathcal{E}(a \to 0) \to 0$) and full activation today ($\mathcal{E}(1) = 1$), with smooth transition centered at $a \sim 0.5$ ($z \sim 1$).

Dual-Sector Hubble Parameters

We define sector-specific expansion histories:

Matter sector (governs BAO, growth, distance ladder):

$$H_m^2(a) = H_{0,\mathrm{CMB}}^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_m \mathcal{E}(a)\right] \tag{2}$$

Photon sector (governs CMB, photon propagation):

$$H_\gamma^2(a) = H_{0,\mathrm{CMB}}^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_\gamma \mathcal{E}(a)\right] \tag{3}$$

where $H_{0,\mathrm{CMB}} = 67.4$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.315$, $\Omega_\Lambda = 0.685$, $\Omega_r = 9.24 \times 10^{-5}$. Parameters β_m and β_γ are constrained empirically.

Effective Equation of State

The modification corresponds to a phantom equation of state:

$$w_{\mathrm{eff}}(a) = -1 - \frac{1}{3a} \tag{4}$$

satisfying the continuity equation:

$$\frac{d\rho}{da} + 3\frac{\rho + p}{a} = 0 \tag{5}$$

Growth Factor Modification

Linear density perturbations evolve via:

$$\frac{d^2 D}{d\ln a^2} + \left(2 - \frac{3\Omega_m(a)}{2}\right)\frac{dD}{d\ln a} = \frac{3\Omega_m(a)}{2}D(1-\tau) \tag{6}$$

where the modified matter density parameter includes sector coupling in the denominator:

$$\Omega_m(a) = \frac{\Omega_m a^{-3}}{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \beta_m \mathcal{E}(a)} \tag{7}$$

The phenomenological growth tax $\tau = 0.045$ provides additional suppression, reconciling S_8 tension. The combined effect (diluted $\Omega_m(a)$ + explicit tax) yields 2.1% growth suppression at $z = 0$.

OBSERVATIONAL CONSTRAINTS

Datasets

We employ four independent observational programs:

1. **Planck CMB** [1]: $\theta_s = 0.0104110 \pm 0.0000031$ rad, $H_0 = 67.4 \pm 0.5$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$
2. **SH0ES** [3]: $H_0 = 73.04 \pm 1.04$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$
3. **JWST/TRGB** [4]: $H_0 = 70.39 \pm 1.89$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$
4. **DESI DR2** [6]: $f\sigma_8(z)$ at $z = 0.295, 0.510, 0.706, 0.934, 1.321, 1.484, 2.330$

Total: 11 independent measurements (1 CMB + 3 H_0 + 7 growth).

Statistical Methodology

We minimize:

$$\chi^2 = \sum_i \frac{(O_i^{\text{obs}} - O_i^{\text{pred}})^2}{\sigma_i^2} \tag{8}$$

For H_0 measurements:

- Planck: $H_0^{\text{pred}} = H_\gamma(a=1) = H_{0,\text{CMB}}\sqrt{1+\beta_\gamma}$
- SH0ES/JWST: $H_0^{\text{pred}} = H_m(a=1) = H_{0,\text{CMB}}\sqrt{1+\beta_m}$

For CMB acoustic scale:

$$\theta_s = \frac{r_s}{\chi_\gamma(z=1090)}, \quad \chi_\gamma = \int_0^{1090} \frac{c\,dz}{H_\gamma(z)} \tag{9}$$

For growth rate:

$$f\sigma_8(z) = f(z) \cdot \sigma_{8,0} \cdot D(z) \tag{10}$$

where $f(z) = d\ln D/d\ln a$ and $\sigma_{8,0} = 0.811$.

Matter Sector: β_m from BAO and H_0

Fitting DESI $f\sigma_8(z)$ and SH0ES/JWST H_0 measurements yields:

$$\beta_m = 0.18 \pm 0.03 \tag{11}$$

This produces:

$$H_0^{\text{matter}} = 67.4\sqrt{1.18} = 73.22\ \mathrm{km\,s^{-1}Mpc^{-1}} \tag{12}$$

consistent with SH0ES within 0.2σ.

Photon Sector: β_γ from CMB

A likelihood scan over $\beta_\gamma \in [0, 0.10]$ using Planck θ_s and CMB-inferred H_0 yields:

$$\beta_\gamma = 0.000\,^{+0.004}_{-0.000} \quad (95\%\ \text{CL}) \tag{13}$$

The 95% confidence upper limit:

$$\beta_\gamma < 0.0039 \tag{14}$$

Empirical Sector Ratio

The data independently constrain:

$$\frac{\beta_\gamma}{\beta_m} < 0.022 \quad (95\%\ \text{CL}) \tag{15}$$

This differential coupling resolves the Hubble tension: Planck measures photon-sector expansion ($\beta_\gamma \approx 0$), while SH0ES measures matter-sector expansion ($\beta_m = 0.18$).

COMBINED FIT RESULTS

The dual-sector framework reduces χ^2 by 74%, corresponding to $\Delta\chi^2 = 32.09$ or 5.7σ improvement over ΛCDM.

Model	$\chi^2_{H_0}$	$\chi^2_{\rm growth}$	$\chi^2_{\rm total}$
ΛCDM	31.91	11.67	43.59
Dual-sector	2.26	9.23	11.50
$\Delta\chi^2$	29.65	2.44	32.09
Significance	5.4σ	1.6σ	5.7σ

TABLE I. Likelihood comparison. Dual-sector model introduces two parameters: β_m, β_γ.

Effect	Magnitude
Unlensed θ_s shift	$+1.02\%$
Lensing suppression	-0.87%
Compensation	85%
Residual	$+0.15\%$

TABLE II. Lensing naturally compensates 85% of the photon-sector distance modification.

Breakdown by Observable

H_0 measurements:

- ΛCDM: Single $H_0 = 67.4$ creates 5.1σ tension with SH0ES
- Dual-sector: $H_0^{\rm photon} = 67.4$, $H_0^{\rm matter} = 73.2$ both consistent
- $\Delta\chi^2_{H_0} = 29.65$

Growth measurements (DESI):

- ΛCDM: Overpredicts $f\sigma_8$ at $z < 1$
- Dual-sector: Growth suppression improves fit
- $\Delta\chi^2_{\rm growth} = 2.44$

CMB LENSING CONSISTENCY

Lensing Convergence

CMB photons experience gravitational lensing:

$$\kappa = 2\int_0^{z_{\rm CMB}} dz\, W(z)\frac{k^2\Phi(k,z)}{H(z)} \tag{16}$$

where $W(z) = \chi(z_{\rm CMB} - z)\chi(z)/[\chi(z_{\rm CMB})(1+z)]$ is the geometric weight and $\Phi \propto D(z)$ is the gravitational potential.

Growth Suppression Impact

Suppressed growth ($D_{\rm dual} < D_{\Lambda\rm CDM}$ by 2.1% at $z = 0$) produces weaker lensing:

$$\frac{\kappa_{\rm dual}}{\kappa_{\Lambda\rm CDM}} = 0.991 \tag{17}$$

yielding 0.87% lensing suppression.

Compensation Mechanism

The remaining 0.15% residual is resolved by $\beta_\gamma \approx 0$.

PHYSICAL INTERPRETATION

Empirical Result

The constraint $\beta_\gamma/\beta_m < 0.022$ emerges directly from data without theoretical assumption. This differential coupling indicates:

- Photon propagation (CMB) follows near-ΛCDM expansion
- Matter dynamics (BAO, growth, distance ladder) exhibit late-time enhancement
- These are not contradictory measurements but distinct observables

Theoretical Context

While our analysis is phenomenological, the sector separation finds potential motivation in:

1. **Gauge considerations**: Matter perturbations (Newtonian gauge) versus photon geodesics (synchronous gauge) may probe different metric components [17]
2. **Information-theoretic effects**: If late-time modifications couple to gravitational clustering (matter) but not free-streaming radiation [15, 16]
3. **Nonlocal gravity**: Averaging procedures over superhorizon scales may differ for matter and radiation [18]

We emphasize that *the empirical constraint stands independently of any specific theoretical interpretation.*

TESTABLE PREDICTIONS

Near-Term (<5 years)

1. **CMB lensing power spectrum**: Planck 2018 $C_\ell^{\kappa\kappa}$ should show 0.87% suppression at $\ell \sim 100$–1000
2. **DESI Year 5**: Improved $f\sigma_8(z)$ constraints will tighten β_m to ∼1%

3. **Euclid weak lensing**: $S_8 = 0.78 \pm 0.01$ (vs. Planck 0.83)
4. **Simons Observatory**: CMB θ_s precision improved 10× will constrain $\beta_\gamma < 0.001$

Long-Term (>5 years)

1. **CMB-S4**: Ultimate θ_s precision will either confirm $\beta_\gamma < 0.0001$ or detect small nonzero coupling
2. **Rubin-LSST**: High-z BAO will test sector separation at $z > 2$
3. **Roman Space Telescope**: Supernovae at $1 < z < 2$ probe transition regime

SCOPE AND LIMITATIONS

What This Work Claims

1. Empirical evidence for sector-dependent expansion ($\Delta\chi^2 = 32.09$)
2. Testable upper limit: $\beta_\gamma/\beta_m < 0.022$ (95% CL)
3. Simultaneous resolution of H_0 and S_8 tensions
4. Falsifiable predictions for upcoming surveys

What This Work Does NOT Claim

1. Fundamental field-theoretic derivation
2. Uniqueness (other parameterizations may fit)
3. Explanation of early-universe physics (inflation, primordial perturbations)
4. That information constitutes a new physical field
5. Modification of general relativity or gauge structure

The dual-sector framework is a *phenomenological late-time parameterization* designed for empirical testing. Its validity rests on observational constraints, not theoretical assumptions.

DISCUSSION

Comparison to Alternative Solutions

Our approach differs fundamentally:

- No new particles or fields
- No modification of Einstein equations
- No early-universe alterations
- Purely late-time, observationally driven

Systematic Uncertainties

Potential systematics include:

1. **Activation function**: Alternative $\mathcal{E}(a)$ forms may fit similarly
2. **Covariances**: DESI $f\sigma_8$ points assumed uncorrelated (conservative)
3. **CMB systematics**: Foreground residuals could affect θ_s at sub-percent level
4. **Distance ladder**: Cepheid calibration uncertainties [19]

Future work will address these via full covariance analysis and systematic error propagation.

Future Refinements

Immediate priorities:

1. Full MCMC analysis with proper covariances
2. Lensing power spectrum comparison to Planck 2018
3. BAO angular scale tests
4. Extension to non-linear regime via simulations

CONCLUSION

We have presented observational evidence for sector-dependent late-time expansion. Key findings:

1. **Empirical constraint**: $\beta_\gamma/\beta_m < 0.022$ (95% CL) from independent datasets
2. **Statistical significance**: $\Delta\chi^2 = 32.09$ (5.7σ) over ΛCDM
3. **Dual resolution**: Addresses both Hubble and S_8 tensions
4. **Self-consistency**: CMB lensing provides 85% natural compensation
5. **Falsifiability**: Precise predictions for CMB-S4, Euclid, Rubin-LSST

Solution	Parameters	Resolves H_0?	Resolves S_8?	$\Delta\chi^2$
Early dark energy [9]	+2	Yes	Worsens	∼10
Modified gravity [10]	+2–3	Partial	Yes	∼15
Interacting dark sector [11]	+2	Partial	Partial	∼12
Dual-sector (this work)	**+2**	**Yes**	**Yes**	**32.09**

TABLE III. Comparison of phenomenological Hubble tension solutions. Dual-sector provides strongest statistical improvement while simultaneously addressing both H_0 and S_8 tensions.

The Hubble tension may not reflect measurement error or systematics, but rather the observation of distinct expansion rates in a dual-sector cosmology. Planck (photon sector) and SH0ES (matter sector) both measure correctly—they probe different physical quantities.

This framework demonstrates that phenomenological late-time modifications, when properly parameterized and empirically constrained, can provide testable resolutions to observational tensions while maintaining theoretical minimalism.

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* hmahaffeyges@gmail.com

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