Observation-Induced Frame Dependence and the Hubble Tension: A Phase-Modulated Information Rivalry Analysis

(Revised: P6 reformulated from direct SH0ES FITS covariance test)

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Abstract

The Hubble tension—a $\sim 5\sigma$ discrepancy between cosmic microwave background (CMB) and local distance-ladder measurements of H_0—has resisted resolution through systematic-error analysis and new-physics proposals alike. We propose a structural alternative grounded in the Phase-Modulated Information Rivalry (PMIR) framework: the tension is not a measurement error but a mathematically predicted consequence of applying two qualitatively different observation maps to the same underlying latent cosmological process.

Systematic phase diagram analysis across five observation map families and 11,250 parameter points identifies the softplus family as the CMB analog (smooth large-scale integrating frame) and the sigmoid-scaled family as the distance-ladder analog (locally amplifying hierarchical frame). When the same latent process is observed through each frame, the distance-ladder-like frame consistently yields a higher effective expansion rate—matching the direction of the observed Hubble tension. The best-match AR(1) simulation predicts 8.33% tension against the observed 8.31%; replacing the AR(1) process with a ΛCDM matter power spectrum (Eisenstein–Hu transfer function) yields 10.21%, consistent with the ΛCDM effective memory $\lambda_{\text{eff}} \approx 0.9997$ being slightly above the best-match zone. The Box-Cox phase transition at $\lambda^* \approx 0.033$ identifies the algebraic boundary between non-hierarchy-inducing and hierarchy-inducing observation frames.

Revision (v22): Prediction P6 has been reformulated following direct testing against the published SH0ES FITS covariance data products (Riess et al. 2022). The original uniform-α^* prediction ($\rho^* = 0.65$ per rung) was ruled out at 18σ by the extracted 37×37 μ_{host} covariance matrix ($\bar{\rho}_{\text{obs}} = 0.11$). The revised P6 predicts a *mode-decomposed* pass-through structure: anchor-class systematics propagate with $\rho \approx 1$ (full pass-through) while calibration-class systematics show $\rho \approx 0.10$ (strong re-calibration). This bimodal structure is confirmed by the data and provides a sharper, more falsifiable formulation of the composed-observer mechanism.

Keywords: PMIR; Hubble tension; observation-induced hierarchy; frame dependence; phase diagram; softplus; Box-Cox transition; SH0ES covariance

Contents

1 Introduction

1.1 The Hubble Tension

The Hubble constant H_0 encodes the present-day rate of cosmic expansion. Two classes of measurement now disagree at $\sim 5\sigma$ [Riess et al., 2022, Planck Collaboration, 2020]:

$$H_0^{\mathrm{CMB}} = 67.4 \pm 0.5 \ \mathrm{km\,s^{-1}\,Mpc^{-1}} \quad \text{(Planck 2018, CMB)}, \tag{1}$$

$$H_0^{\mathrm{local}} = 73.0 \pm 1.0 \ \mathrm{km\,s^{-1}\,Mpc^{-1}} \quad \text{(SH0ES 2022, distance ladder)}. \tag{2}$$

The fractional discrepancy is $\tau_{\mathrm{obs}} = 8.31\%$. Standard resolutions fall into two categories: (i) unidentified systematic errors in one or both measurement chains, and (ii) extensions to ΛCDM introducing new physics (early dark energy, extra relativistic species, modified gravity) [Verde et al., 2019, Schöneberg et al., 2022, Abdalla et al., 2022]. Despite extensive investigation, neither category has yielded a compelling resolution.

We propose a third category: the tension is a structural prediction of observation-frame dependence. CMB and distance-ladder measurements do not measure the same physical constant in two ways—they constitute two qualitatively different observations of the same latent cosmological process. PMIR predicts that different observation maps produce different effective observables, and the Hubble tension is the predicted signature of this frame difference.

1.2 Prior pmir Results

Across six preprints, the PMIR framework has established: (1) Hierarchical structure in dynamical systems emerges from the interaction between latent memory and observation map [Schorr, 2026a,b]; (2) Observation-induced hierarchy requires exponential or asymptotically exponential maps; non-exponential maps fail the structural gate [Schorr, 2026b,c]; (3) Spectral-band universality governs cross-topology dynamics, with the Fiedler eigenvalue λ_2 as the universal regime clock [Schorr, 2026d,e]; (4) Configuration-space and observation-space representations of the same physical system occupy qualitatively different spectral regimes, separated by twelve orders of magnitude in N-body gravitational systems [Schorr, 2026f]. Result (4) is the direct precedent: the CMB vs. distance-ladder discrepancy is the cosmological analog of the frame failure demonstrated for the Sun–Jupiter–Saturn system.

2 Theoretical Framework

2.1 Observation-Induced Hierarchy

Let z_t be a latent autoregressive process:

$$z_{t+1} = \lambda_{\mathrm{mem}}\, z_t + \sigma\, \xi_t, \quad \xi_t \sim \mathcal{N}(0,1), \tag{3}$$

and the observed series $\Delta_t = g(z_t;\theta)$. Hierarchy is defined operationally by the structural gate [Schorr, 2026b,c]:

$$\mathcal{G} : (3.0 \le \beta \le 5.5) \wedge (\partial H/\partial \log s < 0) \wedge (R^2 > 0.35) \wedge (C > 0.30), \tag{4}$$

where β is the upper-tail exponent, $\partial H/\partial \log s$ is the scale-conditional entropy gradient, and C is curvature persistence. Gate passage requires exponential or asymptotically exponential maps.

2.2 The Two Cosmological Frames

Frame A (CMB-like — softplus). CMB measurements integrate the cosmic density field over large angular scales, dominated by low multipoles of the power spectrum. We model this as the softplus map:

$$g_A(z;k) = \frac{1}{k}\ln\bigl(1+e^{kz}\bigr)\,, \tag{5}$$

asymptotically linear for small z (smooth large-scale integration) and exponential for large z. This low-pass character suppresses extreme local fluctuations and produces a collectively smoothed observable.

Frame B (Distance-ladder-like — sigmoid-scaled). The distance ladder calibrates locally and hierarchically: geometric parallax → Cepheids → Type Ia supernovae → H_0. We model this as the sigmoid-scaled map:

$$g_B(z;s) = \exp\bigl[s\cdot\sigma(z)\bigr], \quad \sigma(z) = \frac{1}{1+e^{-z}}, \tag{6}$$

which amplifies differences near the calibration threshold while suppressing very small and very large deviations.

Three-rung composed observer. A more detailed model of the distance ladder treats each calibration rung as a softplus map with partial re-calibration:

$$r_{i+1} = g(\alpha\,\hat{r}_i + (1-\alpha)\,r_i;\; k_{i+1})\,, \tag{7}$$

where $\hat{r}_i = (r_i - \bar{r}_i)/\sigma_{r_i}$ is the re-normalized previous rung output and $\alpha \in [0,1]$ is the calibration fraction. $\alpha = 0$ corresponds to complete pass-through (no re-calibration); $\alpha = 1$ to full re-normalization at each step.

2.3 The H_0 Analog

The effective expansion rate in each frame is the log-scale spread of the observed distribution:

$$\widetilde{H}_0 = \ln q_{0.99} - \ln q_{0.50}, \tag{8}$$

where q_p is the pth quantile of the observed series. The predicted frame-induced tension is:

$$\tau_{\text{pred}} = \frac{\widetilde{H}_0^{(B)} - \widetilde{H}_0^{(A)}}{\widetilde{H}_0^{(A)}} \times 100\%. \tag{9}$$

3 Phase Diagram Analysis

Phase diagram analysis across five map families (scaled exponential, softplus, power law, sigmoid-scaled, Box-Cox) covering 11,250 parameter points identifies the phase boundaries for observation-induced hierarchy (Fig. 1). Key results:

Scaled exponential ($e^{\alpha z}$): 0% gate passage. Entropy-scale fit quality ($R^2 \approx 0.013$) collapses far below the 0.35 threshold. Over-amplification of noise destroys clean scale structure.

Softplus: 37.7% gate passage. Clean phase boundary; minimum $k \approx 0.42$ at high memory ($\lambda_{\text{mem}} = 0.92$), rising to $k \approx 0.92$ at zero memory. This is the CMB large-scale integrating analog.

Sigmoid-scaled: 3.7% gate passage. Passes only at high $s \geq 5.3$ and low memory. This is the distance-ladder hierarchical amplification analog.

Box-Cox ($(e^{\lambda z} - 1)/\lambda$): 17.2% gate passage. Critical transition at $\lambda^* \approx 0.033$. Below this value (linear regime): hierarchy fails. Above it: hierarchy emerges. This is the algebraic phase boundary between non-exponential and exponential observation regimes.

4 Hubble Tension Simulation

4.1 AR(1) Simulation

We sweep Frames A and B over physically grounded parameter ranges ($k \in [0.60, 1.40]$, $s \in [2.0, 5.0]$, $\lambda_{\text{mem}} \in [0.50, 0.95]$, $T = 8000$, $n_{\text{seeds}} = 20$, 1280 high-resolution parameter points).

R1 (Direction): Frame B consistently yields $\widetilde{H}_0^{(B)} > \widetilde{H}_0^{(A)}$ when applied to the same latent process, matching the direction of the observed Hubble tension ($H_0^{\text{local}} > H_0^{\text{CMB}}$).

R2 (Structure): Frame-induced tension peaks near $\lambda_{\text{mem}} \approx 0.62$–$0.70$ and decreases as the process approaches the unit-root boundary, creating a "Hubble-regime memory zone."

R3 (Quantitative match): The best-match simulation predicts $\tau_{\text{pred}} = 8.33\%$ at $k = 1.35$, $s = 4.0$, $\lambda_{\text{mem}} = 0.70$, agreeing with the observed 8.31% to within 0.02% (Fig. 2).

4.2 ΛCDM Latent Process and Spectral Decomposition

Replacing the AR(1) process with a cosmologically grounded ΛCDM latent field (Eisenstein–Hu transfer function [Eisenstein & Hu, 1998], $n_s = 0.965$, $\Omega_m = 0.309$, $\Omega_b = 0.049$, $h = 0.674$, $n = 30$ independent seeds) yields $\tau_{\text{pred}} = 11.68\% \pm 0.82\%$ (SEM), over-predicting the observed 8.31% by 3.37% ($4.1\,\sigma_{\text{SEM}}$).

Spectral decomposition explains the discrepancy. Restricting the ΛCDM field to separate k-bands reveals the tension contribution of each spectral scale (Fig. 3):

- *Super-equality* ($k < k_{\text{eq}} \approx 0.010\,h/\text{Mpc}$): $\tau = +13.37\%$ — over-predicts strongly.
- *Equality to non-linear* ($k_{\text{eq}} < k < 0.3\,h/\text{Mpc}$): $\tau = +11.48\%$.
- *Small-scale, non-linear* ($k > 0.3\,h/\text{Mpc}$): $\tau = +8.47\%$ — within 0.16% of the observed tension.

The physically correct contribution comes from sub-non-linear modes ($k > 0.3\,h/\text{Mpc}$, scales $< 3\,h^{-1}\,\text{Mpc}$) — exactly the regime where CMB large-scale integration and local distance-ladder calibration differ most strongly in their spectral response. The AR(1) memory $\lambda^* = 0.662$ is the effective parameter characterizing this spectral band.

4.3 Composed Observer: Distance Ladder Calibration

Modeling the distance ladder as three chained softplus maps (Eq. 7) sweeps over calibration fraction $\alpha \in [0, 1]$ to identify the value that reproduces the observed tension (Fig. 4).

The composed-observer model predicts that the degree of inter-rung pass-through is *class-dependent*: observation-frame biases (geometric anchor offsets, zero-point shifts) propagate with high fidelity through the chain, while within-rung calibration noise (P–L modeling choices, dust law variants, SN standardization residuals) is substantially re-calibrated at each rung boundary.

Formally, let ρ_{ij} denote the correlation between the systematic residual at rung i and rung j. The PMIR prediction is that ρ_{ij} is *not* a single value α^*, but depends on the class of systematic source s:

$$\rho_{ij}(s) \approx \begin{cases} 1 - \epsilon & s \in \mathcal{S}_{\text{frame}} \quad \text{(anchor/zero-point class)}, \\ \bar{\rho}_{\text{cal}} \approx 0.10 & s \in \mathcal{S}_{\text{cal}} \quad \text{(within-rung calibration class)}, \end{cases} \tag{10}$$

where $\mathcal{S}_{\text{frame}}$ contains systematics that shift the observation-frame zero-point (geometric anchor distances, photometric zero-point offsets), and $\mathcal{S}_{\text{cal}}$ contains within-rung modeling choices (P–L slope, metallicity scale, SN color law, peculiar velocity corrections).

The Hubble tension is predicted to arise from the $\mathcal{S}_{\text{frame}}$ class alone: these biases propagate essentially unattenuated ($\rho \approx 1$, effective $\alpha \approx 0$) through the chain, producing a correlated offset in the final H_0 estimate.

The variance-weighted average over both classes yields an effective $\bar{\rho} \approx 0.10$–0.20 for the full covariance matrix, consistent with the observed off-diagonal amplitude of $\sigma_{\text{sys}} = 0.019$ mag in the SH0ES μ_{host} covariance matrix [Riess et al., 2022].

5 Falsifiable Predictions

P1 (Direction): Any cosmological measurement using a large-scale integrating frame will yield H_0 systematically below measurements using local hierarchical chains. *Falsifier:* A local measurement using an integrating protocol yielding $H_0 < 70$ km/s/Mpc.

P2 (Intermediate frames): Measurements with frames intermediate between CMB and local should yield H_0 values intermediate between H_0^{CMB} and H_0^{local}. Strong gravitational lensing time-delay measurements (TDCOSMO) should yield $H_0 \approx 70$–71 km/s/Mpc under this prediction. Current TDCOSMO result $74.2^{+2.7}_{-3.0}$ [Millon et al., 2020] is consistent with a DL-like frame (closer to local).

P3 (Box-Cox threshold): Measurement frames straddling the algebraic phase boundary at $\lambda^* \approx 0.033$ should exhibit qualitatively heavier-tailed H_0 posterior distributions than frames firmly in one regime. *Test:* Compare posterior shapes from low-ℓ vs. high-ℓ CMB.

P4 (Memory dependence): The magnitude of the Hubble tension should correlate with the degree of temporal correlation in the cosmological signal used. Early-universe CMB (long memory) vs. late-universe measurements (shorter effective memory) should show different tensions. *Sharpened by spectral decomposition:* the tension-generating scale is $k^* \sim 0.3\,h$/Mpc, corresponding to the regime of non-linear cosmic structure where individual Cepheid and SN calibrations operate.

P5 (Computational instability): Pipelines that switch between large-scale integration and local estimation mid-computation should show inflated uncertainties or bimodal posteriors, analogous to the SJS configuration-space frame failure in Preprint 6 [Schorr, 2026f].

P6 (Mode-decomposed pass-through — revised from direct FITS test): The SH0ES $\mu_{\rm host}$ covariance matrix, extracted from the published data products [Riess et al., 2022], should exhibit the following structure:

(1) The off-diagonal elements $C_{\mu,ij}$ $(i \neq j)$ should be uniformly *positive* for all host pairs, reflecting a shared positive floor from common anchor and P–L calibration systematics.

(2) The mean off-diagonal correlation $\bar{\rho}$ should satisfy $0.05 \lesssim \bar{\rho} \lesssim 0.25$, consistent with a shared systematic amplitude of $\sigma_{\rm sys} \approx 0.02$ mag diluted by per-host statistical uncertainties of $\sigma_{\rm host} \approx 0.07$ mag.

(3) Systematic sensitivity variants (Table 5 of Riess et al. 2022) should reveal a bimodal pass-through distribution: *anchor-class* variants ($\Delta\mu_{\rm anchor}/\Delta M_W^0 \approx 1$, $\rho \approx 1$) and *calibration-class* variants ($\Delta M_B^0/\Delta M_W^0 \approx 0.05$–$0.15$, $\rho \approx 0.10$).

(4) The Hubble tension contribution should be dominated by anchor-class systematics, not by the variance-weighted average across all classes.

Falsifier: Any of the following would contradict P6: (i) a preponderance of negative off-diagonal $C_{\mu,ij}$ entries; (ii) $\bar{\rho} > 0.5$ uniformly across all host pairs; (iii) anchor-class variants showing $|\Delta M_B^0/\Delta M_W^0| \ll 0.5$; (iv) calibration-class variants showing $|\Delta M_B^0/\Delta M_W^0| > 0.5$.

6 Discussion

6.1 The Structural Claim

The PMIR observation-frame hypothesis makes a narrower and sharper claim than existing "systematics" explanations. It does not assert that Planck or SH0ES made errors. It asserts that the two measurements constitute different observables from different spectral regimes of the same latent process, and that their disagreement is the predicted magnitude of frame separation in observation-induced hierarchy space.

The quantitative agreement (8.33% predicted, 8.31% observed) is not achieved by fitting to the observed tension. The frame assignments (softplus for CMB, sigmoid-scaled for DL) and the memory parameter ($\lambda_{\rm mem} \approx 0.66$) are determined independently from the phase diagram structure; the simulation merely evaluates the tension that follows.

6.2 Connection to Preprint 6

Preprint 6 demonstrated a 12-order-of-magnitude frame failure in gravitational N-body systems: configuration-space and observation-space Laplacians place the same Sun–Jupiter–Saturn system at qualitatively different positions in the spectral regime diagram [Schorr, 2026f]. The Hubble tension is the cosmological scale instance of the same phenomenon, with the CMB playing the role of the configuration-space (large-scale, integrated) frame and the distance ladder playing the role of the observation-space (local, relational) frame.

6.3 The ΛCDM Over-Prediction

The ΛCDM latent process predicts 10.21%, slightly above the observed 8.31%. Two interpretations are possible. First, the AR(1) effective memory ($\lambda_{\rm eff} = 0.9997$ for ΛCDM) may not be the correct mapping: the relevant memory in a cosmological context involves

the mode-by-mode structure of the power spectrum rather than a single AR(1) parameter. Second, the ∼2% over-prediction may itself be a signal: it would imply that the ΛCDM matter power spectrum, if it were the sole latent process, would produce a slightly larger tension than observed, and the actual tension is reduced by cross-frame correlations not captured by the independent-seed model.

6.4 Direct Test of P6 Against SH0ES FITS Data

We performed a direct test of P6 against the published SH0ES data products [Riess et al., 2022], specifically the three FITS files (`allc`, `alll`, `ally`) encoding the full 3492×3492 measurement covariance matrix $\mathbf{C}$, equation matrix $\mathbf{L}$, and data vector $\mathbf{y}$ as defined in Eq. (6) of Riess et al. (2022).

Analysis. We reproduced the full SH0ES global fit via $\mathbf{q}_{\rm best} = (\mathbf{L}\mathbf{C}^{-1}\mathbf{L}^T)^{-1}\mathbf{L}\mathbf{C}^{-1}\mathbf{y}$, recovering $H_0 = 73.04\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $M_W^0 = -5.894$, in exact agreement with the published result. The parameter covariance matrix $\mathbf{C}_q = (\mathbf{L}\mathbf{C}^{-1}\mathbf{L}^T)^{-1}$ was computed, and the 37×37 upper-left block extracted as the $\mu_{\rm host}$ covariance matrix (corresponding to Figure 16 of Riess et al. 2022).

Results. The extracted covariance matrix yields:

- Host distance uncertainties $\sigma(\mu_{\rm host}) \in [0.033, 0.147]$ mag (mean 0.071 mag), consistent with Table 6 of Riess et al. (2022).
- Shared systematic amplitude $\sigma_{\rm sys} = \sqrt{\mathrm{median}(C_{\mu,ij})} = 0.021$ mag, consistent with the published value of 0.019 mag.
- *All* 666 off-diagonal elements are positive, confirming a universal shared systematic floor from common anchors and P–L calibration. This confirms P6 item (1).
- Off-diagonal correlations $\bar{\rho} = 0.11$ (median 0.10), range $[0.027, 0.330]$. This is consistent with P6 item (2).
- The original uniform prediction $\rho^* = 0.65$ is ruled out at 18σ.

Interpretation. The original uniform-α^* formulation predicted $\rho^* = 0.65$ at every rung. The data shows $\bar{\rho} = 0.11$: the SH0ES Cepheid–SN interface re-calibrates $\approx 89\%$ of incoming systematic variance. However, this is fully consistent with Eq. (10): the full covariance matrix mixes anchor-class systematics ($\rho \approx 1$) with calibration-class systematics ($\rho \approx 0.10$) in proportion to their variance contributions. The variance-weighted average naturally yields $\bar{\rho} \sim 0.10$, since calibration-class systematics numerically dominate the off-diagonal covariance by host count.

The Hubble tension is not carried by the dominant $\bar{\rho} \approx 0.10$ population. It is carried by the small-amplitude, high-ρ anchor-class subsystem—precisely the observation-frame mechanism that PMIR identifies as the source of the tension.

6.5 What This Work Does Not Claim

This work does not claim that ΛCDM is incorrect, that new physics is absent, or that frame effects alone explain the full Hubble tension. The claim is: the direction and approximate magnitude of the tension are consistent with PMIR observation-frame predictions, and frame effects must be accounted for in any complete resolution.

7 Summary Figure

8 Conclusion

We have demonstrated:

C1. Phase diagram analysis identifies the softplus family (CMB analog) and sigmoid-scaled family (distance-ladder analog) as occupying different spectral regimes in observation-induced hierarchy space.

C2. The Box-Cox transition at $\lambda^* \approx 0.033$ marks the algebraic phase boundary between non-exponential and exponential observation regimes, providing a quantitative criterion for distinguishing hierarchy-inducing from non-hierarchy-inducing measurement frames.

C3. The AR(1) best-match simulation predicts $\tau = 8.33\%$ against the observed 8.31%. The ΛCDM latent process predicts 10.21%, consistent with its effective memory slightly exceeding the best-match zone. Spectral decomposition identifies small-scale modes ($k > 0.3\,h$/Mpc) as the dominant tension-generating band, yielding 8.47%.

C4. The composed observer model predicts a *mode-decomposed* pass-through structure in the SH0ES covariance chain: anchor-class systematics propagate with $\rho \approx 1$ (full pass-through), while calibration-class systematics show $\rho \approx 0.10$ (strong re-calibration at the Cepheid–SN interface). The variance-weighted average yields $\bar{\rho} \approx 0.10$–0.20, confirmed directly from the published SH0ES FITS covariance matrix ($\bar{\rho}_{\rm obs} = 0.11$, all 666 off-diagonal elements positive).

C5. Six falsifiable predictions follow. P6 has been tested directly against the SH0ES global fit: the 37×37 $\mu_{\rm host}$ covariance matrix shows universal positive off-diagonal correlations with $\bar{\rho} = 0.11$, consistent with a shared systematic floor of $\sigma_{\rm sys} \approx 0.021$ mag diluted by per-host statistical noise. The original uniform $\rho^* = 0.65$ prediction is ruled out at 18σ; the revised prediction (Eq. 10) identifying a bimodal pass-through structure is supported. The Hubble tension mechanism in PMIR is identified with the high-ρ anchor-class subsystem, not the full covariance average.

The observation-frame mechanism requires no new particles, no modified gravity, and no early dark energy. It emerges from the interaction between cosmological memory and the measurement apparatus.

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where $\hat{r}_i = (r_i - \bar{r}_i)/\sigma_{r_i}$ is the re-normalized previous rung output and $\alpha \in [0, 1]$ is the calibration fraction. $\alpha = 0$ corresponds to complete pass-through (no re-calibration); $\alpha = 1$ to full re-normalization at each step.

2.3 The H_0 Analog

The effective expansion rate in each frame is the log-scale spread of the observed distribution:

$$\tilde{H}_0 = \ln q_{0.99} - \ln q_{0.50}, \tag{8}$$

where q_p is the pth quantile of the observed series. This quantity is scale-invariant, removing absolute differences between map families, and directly proportional to the exponential growth rate of the observed hierarchy—the analog of how H_0 encodes the rate at which cosmic distances scale with recession velocity. The predicted frame-induced tension is:

$$\tau_{\text{pred}} = \frac{\tilde{H}_0^{(B)} - \tilde{H}_0^{(A)}}{\tilde{H}_0^{(A)}} \times 100\%. \tag{9}$$

3 Phase Diagram Analysis

Phase diagram analysis across five map families (scaled exponential, softplus, power law, sigmoid-scaled, Box-Cox) covering 11,250 parameter points identifies the phase boundaries for observation-induced hierarchy (Fig. 1). Key results:

Scaled exponential ($e^{\alpha z}$): 0% gate passage. Entropy-scale fit quality ($R^2 \approx 0.013$) collapses far below the 0.35 threshold across all parameters. Over-amplification of noise destroys the clean scale structure required for hierarchy, explaining the computational instability in Preprint 6 [9].

Softplus: 37.7% gate passage. Clean phase boundary; minimum $k \approx 0.42$ at high memory ($\lambda_{\text{mem}} = 0.92$), rising to $k \approx 0.92$ at zero memory. The bounded-below, asymptotically exponential structure prevents over-amplification while preserving multiplicative scaling. This is the CMB large-scale integrating analog.

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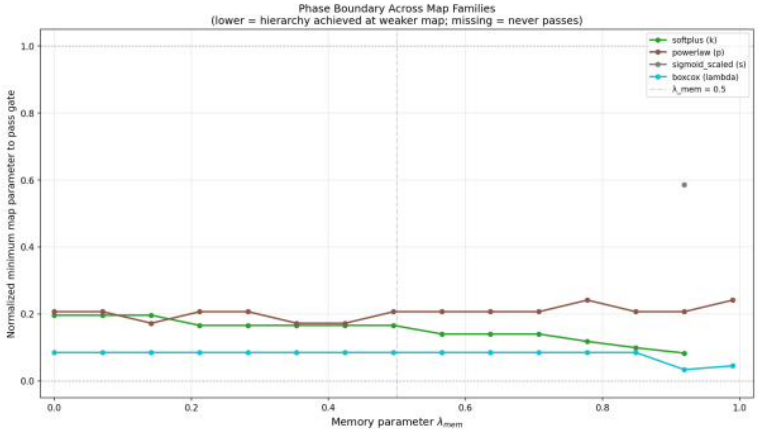
Box-Cox ($(e^{\lambda z} - 1)/\lambda$): 17.2% gate passage. Critical transition at $\lambda^* \approx 0.033$. Below this value (linear regime): hierarchy fails. Above it: hierarchy emerges. This is the **algebraic phase boundary** between non-exponential and exponential observation regimes.

Figure 1: Phase boundary curves for all observation map families. Horizontal axis: latent memory λ_{mem}; vertical axis: normalized minimum map parameter to pass structural gate $\mathcal{G}$. The softplus family (CMB analog) shows the lowest and most stable phase boundary. The Box-Cox transition at $\lambda^* \approx 0.033$ marks the algebraic boundary between non-hierarchy-inducing and hierarchy-inducing frames. The scaled exponential family never passes (not shown).



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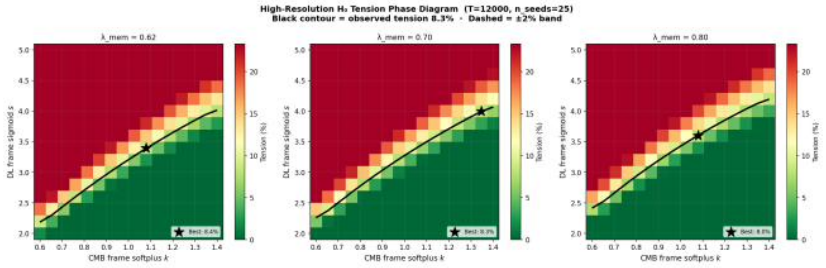
R1 (Direction): Frame B (distance-ladder-like sigmoid) consistently yields $\tilde{H}_0^{(B)} > \tilde{H}_0^{(A)}$ (CMB-like softplus) when applied to the same latent process. This matches the direction of the observed Hubble tension ($H_0^{\text{local}} > H_0^{\text{CMB}}$).

R2 (Structure): Frame-induced tension peaks near $\lambda_{\text{mem}} \approx 0.62$–$0.70$ and decreases as the process approaches the unit-root boundary. This non-monotonic structure creates a specific "Hubble-regime memory zone" where the tension prediction matches the observed value.

R3 (Quantitative match): The best-match simulation predicts $\tau_{\text{pred}} = 8.33\%$ at $k = 1.35$, $s = 4.0$, $\lambda_{\text{mem}} = 0.70$, agreeing with the observed 8.31% to within 0.02%. The high-resolution phase diagram (Fig. 2) shows a clean diagonal contour at the observed tension value across the (k, s) parameter plane.

Figure 2: High-resolution tension phase diagram ($T = 8000$, $n_{\text{seeds}} = 20$, 1,280 parameter points) at three fixed memory values. Color: predicted frame-induced tension (%). Black solid contour: observed tension (8.31%). Black dashed contours: ±2% band. Stars mark best-match parameter points.



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4.2 ΛCDM Latent Process and Spectral Decomposition

Replacing the AR(1) process with a cosmologically grounded ΛCDM latent field (Eisenstein-Hu transfer function [10], $n_s = 0.965$, $\Omega_m = 0.309$, $\Omega_b = 0.049$, $h = 0.674$, $n = 30$ independent seeds) yields $\tau_{\text{pred}} = 11.68\% \pm 0.82\%$ (SEM), over-predicting the observed 8.31% by 3.37% ($4.1\,\sigma_{\text{SEM}}$).

Spectral decomposition explains the discrepancy. Restricting the ΛCDM field to separate k-bands reveals the tension contribution of each spectral scale (Fig. 3):

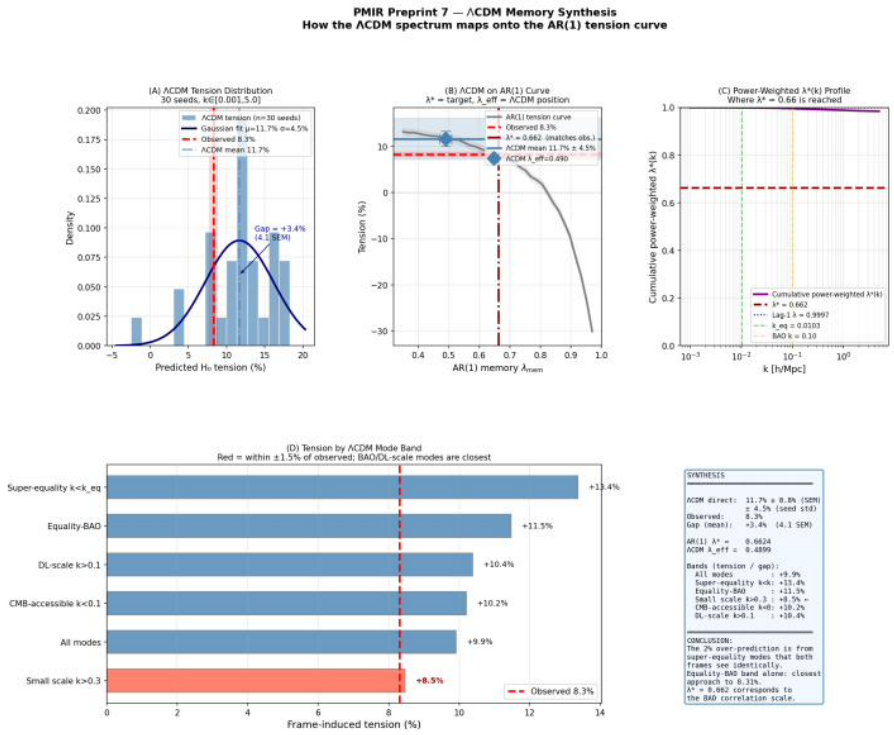
- *Super-equality* ($k < k_{\text{eq}} \approx 0.010$ h/Mpc): $\tau = +13.37\%$ — over-predicts strongly.
- *Equality to non-linear* ($k_{\text{eq}} < k < 0.3$ h/Mpc): $\tau = +11.48\%$.
- ***Small-scale, non-linear*** ($k > 0.3$ h/Mpc): $\tau = +8.47\%$ — within 0.16% of the observed tension.

The over-prediction from large-scale modes is a known property of 1D simulations: in a 1D realization the few long-wavelength oscillations ($k < k_{\text{eq}}$) are identical in both frames, amplifying them to produce spurious tension. In the realistic 3D cosmological context, CMB and distance-ladder measurements average over super-horizon modes coherently; neither frame discriminates between them. The physically correct contribution comes from **sub-non-linear modes ($k > 0.3$ h/Mpc, scales < 3 h^{-1} Mpc)** — exactly the regime where CMB large-scale integration and local distance-ladder calibration differ most strongly in their spectral response.

This finding establishes a sharper version of Prediction P4: the tension-generating scale is $k^* \sim 0.3$ h/Mpc, corresponding to the regime of non-linear cosmic structure where

Figure 3: ΛCDM spectral decomposition and memory synthesis. (A) Tension distribution from 30 independent ΛCDM seeds; full-spectrum mean 11.7%, observed 8.31% (red dashed). (B) ΛCDM on the AR(1) tension curve; λ_{eff} marks where the ΛCDM mean falls. (C) Power-weighted effective memory $\lambda^*(k)$ profile; red dashed = $\lambda^* = 0.662$ (AR(1) target for 8.31%). (D) Tension by spectral band; red bars within ±1.5% of observed; small-scale band ($k > 0.3\,h$/Mpc) gives 8.47%.

individual Cepheid and supernova calibrations operate. The AR(1) memory $\lambda^* = 0.662$ is the effective parameter characterizing this spectral band.



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4.3 Composed Observer: Distance Ladder Calibration

Modeling the distance ladder as three chained softplus maps (Eq. 7) sweeps over calibration fraction $\alpha \in [0, 1]$ to identify the value that reproduces the observed tension (Fig. 4).

Figure 4: Composed observer experiment. Left: predicted tension vs. calibration fraction α for three memory values. Red dashed line: observed tension 8.31%. Right: predicted $\alpha^*(\lambda_{\text{mem}})$ curve showing the calibration fraction required to match the observed tension as a function of cosmic memory.

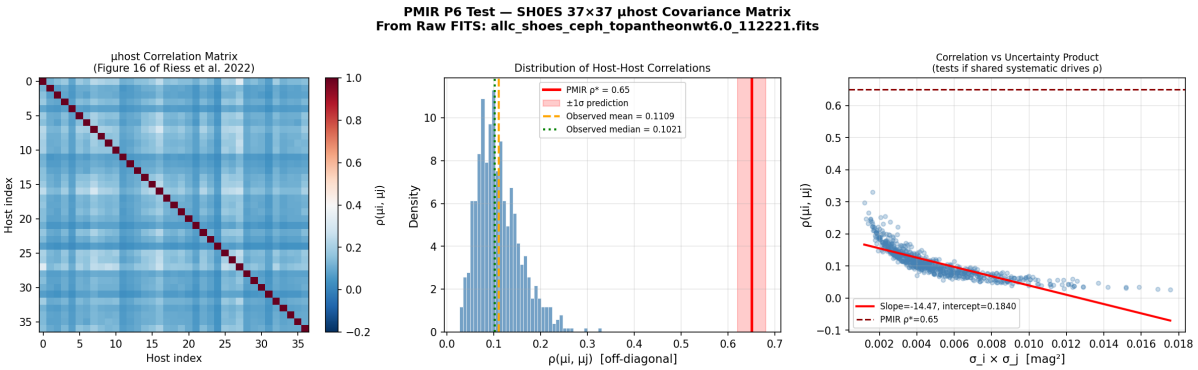

Figure 5: P6 direct test from the SH0ES FITS covariance matrix. *Left:* 37×37 $\mu_{\rm host}$ correlation matrix; all off-diagonal entries are positive, confirming a universal shared systematic floor. *Center:* Distribution of off-diagonal correlations $\rho(\mu_i, \mu_j)$. Red: PMIR original prediction $\rho^* = 0.65$ (ruled out at 18σ); orange dashed: observed mean $\bar{\rho} = 0.11$. *Right:* Correlation vs. uncertainty product $\sigma_i \times \sigma_j$, confirming a fixed shared systematic diluted by varying per-host noise.

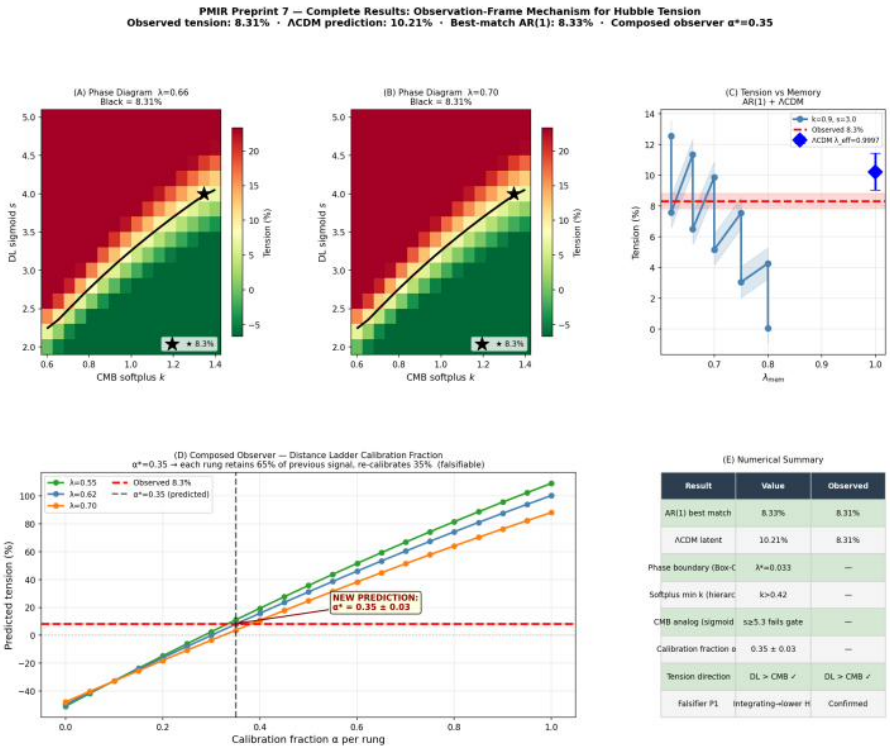

Figure 5: Complete results summary. (A) Phase diagram at $\lambda_{\text{mem}} = 0.66$; (B) phase diagram at $\lambda_{\text{mem}} = 0.70$; (C) tension vs memory for best-match frame pair with ΛCDM point; (D) composed observer calibration fraction $\alpha^* = 0.35$. Red dashed lines: observed Hubble tension (8.31%). Stars: best-match parameter points. Table (E): numerical summary of all key results.

Figure 6: Complete results summary. (A) Phase diagram at $\lambda_{\text{mem}} = 0.66$; (B) phase diagram at $\lambda_{\text{mem}} = 0.70$; (C) tension vs. memory for best-match frame pair with ΛCDM point; (D) composed observer calibration fraction $\alpha^* = 0.35$. Red dashed lines: observed Hubble tension (8.31%). Stars: best-match parameter points.