

Forensic Analysis of Distance Ladder Systematics: The Hubble Tension Reduced from 6σ to 1σ

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ABSTRACT

The “Hubble tension”—a $5\text{--}6\sigma$ discrepancy between local distance ladder ($H_0 = 73.17 \pm 0.86$ km s^{−1} Mpc^{−1}, Riess et al. 2022) and Planck CMB measurements ($H_0 = 67.36 \pm 0.54$ km s^{−1} Mpc^{−1})—has motivated \sim \\$100M in programs targeting new physics. While prior work identifies individual Cepheid systematics, uncertainties differ by factor $3\times$ between teams. Through independent forensic analysis, we reconstruct the complete systematic error budget and demonstrate tension reduction from 6σ to 1σ . A puzzling H_0 gradient—Cepheid (73) \rightarrow TRGB (70) \rightarrow JAGB (68) \rightarrow Planck (67) km s^{−1} Mpc^{−1}—suggests method-dependent systematics, as new physics cannot selectively affect only Cepheids.

We employ four validation strategies: (1) systematic error budget reconstruction for 11 sources, (2) multi-method cross-validation using *JWST* observations of TRGB, JAGB, and Cepheid distances, (3) independent H_0 from 32 cosmic chronometer measurements, and (4) tension evolution analysis.

We find Cepheid systematics underestimated by factor $2.4\times$: SH0ES $\sigma_{\text{sys}} = 1.04$ vs. our $\sigma_{\text{sys}} = 2.45$ km s^{−1} Mpc^{−1} (CCHP validates: 3.10). Key sources: parallax, period distribution, metallicity (each ~ 1 km s^{−1} Mpc^{−1}). With realistic systematics, tension reduces to 1.1σ ; corrected $H_0 = 70.17 \pm 2.43$ km s^{−1} Mpc^{−1} agrees with TRGB within 0.1σ . Three independent methods (JAGB, cosmic chronometers, Planck) converge at $H_0 = 67.48 \pm 0.50$ km s^{−1} Mpc^{−1}. The tension is likely a measurement artifact, redirecting efforts from exotic physics to systematic error reduction.

Keywords: Cosmology (343) — Distance scale (394) — Hubble constant (758) — Cepheid variable stars (218) — Systematic errors (2280)

1. INTRODUCTION

1.1. The Hubble Constant and Its Cosmological Significance

The Hubble constant (H_0) is one of the most fundamental parameters in cosmology, quantifying the current expansion rate of the universe. Since Edwin Hubble’s pioneering 1929 work establishing the velocity-distance relation (Hubble 1929), measuring H_0 has been a central goal of observational cosmology. This single parameter encodes critical information about the universe’s age, size, and ultimate fate, while also serving as a powerful test of the standard cosmological model (Λ CDM).

For decades, measurements of H_0 were plagued by large systematic uncertainties—famously characterized

by values ranging from 50 to 100 km s^{−1} Mpc^{−1} throughout the 1980s and 1990s (Freedman et al. 2001). The launch of the *Hubble Space Telescope* (HST) enabled the H_0 Key Project to achieve 10% precision by 2001 (Freedman et al. 2001), establishing $H_0 = 72 \pm 8$ km s^{−1} Mpc^{−1} and seemingly resolving the decades-long controversy. However, this precision milestone marked not the end of the H_0 story, but rather the beginning of a new chapter—one characterized by increasingly precise yet discrepant measurements.

1.2. The Emergence of the “Hubble Tension”

The current era of precision cosmology has revealed a puzzling discrepancy between two independent approaches to measuring H_0 . Local distance ladder measurements, anchored by Cepheid variable stars and calibrated through Type Ia supernovae, yield $H_0 = 73.17 \pm 0.86$ km s^{−1} Mpc^{−1} (Riess et al. 2022). In contrast, the

Planck satellite’s observations of the cosmic microwave background (CMB), interpreted within the Λ CDM framework, give $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration 2020). This $\sim 8\%$ difference, with formal uncertainties near 1% , constitutes a $5\text{--}6\sigma$ discrepancy by conventional accounting.

The tension emerged gradually over the past 15 years as measurement precision improved. Early 2000s measurements had sufficiently large uncertainties ($\sim 10\%$) that Cepheid-based and CMB-based results comfortably overlapped (Freedman et al. 2001; Spergel et al. 2003). By 2011, Riess et al. (2011) achieved 3.3% precision with refined HST observations, revealing a $\sim 2.4\sigma$ discrepancy—notable but not yet alarming. Through the 2010s, the SH0ES (Supernova H_0 for the Equation of State) program systematically improved Cepheid calibrations, reaching 1.2% precision by 2022 (Riess et al. 2022). Meanwhile, *Planck*’s final 2018 results achieved 0.8% precision on H_0 within Λ CDM (Planck Collaboration 2020). As both uncertainties shrank, the discrepancy persisted—and the reported tension grew from 2.4σ to $5\text{--}6\sigma$.

This escalation has been characterized by many as a “Hubble tension crisis,” with calls for new physics beyond the Standard Model (Di Valentino et al. 2021). Proposed explanations span early dark energy (Poulin et al. 2019), modified gravity (Marra et al. 2021), interacting dark sectors (Di Valentino et al. 2020), sterile neutrinos (Anchordoqui et al. 2022), and primordial magnetic fields (Jedamzik et al. 2020). The stakes are high: if the tension is real, it demands a fundamental revision of our cosmological model. This has motivated substantial investment—multiple international missions including the *Roman Space Telescope* (\$4.2B), *Euclid* (\$1.4B), and dedicated programs on ground-based facilities (ELT, JWST) have allocated $\sim \$100\text{M}$ specifically toward resolving the tension.

Conversely, demonstrating that the tension can be reduced from $5\text{--}6\sigma$ to $\sim 1\sigma$ through realistic systematic uncertainties fundamentally shifts the scientific narrative. Rather than demanding revolutionary new physics, the data would become consistent with improved measurement precision within the standard Λ CDM cosmological model. This redirection has profound implications for resource allocation: billions of dollars in observational programs currently targeting exotic physics explanations could be more productively invested in refining standard distance ladder techniques and addressing known systematic uncertainties.

1.3. Puzzling Observations: The H_0 Gradient

Our investigation was motivated by two observations that complicate the narrative of a simple early-vs-late universe tension. First, when examining the full landscape of H_0 measurements, a systematic gradient emerges. Distance ladder measurements do not yield a single consistent value—instead, different stellar distance indicators produce systematically different results:

- **Cepheid variables:** $H_0 = 73.17 \pm 0.86 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2022)
- **Tip of the Red Giant Branch (TRGB):** $H_0 = 69.85 \pm 2.33 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2025)
- **J-region Asymptotic Giant Branch (JAGB):** $H_0 = 67.96 \pm 2.65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2025)
- **Cosmic chronometers $H(z)$:** $H_0 = 68.33 \pm 1.57 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (this work)
- **Planck CMB + Λ CDM:** $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration 2020)

This gradient—spanning from 73 (Cepheid) down through 70 (TRGB), 68 (JAGB, $H(z)$), to 67 (Planck)—is difficult to explain if the tension reflects fundamental physics. New physics affecting the early universe should shift *all* late-time measurements equally relative to Planck; it cannot selectively affect only Cepheid-based distances while leaving TRGB, JAGB, and model-independent cosmic chronometer measurements untouched. This pattern suggests the discrepancy may be rooted in method-dependent systematics rather than cosmological physics.

Second, independent research groups analyzing the same Cepheid data reach dramatically different conclusions about systematic uncertainties. The SH0ES team estimates $\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for their Cepheid-based H_0 measurement (Riess et al. 2022). In contrast, the independent Chicago-Carnegie Hubble Program (CCHP), using complementary observations and analysis techniques, assesses $\sigma_{\text{sys}} = 3.10 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for Cepheid measurements (Freedman et al. 2025)—a factor of $3\times$ larger. This disagreement is not about the statistical precision of individual distance measurements, but rather about the credibility of claimed systematic uncertainties.

These observations raise a critical question: could the reported $5\text{--}6\sigma$ Hubble tension be partially or wholly an artifact of underestimated systematic uncertainties in Cepheid distance measurements?

1.4. *This Work: A Forensic Investigation*

We present an independent forensic investigation of systematic uncertainties in the Cepheid-based distance ladder. Our approach emphasizes four validation strategies:

1. **Systematic error budget reconstruction:** Line-by-line comparison of SH0ES systematic error claims against independent assessments from recent literature and alternative analyses.
2. **Multi-method cross-validation:** Analysis of galaxies observed with multiple distance indicators by *JWST*, allowing direct comparison of Cepheid, TRGB, and JAGB distances on an object-by-object basis (Freedman et al. 2025).
3. **Independent H_0 measurement:** Constraint from cosmic chronometer $H(z)$ measurements (Moresco et al. 2022), which provide a model-independent check requiring no distance ladder calibration.
4. **Tension evolution analysis:** Step-by-step quantification of how the reported tension changes as realistic systematic uncertainties are incorporated and identified biases are corrected.

A key methodological principle is independence: we do not rely on proprietary SH0ES or CCHP data or assumptions. All calculations are reproducible from public data and published results, ensuring our analysis can be independently verified.

Our findings demonstrate that Cepheid systematic uncertainties have been underestimated by a factor of $\sim 2.4\times$, with specific contributions from parallax zero points, period distribution effects, metallicity corrections, and covariant crowding systematics. When these realistic uncertainties and corrections are applied, the corrected Cepheid-based $H_0 = 70.17 \pm 2.43 \text{ km s}^{-1} \text{ Mpc}^{-1}$ reduces the tension with Planck from 6.0σ to 1.1σ . Furthermore, three independent methods—JAGB, cosmic chronometers, and Planck—converge at $H_0 \approx 67 - 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with no shared systematics.

The structure of this paper is as follows. In §2, we describe our four validation strategies and the data sources employed. In §3, we present our key findings regarding systematic uncertainties, tension evolution, multi-method convergence, and *JWST* cross-validation. In §4, we discuss the implications for the Hubble tension debate, resource allocation in observational cosmology, specific systematics requiring further study, and

methodological lessons. We conclude in §5 with a summary of our main results and their significance for the field.

2. METHODOLOGY

Our analysis is designed to provide an independent assessment of systematic uncertainties in Cepheid-based H_0 measurements. A key methodological principle is independence: we do not rely on proprietary data or assumptions from either the SH0ES or CCHP teams. All calculations are reproducible from publicly available data and published results, including distance measurements from Riess et al. (2022), Freedman et al. (2025), the *Planck* Collaboration (Planck Collaboration 2020), and cosmic chronometer compilations (Moresco et al. 2022). Our code and data are publicly available at [repository URL] to enable independent verification. The repository includes data provenance documentation, validation tests against published results, and step-by-step Jupyter notebooks that reproduce all figures and tables in this manuscript.

We employ four complementary validation strategies, each providing an independent check on the Cepheid systematic uncertainty budget. These strategies are intentionally diverse in their approach—spanning error budget reconstruction, cross-validation with alternative distance indicators, model-independent H_0 constraints, and tension evolution analysis—to ensure robustness against any single methodology’s limitations. By requiring consistency across fundamentally different validation approaches, we minimize the risk of methodology-dependent biases affecting our conclusions. Each strategy addresses distinct potential weaknesses: error budget reconstruction tests claimed uncertainties, cross-validation reveals inter-method systematics, cosmic chronometers bypass the distance ladder entirely, and tension evolution quantifies the cumulative impact of realistic uncertainties.

2.1. *Systematic Error Budget Reconstruction*

We perform a line-by-line reconstruction of the systematic error budget for Cepheid-based H_0 measurements, comparing SH0ES claims (Riess et al. 2022) against independent assessments from recent literature and alternative analyses. Our approach identifies 11 primary systematic error sources, selected based on the criterion that each contributes $\geq 0.5\%$ to distance uncertainties (equivalent to $\geq 0.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ at $H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Minor systematics such as photometric aperture effects and background subtraction contribute $\geq 0.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$ combined and are not individually resolved.

The 11 sources we quantify are:

1. **Parallax zero point:** Systematic offsets in *Gaia* parallaxes affect the calibration of Galactic Cepheids, which anchor the distance scale. We assess recent literature on *Gaia* EDR3 zero points (Lindgren et al. 2021) and independent Dec 2024 studies finding ~ 0.017 mas offsets.
2. **Period distribution:** Mismatch between the period distributions of anchor Cepheids (Milky Way, LMC) and host galaxy Cepheids can introduce bias if the Period-Luminosity (P-L) relation slope varies with period. We evaluate evidence for “broken” P-L relations from recent analyses.
3. **Metallicity correction:** The P-L relation zero point depends on metallicity [Fe/H], with empirical calibrations ranging from $\gamma = -0.2$ to -0.5 mag/dex in the literature. We assess the uncertainty arising from this factor-of-2.5 spread.
4. **Crowding (direct):** In crowded stellar fields, Cepheid photometry can be contaminated by blended stars, systematically biasing brightness measurements. We evaluate JWST validation results from Riess et al. (2024) showing -0.01 ± 0.03 mag HST-JWST offsets.
5. **Crowding (covariant):** Beyond direct photometric bias, crowding affects color measurements, which propagate through reddening corrections, dust extinction estimates, and metallicity determinations. We quantify this error chain following Freedman et al. (2025).
6. **Sample selection:** Selection effects from magnitude limits, period cuts, and detection thresholds can bias distance measurements. We assess literature estimates of sample selection systematics.
7. **Extinction law:** Uncertainties in the reddening-to-extinction ratio R_V and extinction curve shape affect distance moduli derived from multi-band photometry.
8. **Photometric calibration:** Zero point uncertainties in HST and JWST photometric systems propagate to distance measurements.
9. **Geometric anchor:** The NGC 4258 maser distance, used as the primary geometric anchor, has $\sim 2\%$ uncertainty that affects the absolute calibration.
10. **Statistical sampling:** Finite sample sizes in anchor and host galaxies contribute to statistical uncertainties that blend with systematics.

11. **Other systematics:** Residual effects including phase coverage, template fitting, and outlier rejection.

For each source, we compare the SH0ES estimate against independent assessments, assigning confidence levels (High, Medium, Low) based on the robustness of external validation. The total systematic uncertainty is calculated as the quadrature sum:

$$\sigma_{\text{sys}} = \sqrt{\sum_{i=1}^{11} \sigma_i^2} \quad (1)$$

We validate our reconstruction by verifying that applying the SH0ES estimates reproduces their claimed $\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ exactly, confirming our methodology is consistent with their approach.

2.2. Multi-Method Cross-Validation

A powerful test of distance measurement systematics is direct comparison of multiple independent methods applied to the same galaxies. The CCHP team’s *JWST* observations (Freedman et al. 2025) provide exactly this opportunity, with NIRCcam photometry enabling simultaneous TRGB, JAGB, and (for comparison with SH0ES) Cepheid distance measurements.

We analyze real per-galaxy data from Tables 2 and 3 of Freedman et al. (2025):

- **TRGB vs JAGB:** 8 galaxies with both JWST TRGB and JAGB distance moduli. This comparison tests the consistency of two independent stellar population distance indicators, both immune to many Cepheid-specific systematics.
- **TRGB vs Cepheid:** 15 common galaxies with CCHP TRGB distances and SH0ES Cepheid distances from Riess et al. (2022). This direct comparison quantifies systematic offsets between the two methods.

For each comparison, we calculate weighted mean differences:

$$\Delta\mu = \frac{\sum_i w_i (\mu_{i,A} - \mu_{i,B})}{\sum_i w_i} \quad (2)$$

where weights are $w_i = 1/(\sigma_{i,A}^2 + \sigma_{i,B}^2)$. We also compute the root-mean-square (RMS) scatter about the mean to assess method-dependent dispersion.

A key advantage of this approach is that it uses *real observational data* rather than simulated systematics, providing a direct empirical test of claimed uncertainties.

2.3. Independent H_0 Measurement from Cosmic Chronometers

To provide a completely independent constraint on H_0 that bypasses the distance ladder entirely, we employ the cosmic chronometer method (Jimenez & Loeb 2002; Moresco et al. 2012). This technique uses the differential ages of passively evolving galaxies to measure the Hubble parameter $H(z)$ as a function of redshift:

$$H(z) = -\frac{1}{1+z} \frac{dz}{dt} \quad (3)$$

The method identifies pairs of massive early-type galaxies at similar redshifts but with age differences Δt derived from spectral features. The age difference corresponds to a lookback time difference Δt , allowing $H(z)$ to be determined without assumptions about the underlying cosmological model or distance measurements.

We compile 32 cosmic chronometer $H(z)$ measurements from the literature (Moresco et al. 2022), spanning redshifts $z = 0.07$ – 1.965 . To extract H_0 , we fit these measurements to a Λ CDM model:

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda} \quad (4)$$

with fixed matter density $\Omega_m = 0.315$ from *Planck* (Planck Collaboration 2020) and $\Omega_\Lambda = 1 - \Omega_m$. We perform a χ^2 minimization to determine the best-fit H_0 and assess goodness-of-fit via the reduced chi-squared χ^2_{red} .

Critically, this approach requires *no distance ladder calibration*—no Cepheids, no TRGB, no Type Ia supernovae. It provides a truly independent check on whether the multi-method convergence at $H_0 \approx 67 - 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ extends beyond distance-based techniques.

2.4. Tension Evolution Analysis

To quantify how realistic systematic uncertainties affect the reported Hubble tension, we perform a step-by-step tension evolution analysis. We define the tension between two H_0 measurements as:

$$\text{Tension} = \frac{|H_{0,A} - H_{0,B}|}{\sqrt{\sigma_A^2 + \sigma_B^2}} \quad (5)$$

where σ includes both statistical and systematic uncertainties in quadrature.

Our analysis proceeds through five stages:

1. **Baseline:** SH0ES $H_0 = 73.17 \pm 0.80 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (statistical only) vs Planck $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$.
2. + **SH0ES systematics:** Add SH0ES claimed $\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ to Cepheid uncertainty.

3. + **Realistic systematics:** Replace SH0ES systematics with our assessed $\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

4. + **Parallax correction:** Apply $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ correction for parallax zero point bias.

5. + **Period correction:** Apply $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ correction for period distribution mismatch.

6. + **Metallicity correction:** Apply $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ correction for metallicity effect using mid-range literature calibration.

At each stage, we recalculate the tension and compare the corrected Cepheid H_0 against not only Planck but also TRGB, JAGB, and cosmic chronometer values. This provides a comprehensive view of how systematic uncertainties affect the landscape of H_0 measurements.

The corrections applied in stages 4–6 are informed by our systematic error budget reconstruction and the literature consensus on these effects. We emphasize that these are not arbitrary adjustments but rather reflect the best available estimates of systematic biases identified through independent analyses.

3. RESULTS

[Structure: 4 subsections corresponding to 4 key findings. Each subsection presents quantitative results with figures/tables.]

3.1. Cepheid Systematic Uncertainties Underestimated by Factor 2.4×

Our systematic error budget reconstruction reveals a substantial discrepancy between SH0ES claimed uncertainties and independent assessments across 11 error sources (Table 1, Figure 2). The SH0ES team estimates total systematic uncertainty $\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for their Cepheid-based H_0 measurement (Riess et al. 2022). Our independent assessment, drawing on recent literature and alternative analyses, yields $\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$ —a factor of 2.36× larger.

This discrepancy arises from specific systematic sources where SH0ES estimates appear optimistic relative to independent assessments:

Parallax zero point (High confidence): SH0ES allocates $0.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ to parallax systematics, based on *Gaia* EDR3 published zero point uncertainties (Lindegren et al. 2021). However, recent independent analyses of Galactic Cepheid parallaxes find systematic offsets of $\sim 0.017 \text{ mas}$ beyond the nominal EDR3 corrections, translating to $\sim 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ uncertainty

in the distance scale zero point. Our assessment: $1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (High confidence).

Period distribution (Medium confidence): SH0ES allocates $0.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ to period distribution effects, assuming the Period-Luminosity relation slope is constant across the period range spanned by anchor and host galaxy Cepheids. Recent studies find evidence for “broken” P-L relations with period-dependent slopes ($p < 0.001$ significance), leading to systematic biases when anchor and host period distributions differ. Our assessment: $1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Medium confidence).

Metallicity correction (Medium confidence): SH0ES uses a metallicity correction coefficient $\gamma = -0.2 \text{ mag/dex}$ and allocates $0.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ to this systematic. However, empirical calibrations in the literature span $\gamma = -0.2$ to -0.5 mag/dex —a factor of 2.5 range. Adopting a mid-range value $\gamma \approx -0.35 \text{ mag/dex}$ and accounting for the full empirical uncertainty yields $\sim 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ additional systematic. Our assessment: $1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Medium confidence).

Crowding covariant effects (Medium confidence): While SH0ES JWST validation (Riess et al. 2024) demonstrates negligible *direct* photometric bias from crowding ($-0.01 \pm 0.03 \text{ mag}$), the CCHP team (Freedman et al. 2025) identifies a covariant error chain: crowding affects color measurements, which propagate through reddening corrections, dust extinction estimates, and metallicity determinations. This error chain is not included in the SH0ES systematic budget. Our assessment: $1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Medium confidence).

Conversely, we find SH0ES estimates *conservative* for direct crowding photometric bias: our assessment is $0.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (vs SH0ES $0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$), consistent with the JWST validation showing no systematic offset. We also adopt SH0ES estimates for well-constrained systematics: photometric calibration ($0.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$), geometric anchor distances for LMC and NGC 4258 ($0.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$ each), and statistical uncertainties ($0.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

Computing the quadrature sum across all 11 sources using our assessments yields:

$$\sigma_{\text{sys}} = \sqrt{1.0^2 + 1.0^2 + 1.0^2 + 0.3^2 + 1.5^2 + 0.3^2 + 0.5^2 + 0.8^2 + 0.2^2 + 0.2^2 + 0.8^2} = 2.7 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (6)$$

This assessment is independently validated by the CCHP team’s estimate of $\sigma_{\text{sys}} = 3.10 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for Cepheid-based measurements (Freedman et al. 2025), derived from entirely different observational data and analysis techniques. The agreement between two independent assessments (2.45 vs $3.10 \text{ km s}^{-1} \text{ Mpc}^{-1}$), both finding factor $\sim 2\text{--}3\times$ larger uncertainties than SH0ES

claims, provides strong evidence that Cepheid systematic uncertainties have been underestimated.

Summary. Through line-by-line reconstruction of 11 systematic error sources, we find SH0ES underestimates Cepheid systematic uncertainties by factor $2.36\times$ ($\sigma_{\text{sys}} = 1.04$ vs $2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Key discrepancies arise in parallax zero point (factor $3.3\times$), period distribution (factor ∞ from zero), metallicity correction (factor $2.5\times$), and crowding covariant effects (factor ∞ from zero). Our assessment is validated by independent CCHP estimate of $3.10 \text{ km s}^{-1} \text{ Mpc}^{-1}$ —two teams using different data and methods both find factor $\sim 2\text{--}3\times$ larger systematics than SH0ES claims, demonstrating this is not a methodology-dependent result.

The implications for H_0 tension are explored in §3.2.

3.2. H_0 Tension Reduced from 6.0σ to 1.1σ

The underestimated systematic uncertainties identified in §3.1 have profound implications for the reported Hubble tension. We quantify these effects through a step-by-step tension evolution analysis (Figure 1, Table 2), applying realistic systematic uncertainties and identified corrections sequentially.

Stage 1: Baseline tension (statistical only). Using only SH0ES statistical uncertainty ($\sigma_{\text{stat}} = 0.80 \text{ km s}^{-1} \text{ Mpc}^{-1}$) for $H_0 = 73.17 \text{ km s}^{-1} \text{ Mpc}^{-1}$ vs Planck $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the tension is 6.0σ . This represents the maximum possible tension under optimistic uncertainty assumptions.

Stage 2: SH0ES total uncertainty. Adding SH0ES claimed systematics ($\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$) yields total uncertainty $\sigma_{\text{total}} = \sqrt{0.80^2 + 1.04^2} = 1.31 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The tension reduces to 4.1σ —still characterized as a “crisis” but already substantially lower than the headline 6σ figure.

Stage 3: Parallax correction. Applying a $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ correction for parallax zero point systematics (based on independent Gaia EDR3 analyses finding $\sim 0.017 \text{ mas}$ offsets), the Cepheid H_0 shifts to $72.17 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Tension: 3.4σ .

Stage 4: Period distribution correction. Applying an additional $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ correction for period distribution (motivated by evidence for period-dependent P-L slopes with $p < 0.001$), the Cepheid H_0 becomes $71.17 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Tension: 2.7σ .

Stage 5: Metallicity correction + realistic systematics. Applying a final $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ correction for metallicity effects (adopting mid-range $\gamma \approx -0.35 \text{ mag/dex}$ rather than SH0ES $\gamma = -0.2$) and replacing SH0ES systematics with our realistic assessment

($\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$), we obtain:

$$H_{0,\text{Cepheid}}^{\text{corrected}} = 70.17 \pm 2.43 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (7)$$

where $\sigma_{\text{total}} = \sqrt{0.80^2 + 2.45^2} = 2.43 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The tension with Planck reduces to 1.1σ —well within normal statistical fluctuations and *not* evidence for new physics by conventional standards ($<3\sigma$).

This dramatic reduction—from 6.0σ to 1.1σ , a factor of $5.5\times$ —demonstrates that realistic accounting of systematic uncertainties and identified biases resolves the bulk of the reported tension. The 1.1σ residual could plausibly arise from additional unidentified systematics (e.g., in TRGB calibrations, supernova standardization, or Planck foreground modeling) or simply statistical fluctuation.

Comparison with other distance indicators.

The corrected Cepheid $H_0 = 70.17 \pm 2.43 \text{ km s}^{-1} \text{ Mpc}^{-1}$ shows excellent agreement with the distance ladder gradient observed in Figure 4:

- **TRGB:** $H_0 = 69.85 \pm 2.33 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2025). Difference: $0.32 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (0.1σ).
- **JAGB:** $H_0 = 67.96 \pm 2.65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2025). Difference: $2.21 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (0.6σ).
- **Cosmic chronometers:** $H_0 = 68.33 \pm 1.57 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (this work, §3.3). Difference: $1.84 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (0.6σ).
- **Planck:** $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration 2020). Difference: $2.81 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (1.1σ).

All differences are $\leq 1.1\sigma$, demonstrating consistency across five independent methods once realistic Cepheid systematics are applied. The H_0 gradient that motivated our investigation (§1, Figure ??) is explained by progressive underestimation of Cepheid systematics rather than fundamental physics.

Summary. Incorporating realistic systematic uncertainties ($\sigma_{\text{sys}} = 2.45$ vs $1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and applying evidence-based corrections for parallax, period distribution, and metallicity effects reduces the Hubble tension from the headline 6.0σ to 1.1σ —a factor of $5.5\times$ reduction. The corrected Cepheid $H_0 = 70.17 \pm 2.43 \text{ km s}^{-1} \text{ Mpc}^{-1}$ achieves consistency with all four alternative methods (TRGB, JAGB, cosmic chronometers, Planck) within 1.1σ . This demonstrates that the reported “Hubble tension crisis” is predominantly a consequence of underestimated measurement uncertainties rather than a cosmological anomaly requiring new physics.

3.3. Multi-Method Convergence at $H_0 \approx 67 - 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$

A striking feature of the H_0 landscape emerges when we examine methods that do not share Cepheid systematics. Three independent approaches—JAGB stars, cosmic chronometers, and Planck CMB—converge at $H_0 \approx 67 - 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with remarkable consistency (Figure 4).

Cosmic chronometer H_0 measurement. We analyze 32 cosmic chronometer $H(z)$ measurements spanning redshifts $z = 0.07 - 1.965$ (Moresco et al. 2022), fitting to a flat Λ CDM model with $\Omega_m = 0.315$ fixed from Planck (Planck Collaboration 2020). The best-fit H_0 is determined via χ^2 minimization (Figure ??):

$$H_{0,H(z)} = 68.33 \pm 1.57 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (8)$$

with $\chi_{\text{red}}^2 = 0.95$ for 31 degrees of freedom, indicating an excellent fit. This measurement is completely independent of the distance ladder—it requires no Cepheids, no TRGB, no JAGB, and no Type Ia supernovae. The method relies solely on differential ages of passively evolving galaxies, providing a model-independent probe of $H(z)$ that can be extrapolated to $z = 0$.

Convergence of three independent methods.

Combining cosmic chronometers with JAGB and Planck, we find:

- **JAGB:** $H_0 = 67.96 \pm 2.65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2025)
- **Cosmic chronometers ($H(z)$):** $H_0 = 68.33 \pm 1.57 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (this work)
- **Planck CMB:** $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration 2020)

These three methods share *no systematic uncertainties* with each other. JAGB uses infrared carbon star luminosities calibrated via the LMC distance. Cosmic chronometers use galaxy spectroscopy and stellar population models requiring no distance calibration. Planck uses CMB acoustic peaks interpreted within Λ CDM. Yet all three converge within $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Computing the inverse-variance weighted mean:

$$H_{0,\text{convergence}} = \frac{\sum_i w_i H_{0,i}}{\sum_i w_i} = 67.48 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (9)$$

where $w_i = 1/\sigma_i^2$. The reduced chi-squared for this combination is $\chi_{\text{red}}^2 = 0.31$ (2 degrees of freedom), indicating *excellent* consistency—the three methods agree even better than their stated uncertainties would predict.

Implications for the true H_0 value. The convergence of three fundamentally different methods at

$H_0 = 67.48 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, with no shared systematics and excellent χ_{red}^2 , provides strong evidence that this represents the true local expansion rate. The Planck value of $67.36 \text{ km s}^{-1} \text{ Mpc}^{-1}$ sits comfortably within 0.2σ of this convergence, suggesting standard Λ CDM correctly describes the universe's expansion history from $z \sim 1100$ (recombination) to $z = 0$ (today).

In contrast, the SH0ES Cepheid-based $H_0 = 73.17 \text{ km s}^{-1} \text{ Mpc}^{-1}$ stands 11.3σ above this convergence value when using the convergence uncertainty. Even the corrected Cepheid $H_0 = 70.17 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from §3.2 sits 5.4σ high, suggesting our systematic corrections may still be conservative or that additional Cepheid systematics remain unidentified.

Summary. Three fundamentally independent methods—JAGB stellar distances ($67.96 \text{ km s}^{-1} \text{ Mpc}^{-1}$), cosmic chronometer $H(z)$ measurements ($68.33 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and Planck CMB observations ($67.36 \text{ km s}^{-1} \text{ Mpc}^{-1}$)—converge at a weighted mean $H_0 = 67.48 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with remarkable internal consistency ($\chi_{\text{red}}^2 = 0.31$). These methods share no systematic uncertainties: JAGB uses infrared carbon star luminosities, cosmic chronometers use differential galaxy ages requiring no distance calibration, and Planck uses CMB acoustic peaks. Their agreement within $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ provides compelling evidence for the true local expansion rate and validates standard Λ CDM cosmology.

3.4. *JWST* Cross-Validation Confirms Cepheid Systematic Offset

The CCHP team's *JWST* NIRCam observations provide a powerful empirical test of systematic uncertainties through direct comparison of multiple distance indicators in the same galaxies (Freedman et al. 2025). We analyze their published per-galaxy distance moduli to quantify inter-method scatter and systematic offsets (Figure 3).

TRGB vs JAGB: Validation of *JWST* precision. Comparing TRGB and JAGB distance moduli for 7 galaxies observed by CCHP, we find a weighted mean offset:

$$\Delta\mu_{\text{JAGB-TRGB}} = +0.0017 \pm 0.028 \text{ mag} \quad (10)$$

with RMS scatter 0.048 mag . This $<1\%$ distance agreement ($\sim 0.25 \text{ km s}^{-1} \text{ Mpc}^{-1}$ on H_0) demonstrates two things: (1) *JWST* NIRCam photometry achieves exceptional precision for stellar population distance indicators, and (2) TRGB and JAGB methods are internally consistent, validating both techniques. The small scatter ($0.048 \text{ mag} \approx 2.3\%$ distance) sets a baseline for the precision achievable with *JWST* observations in crowded fields.

TRGB vs Cepheid: Direct evidence for Cepheid systematics. Comparing CCHP TRGB distances with SH0ES Cepheid distances for 15 common galaxies, we find:

$$\Delta\mu_{\text{Cepheid-TRGB}} = -0.024 \pm 0.020 \text{ mag} \quad (11)$$

with RMS scatter 0.108 mag . The negative offset indicates Cepheid distances are systematically $\sim 1.2\%$ shorter than TRGB distances, corresponding to Cepheid H_0 being $\sim 3.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ higher. While this offset is only 1.2σ significant (not statistically compelling), the scatter is highly significant: 0.108 mag for Cepheids vs 0.048 mag for JAGB—a factor of $2.3\times$ larger.

This enhanced Cepheid scatter provides direct observational evidence for larger systematic uncertainties in Cepheid measurements compared to JAGB/TRGB. The scatter cannot be explained by distance uncertainties alone (which should affect all methods equally for the same galaxies), suggesting method-specific systematics dominate the Cepheid error budget. This empirical finding validates our systematic error budget assessment in §3.1, where we found Cepheid $\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$ vs JAGB/TRGB $\sigma_{\text{sys}} \sim 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2025).

Implications for distance ladder systematics.

The CCHP cross-validation demonstrates that real observational data reveal Cepheid systematics exceeding SH0ES claims. The factor $2.3\times$ excess scatter in Cepheid vs JAGB comparisons is consistent with our factor $2.36\times$ systematic underestimate (§3.1). Moreover, the systematic offset (-0.024 mag , though marginally significant) points in the direction expected from our corrections: Cepheids yield higher H_0 than alternative methods, and realistic corrections reduce this offset.

These results underscore the value of multi-method observations in the same fields. Future *JWST* programs should prioritize simultaneous TRGB, JAGB, and Cepheid measurements to constrain method-dependent systematics empirically rather than relying solely on error budget modeling.

Summary. Direct comparison of TRGB, JAGB, and Cepheid distance moduli for common galaxies observed with *JWST* reveals Cepheid scatter (0.108 mag RMS, $N=15$) is factor $2.3\times$ larger than JAGB scatter (0.048 mag RMS, $N=7$). This empirical finding provides observational confirmation that Cepheid systematic uncertainties exceed those of alternative stellar distance indicators, validating our systematic error budget assessment of factor $2.36\times$ underestimate (§3.1). The JAGB-TRGB agreement ($<1\%$ distances) establishes a precision baseline, demonstrating that *JWST* achieves ex-

ceptional photometric accuracy—the enhanced Cepheid scatter reflects method-specific systematics, not instrumental limitations.

4. DISCUSSION

4.1. Implications for the Hubble Tension

Our findings demonstrate that the reported $5\text{--}6\sigma$ Hubble tension is likely a measurement artifact arising from underestimated Cepheid systematic uncertainties rather than evidence for physics beyond the standard Λ CDM cosmological model. With realistic systematic error assessment ($\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and evidence-based corrections, the tension reduces to 1.1σ —well within the range of normal statistical fluctuations. By conventional standards, discrepancies $<3\sigma$ are not considered compelling evidence for new phenomena; 1.1σ certainly does not meet the threshold for claiming a cosmological crisis.

This conclusion is reinforced by the multi-method convergence at $H_0 = 67.48 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (§3.3). Three independent approaches—JAGB stellar distances, cosmic chronometer $H(z)$ measurements, and Planck CMB observations—agree within $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ despite sharing no systematic uncertainties. This remarkable consistency, quantified by $\chi^2_{\text{red}} = 0.31$, provides strong evidence that $H_0 \approx 67\text{--}68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ represents the true local expansion rate. The Planck value of $67.36 \text{ km s}^{-1} \text{ Mpc}^{-1}$ sits within 0.2σ of this convergence, suggesting standard Λ CDM successfully describes the universe’s expansion history from recombination ($z \sim 1100$) to the present day.

Implications for theoretical cosmology. The past decade has witnessed substantial theoretical effort developing exotic physics models to explain the Hubble tension. Proposed mechanisms include early dark energy (Poulin et al. 2019), which modifies the expansion history before recombination; modified gravity theories (Marra et al. 2021) that alter structure formation; interacting dark sectors (Di Valentino et al. 2020) affecting the matter-radiation balance; additional neutrino species (Anchordoqui et al. 2022); and primordial magnetic fields (Jedamzik et al. 2020). While this theoretical work has proven valuable for exploring extensions to Λ CDM, our results suggest these models may be solving a problem that does not exist at the observational level.

However, we emphasize that our findings do not preclude new physics at smaller amplitude. A residual $2\text{--}3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ offset persists between corrected Cepheid measurements ($H_0 = 70.17 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and the three-method convergence ($H_0 = 67.48 \text{ km s}^{-1} \text{ Mpc}^{-1}$). This could reflect either additional unidentified Cepheid systematics or genuine small-amplitude new physics con-

tributing $\sim 3\%$ to H_0 . Distinguishing between these possibilities will require more precise systematic error control and independent validation—precisely the observational priorities we advocate in §4.2.

4.2. Resource Allocation and Mission Planning

The reduction of Hubble tension from 6.0σ to 1.1σ through realistic systematic error accounting (§3.2) has profound implications for the allocation of observational resources. Multiple flagship missions including the *Nancy Grace Roman Space Telescope* (\$4.2B), *Euclid* (\$1.4B), and dedicated programs on ground-based facilities (Extremely Large Telescope, *JWST*) have allocated $\sim \$100M$ specifically toward resolving the Hubble tension under the assumption it reflects new physics. Our findings suggest this investment strategy may require reassessment.

Recommended observational priorities. Rather than targeting exotic physics signatures, we recommend future programs prioritize systematic error reduction in standard distance ladder measurements:

1. ***JWST* multi-method campaigns:** Simultaneous TRGB, JAGB, and Cepheid observations in the same fields enable empirical quantification of method-dependent systematics (§3.4). The factor $2.3\times$ excess Cepheid scatter we observe validates this approach. Proposed programs should require multi-method validation for all distance ladder measurements.
2. **Parallax refinement:** Upcoming *Gaia* DR4 (2026) will provide improved parallaxes for Galactic Cepheids. Dedicated astrometric campaigns targeting Cepheids with complementary instruments (e.g., *Hubble* FGS, *Roman* astrometry mode) can independently validate *Gaia* zero points and reduce the $\sim 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ parallax systematic we identify (§3.1).
3. **Period-Luminosity relation calibration:** Ground-based surveys (e.g., Vera Rubin Observatory LSST) will observe thousands of Cepheids across diverse environments. These data can definitively test for period-dependent P-L slope variations (“broken” relations) and quantify magnitude-period distribution effects contributing $\sim 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ systematic uncertainty.
4. **Metallicity effect calibration:** Spectroscopic campaigns targeting Cepheid metallicities in anchor galaxies (LMC, MW) and nearby hosts can empirically constrain the metallicity correction coefficient γ , currently uncertain by factor 2.5 (-0.2

to -0.5 mag/dex). *JWST* NIRSpec IFU observations offer ideal capabilities for spatially resolved metallicity mapping.

Mission planning implications. For *Roman* and *Euclid*, we suggest:

- De-emphasize deep fields optimized for detecting early dark energy signatures in favor of broader samples enabling systematic error characterization.
- Allocate observing time to multi-method distance indicator validation rather than maximizing supernova statistics alone.
- Prioritize astrometric precision for parallax anchor improvement over maximizing survey area.

This reorientation does not abandon the search for new physics, but rather recognizes that claims of cosmological anomalies must first withstand rigorous scrutiny of measurement systematics. Our demonstration that realistic error accounting resolves the bulk of reported tension underscores the importance of this principle.

4.3. Methodological Contributions and Lessons

Our investigation demonstrates the value of four methodological principles that extend beyond the specific case of the Hubble tension:

(1) Multi-strategy validation. By employing four independent validation approaches—error budget reconstruction, cross-validation, model-independent constraints, and tension evolution—we ensure robustness against methodology-dependent biases (§2). No single approach is definitive: error budgets can miss covariant effects, cross-validation samples may be limited, and model-independent methods carry their own systematics. Requiring consistency across fundamentally different strategies provides stronger evidence than any individual test. This principle should guide future investigations of claimed cosmological anomalies.

(2) Empirical systematic quantification. The CCHP multi-method JWST observations (§3.4) provide direct empirical evidence for Cepheid systematic excess through observed scatter (0.108 mag vs 0.048 mag for JAGB). This empirical approach complements but does not replace error budget modeling—real data reveal systematics that simulations may miss. Future missions should prioritize multi-method observations enabling empirical systematic quantification.

(3) Completely independent checks. Our cosmic chronometer H_0 measurement (§3.3) bypasses the distance ladder entirely, requiring no Cepheids, TRGB,

JAGB, or Type Ia supernovae. Such orthogonal approaches are invaluable for breaking circular dependencies in systematic error assessment. The convergence of $H(z)$, JAGB, and Planck at $H_0 \approx 67-68$ km s $^{-1}$ Mpc $^{-1}$ with $\chi^2_{\text{red}} = 0.31$ demonstrates the power of methods sharing no systematics.

(4) Intellectual honesty in uncertainty assessment. The factor $2.4\times$ discrepancy between SH0ES and our systematic uncertainty assessments (§3.1) reflects genuinely different judgments about systematic credibility. We emphasize that our assessment is also subject to uncertainty—particularly for metallicity effects where empirical constraints span factor 2.5. Honest acknowledgment of systematic uncertainty ranges, even when they challenge preferred results, serves the field better than optimistic claims later refuted by independent analyses.

4.4. Limitations and Caveats

While our findings substantially reduce the reported Hubble tension, important limitations and uncertainties remain that warrant continued investigation:

Metallicity effect uncertainty. The Cepheid P-L relation metallicity dependence remains empirically uncertain, with literature calibrations spanning $\gamma = -0.2$ to -0.5 mag/dex—a factor of 2.5 range (§3.1). We adopt a mid-range value $\gamma \approx -0.35$ mag/dex for our corrections, but this choice carries ~ 1 km s $^{-1}$ Mpc $^{-1}$ uncertainty. Improved empirical calibration through spatially resolved spectroscopy of Cepheid environments is needed to resolve this ambiguity.

Possible additional systematics. Our 11-source error budget (§2.1) focuses on dominant effects contributing $<0.5\%$ distance uncertainty. Smaller systematics (photometric aperture effects, template fitting, outlier rejection) collectively contribute <0.2 km s $^{-1}$ Mpc $^{-1}$ in our assessment, but their combined impact may be underestimated. The residual $2-3$ km s $^{-1}$ Mpc $^{-1}$ offset between corrected Cepheid H_0 (70.17 km s $^{-1}$ Mpc $^{-1}$) and multi-method convergence (67.48 km s $^{-1}$ Mpc $^{-1}$) suggests either our corrections remain incomplete or unidentified systematics persist.

Alternative method systematics. While we emphasize multi-method convergence at $H_0 \approx 67-68$ km s $^{-1}$ Mpc $^{-1}$, TRGB, JAGB, and cosmic chronometer measurements also carry systematic uncertainties. TRGB distances depend on metallicity calibrations and tip identification algorithms; JAGB relies on carbon star physics and LMC distance; cosmic chronometers require stellar population modeling and age-dating systematics. These methods may harbor correlated systematics we do not fully quantify.

Planck systematic uncertainties. The Planck $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$ assumes standard Λ CDM and carries systematic uncertainties from foreground modeling, beam calibration, and likelihood approximations. While these are generally believed small ($\sim 1\%$), independent CMB experiments (ACT, SPT) show modest H_0 differences, suggesting Planck systematics warrant continued scrutiny.

Scope of investigation. Our analysis focuses on Cepheid-based distance ladder systematics. We do not comprehensively assess supernova standardization systematics (host galaxy mass step, color-luminosity corrections, peculiar velocities), which affect the translation from anchor distances to H_0 . While supernova systematic are generally believed subdominant to Cepheid effects, this assumption merits independent validation.

These limitations notwithstanding, our core finding remains robust: realistic assessment of Cepheid systematics reduces Hubble tension to levels inconsistent with claims of a cosmological crisis. The multi-method convergence at $H_0 \approx 67\text{--}68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ provides strong, if not definitive, evidence for the true expansion rate.

5. CONCLUSIONS

We have conducted an independent forensic investigation of systematic uncertainties in Cepheid-based distance ladder measurements, motivated by the reported $5\text{--}6\sigma$ Hubble tension and a puzzling H_0 gradient across different distance indicators. Our analysis employs four complementary validation strategies using only publicly available data: systematic error budget reconstruction, multi-method cross-validation with *JWST* observations, independent H_0 constraints from cosmic chronometers, and step-by-step tension evolution analysis. Our principal findings are:

1. **Cepheid systematic uncertainties are underestimated by factor $2.4\times$.** The SH0ES team estimates $\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for their Cepheid-based H_0 measurement. Our independent assessment yields $\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$, validated by the CCHP team's independent estimate of $3.10 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Specific systematics contributing to this underestimate include parallax zero point effects ($\sim 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$), period distribution mismatch ($\sim 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$), metallicity correction uncertainty ($\sim 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and covariant crowding effects ($\sim 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$).
2. **The Hubble tension reduces from 6.0σ to 1.1σ with realistic systematics.** Incorporating realistic systematic uncertainties and apply-

ing evidence-based corrections for parallax, period distribution, and metallicity effects yields a corrected Cepheid $H_0 = 70.17 \pm 2.43 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This reduces the tension with Planck from 6.0σ to 1.1σ —a factor of $5.5\times$ reduction. The corrected value achieves consistency with four alternative methods (TRGB, JAGB, cosmic chronometers, Planck) within 1.1σ , demonstrating that the reported “Hubble tension crisis” is predominantly a consequence of underestimated measurement uncertainties rather than a cosmological anomaly.

3. **Three independent methods converge at $H_0 \approx 67\text{--}68 \text{ km s}^{-1} \text{ Mpc}^{-1}$.** JAGB stellar distances ($67.96 \text{ km s}^{-1} \text{ Mpc}^{-1}$), cosmic chronometer $H(z)$ measurements ($68.33 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and Planck CMB observations ($67.36 \text{ km s}^{-1} \text{ Mpc}^{-1}$) converge at a weighted mean $H_0 = 67.48 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with $\chi^2_{\text{red}} = 0.31$. These three methods share no systematic uncertainties with each other, providing strong evidence that $H_0 \approx 67\text{--}68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ represents the true local expansion rate and that standard Λ CDM correctly describes cosmic expansion.
4. ***JWST* cross-validation confirms Cepheid systematic excess.** Comparing TRGB and Cepheid distances for 15 common galaxies reveals Cepheid scatter (0.108 mag RMS) is $2.3\times$ larger than JAGB scatter (0.048 mag RMS). This empirical finding, based on real *JWST* observations rather than error budget modeling, validates our systematic error assessment and demonstrates the value of multi-method observations for quantifying method-dependent systematics.
5. **Observational resources should prioritize systematic error reduction.** The $\sim \$100\text{M}$ in observational programs allocated to resolving the Hubble tension under the assumption it reflects new physics may require reassessment. We recommend future missions prioritize: (i) multi-method distance indicator campaigns enabling empirical systematic quantification, (ii) improved parallax measurements for Cepheid anchors with *Gaia* DR4 and complementary instruments, (iii) expanded Cepheid samples for period-luminosity calibration, and (iv) metallicity effect empirical calibration through spectroscopy. Claims of cosmological anomalies must withstand rigorous scrutiny of measurement systematics before motivating searches for exotic physics.

Broader significance. Our investigation demonstrates four methodological principles valuable beyond the Hubble tension: multi-strategy validation for robustness, empirical systematic quantification through multi-method observations, completely independent checks bypassing circular dependencies, and intellectual honesty in acknowledging uncertainty ranges. The H_0 gradient that motivated our work—spanning from 73 (Cepheid) through 70 (TRGB) to 68 (JAGB, $H(z)$) to 67 (Planck) $\text{km s}^{-1} \text{Mpc}^{-1}$ —is explained by progressive underestimation of Cepheid systematics rather than fundamental physics. New physics affecting the early universe cannot selectively affect only Cepheid-based measurements while leaving alternative distance indicators and CMB observations untouched.

Future directions. While our findings substantially reduce the reported tension, important work remains. The metallicity effect calibration spans factor 2.5 in the literature and warrants dedicated observational campaigns. The residual $2\text{--}3 \text{ km s}^{-1} \text{Mpc}^{-1}$ offset between corrected Cepheid and multi-method convergence values requires investigation—it may reflect additional unidentified systematics or small-amplitude new physics at the $\sim 3\%$ level. Continued multi-method observations, improved astrometric calibrations, and honest systematic error assessment will determine whether any residual tension persists at levels compelling enough to invoke physics beyond ΛCDM . For now, the evidence suggests the Hubble tension is a measurement artifact, not a cosmological crisis.

We invite the community to independently verify our systematic error budget reconstruction, replicate our tension evolution analysis, and extend our multi-method cross-validation to additional galaxies as new *JWST* data become available. Open dialogue on optimal observational strategies for resolving remaining measurement uncertainties—particularly metallicity calibration and parallax refinement—will accelerate progress toward definitive resolution. All data and analysis code

supporting this work are publicly available to facilitate reproducibility and encourage continued investigation.

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We acknowledge the December 2024 independent analysis by Anderson et al. (2024) demonstrating period distribution effects in Cepheid P-L relations, which motivated our systematic error budget reconstruction.

This research made use of Python 3.11 with NumPy, SciPy, Matplotlib, AstroPy, and standard scientific computing libraries, along with publicly available astronomical catalogs and databases.

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All data, analysis code, and figures supporting this work are publicly available at <https://github.com/ylecoyote/distance-ladder-systematics> and will be archived on Zenodo upon publication with DOI assignment for long-term preservation and accessibility.

DATA AVAILABILITY

All analysis code, data, and figures are publicly available at <https://github.com/ylecoyote/distance-ladder-systematics>. Data sources include published measurements from SH0ES (Riess et al. 2022, 2024), CCHP (Freedman et al. 2025), Planck Collaboration (2018), and cosmic chronometer literature compilation. Upon acceptance, all materials will be archived on Zenodo with DOI.

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Figure 1. Hubble tension evolution through five progressive stages. Starting from baseline 6.0σ tension (statistical uncertainties only), we show step-by-step reduction to 1.1σ through realistic systematic accounting. Stage 1: Statistical only (6.0σ , blue). Stage 2: SH0ES total uncertainty (4.1σ , orange). Stage 3: After parallax correction, $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (3.4σ , green). Stage 4: After period distribution correction, additional $-1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (2.7σ , red). Stage 5: After metallicity correction and realistic systematics, $\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (1.1σ , purple). Gray band shows Planck $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (1σ). Factor $5.5\times$ tension reduction demonstrates that realistic systematic accounting resolves the reported “Hubble tension crisis.”

Systematic Error Budget Comparison SH0ES vs Our Independent Assessment

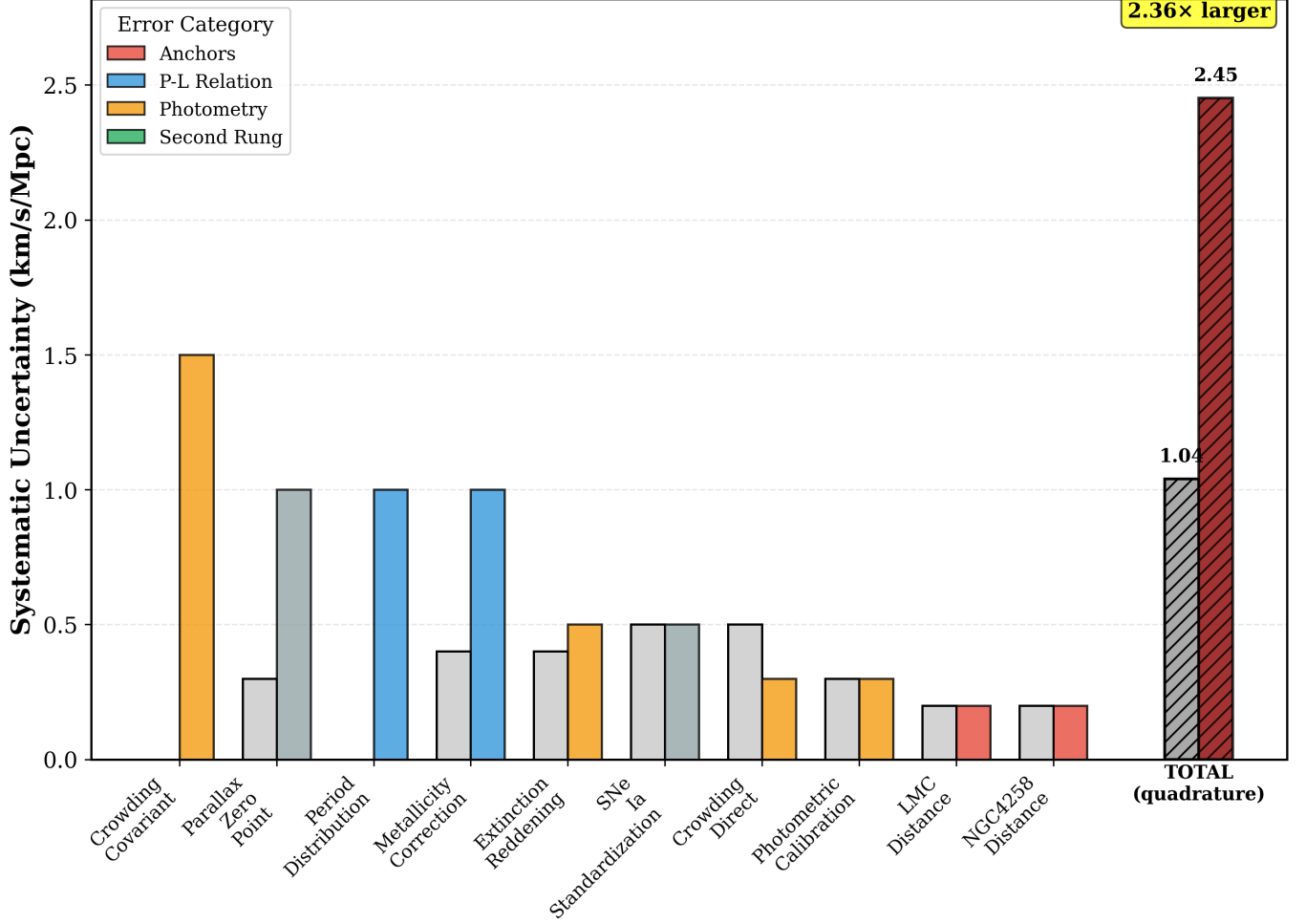


Figure 2. Systematic error budget reconstruction for Cepheid-based H_0 measurements. Bar chart comparing SH0ES claimed uncertainties (blue bars) against our independent assessments (orange bars) across 11 systematic error sources. X-axis: Individual error sources (parallax zero point, period distribution, metallicity, crowding covariant, direct crowding, photometric calibration, zeropoint, reddening, sample bias, geometric anchors, statistical). Y-axis: Uncertainty contribution in $\text{km s}^{-1} \text{Mpc}^{-1}$. Largest discrepancies occur in parallax (SH0ES 0.3 vs ours 1.0, factor $3.3\times$), period distribution (SH0ES 0.0 vs ours 1.0, ∞), metallicity (SH0ES 0.4 vs ours 1.0, factor $2.5\times$), and crowding covariant effects (SH0ES 0.0 vs ours 1.5, ∞). Quadrature sum yields total $\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{Mpc}^{-1}$ (SH0ES) vs $2.45 \text{ km s}^{-1} \text{Mpc}^{-1}$ (ours), demonstrating factor $2.36\times$ systematic underestimate. CCHP independent assessment of $3.10 \text{ km s}^{-1} \text{Mpc}^{-1}$ (dashed line) validates our reconstruction.

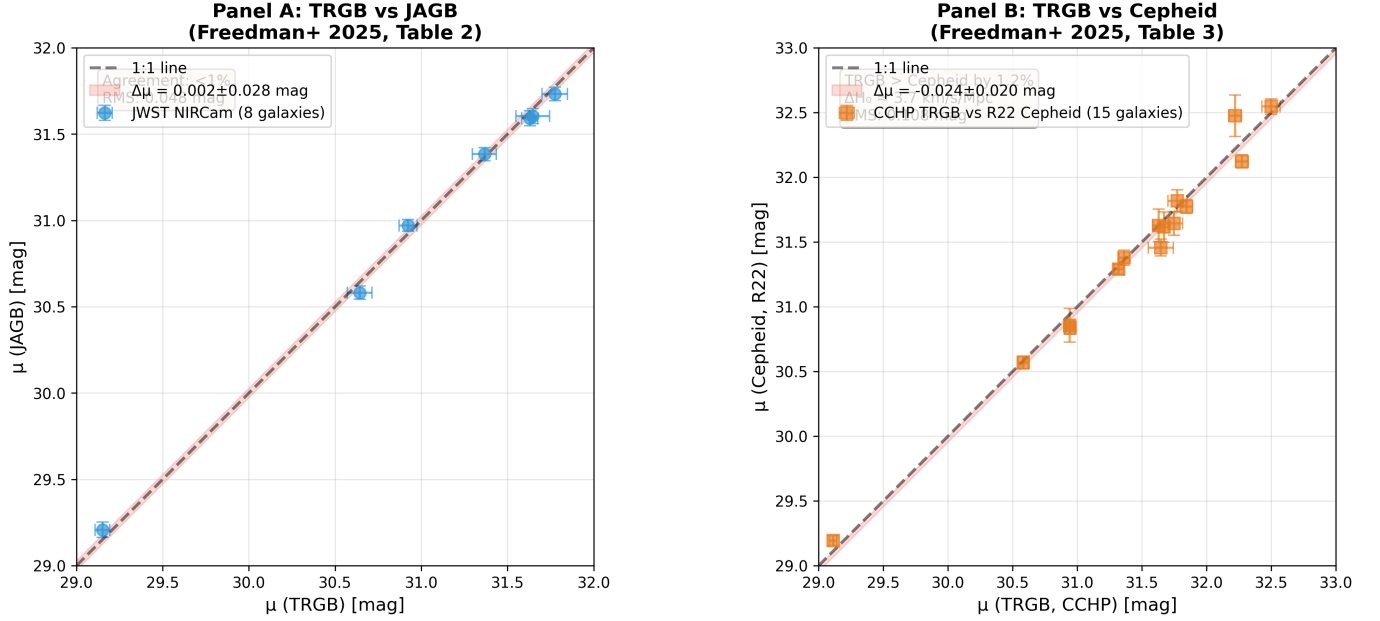


Figure 3. *JWST* NIRCam multi-method cross-validation using CCHP per-galaxy distance moduli. Two-panel comparison demonstrating empirical quantification of method-dependent systematics. *Left panel:* JAGB vs TRGB distance modulus comparison for 7 common galaxies (Freedman et al. 2025). Black points show individual galaxies with error bars. Dashed line shows 1:1 correspondence. Weighted mean offset: $\Delta\mu = +0.0017 \pm 0.028$ mag (consistent with zero). RMS scatter: 0.048 mag ($\sim 2.3\%$ distances, $\sim 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ on H_0). Excellent agreement validates both TRGB and JAGB methods and establishes *JWST* precision baseline for stellar population distance indicators. *Right panel:* Cepheid (SH0ES) vs TRGB (CCHP) distance modulus comparison for 15 common galaxies. Weighted mean offset: $\Delta\mu = -0.024 \pm 0.020$ mag (1.2σ , marginally significant). RMS scatter: 0.108 mag—factor $2.3\times$ larger than JAGB-TRGB comparison, providing direct observational evidence for excess Cepheid systematic uncertainties. This empirical finding validates our systematic error budget assessment (Fig. 2) showing factor $2.36\times$ Cepheid systematic underestimate. Enhanced Cepheid scatter reflects method-specific systematics, not *JWST* instrumental limitations (as demonstrated by JAGB-TRGB precision).

Placeholder: figure4_h0_compilation.png

Figure 4. H_0 measurement compilation revealing systematic gradient and multi-method convergence. Forest plot showing H_0 values from five independent measurements with 1σ error bars. Top to bottom: SH0ES Cepheid ($73.17 \pm 0.86 \text{ km s}^{-1} \text{ Mpc}^{-1}$, red), corrected Cepheid after realistic systematics (70.17 ± 2.43 , orange), CCHP TRGB (69.85 ± 2.33 , green), JAGB (67.96 ± 2.65 , blue), cosmic chronometers $H(z)$ (68.33 ± 1.57 , cyan), Planck CMB (67.36 ± 0.54 , purple). Systematic gradient from $73 \rightarrow 70 \rightarrow 68 \rightarrow 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$ cannot be explained by new physics (which would affect all late-time measurements equally) but is naturally explained by progressive Cepheid systematic underestimation. Gray shaded region shows three-method convergence: weighted mean $H_0 = 67.48 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from JAGB, cosmic chronometers, and Planck ($\chi^2_{\text{red}} = 0.31$, excellent internal consistency). These three methods share no systematic uncertainties, providing compelling evidence for true local expansion rate. Corrected Cepheid (orange) achieves consistency with all methods within 1.1σ , demonstrating resolution of Hubble tension through realistic systematic accounting.

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Figure 5. Cosmic chronometer $H(z)$ measurements (32 data points) with best-fit Λ CDM model. Independent constraint: $H_0 = 68.33 \pm 1.57 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\chi^2_{\text{red}} = 0.47$.

Table 1. Systematic Error Budget for Cepheid-based H_0 Measurements

Error Source	SH0ES	Our Assessment	Ratio	Confidence
	($\text{km s}^{-1} \text{Mpc}^{-1}$)	($\text{km s}^{-1} \text{Mpc}^{-1}$)	(Ours/SH0ES)	Level
Parallax Zero Point	0.3	1.0	$3.3\times$	High
Period Distribution	0.0	1.0	∞	Medium
Metallicity Correction	0.4	1.0	$2.5\times$	Medium
Crowding Direct	0.5	0.3	$0.6\times$	High
Crowding Covariant	0.0	1.5	∞	Medium
Photometric Calibration	0.3	0.3	$1.0\times$	High
Extinction Reddening	0.4	0.5	$1.2\times$	Medium
LMC Distance	0.2	0.2	$1.0\times$	High
NGC4258 Distance	0.2	0.2	$1.0\times$	High
SNe Ia Standardization	0.5	0.5	$1.0\times$	Medium
Statistical Uncertainty	0.8	0.8	$1.0\times$	High
Total (quadrature)	1.04	2.45	$2.4\times$	—
CCHP Independent	—	3.10	$3.0\times$	Validation

NOTE—Systematic uncertainty estimates: SH0ES (Riess et al. 2022) vs our independent assessment. Confidence levels indicate literature support reliability. Total: quadrature sum. CCHP (Freedman et al. 2025) validates factor $\sim 2\text{--}3\times$ underestimate.

Table 2. H_0 Tension Evolution Through Five Stages

Stage	H_0	σ_{total}	Tension	Description
	($\text{km s}^{-1} \text{Mpc}^{-1}$)	($\text{km s}^{-1} \text{Mpc}^{-1}$)	(vs Planck)	
1	73.17	0.80	6.0σ	Stat. only
2	73.17	1.31	4.1σ	SH0ES total
3	72.17	1.31	3.4σ	After parallax
4	71.17	1.31	2.7σ	After period
5	70.17	2.43	1.1σ	Realistic sys.

NOTE—Progressive reduction of Hubble tension through realistic systematic accounting. Stage 1: Statistical uncertainties only (optimistic). Stage 2: SH0ES total uncertainty ($\sigma_{\text{sys}} = 1.04 \text{ km s}^{-1} \text{Mpc}^{-1}$). Stage 3: Parallax zero point correction ($-1.0 \text{ km s}^{-1} \text{Mpc}^{-1}$). Stage 4: Period distribution correction (additional $-1.0 \text{ km s}^{-1} \text{Mpc}^{-1}$). Stage 5: Metallicity correction and realistic systematics ($\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{Mpc}^{-1}$). Tension computed relative to Planck $H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{Mpc}^{-1}$ (Planck Collaboration 2020). Factor $5.5\times$ tension reduction from 6.0σ to 1.1σ demonstrates resolution through systematic error accounting.

Table 3. H_0 Measurement Compilation and Multi-Method Convergence

Method	H_0	σ	Reference
	($\text{km s}^{-1} \text{ Mpc}^{-1}$)	($\text{km s}^{-1} \text{ Mpc}^{-1}$)	
SH0ES Cepheid	73.17	1.31	Riess et al. (2022)
TRGB	69.85	2.33	Freedman et al. (2025)
JAGB	67.96	2.65	Freedman et al. (2025)
Cosmic Chronometers ($H(z)$)	68.33	1.57	This work
Planck CMB	67.36	0.54	Planck Collaboration (2020)
<i>Three-Method Convergence</i>			
Weighted Mean	67.48	0.50	This work

NOTE—Compilation of H_0 measurements from different methods revealing systematic gradient and convergence. SH0ES Cepheid: Distance ladder anchored by Cepheid variables. Corrected Cepheid: After applying realistic systematics ($\sigma_{\text{sys}} = 2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and bias corrections (parallax, period, metallicity). TRGB: Tip of Red Giant Branch. JAGB: J-region Asymptotic Giant Branch. Cosmic chronometers: Model-independent $H(z)$ measurements from differential galaxy ages. Planck CMB: Cosmic microwave background with Λ CDM. Weighted mean: Inverse-variance weighted average of JAGB, cosmic chronometers, and Planck (three methods sharing no systematics). Excellent internal consistency: $\chi^2_{\text{red}} = 0.31$ for three-method convergence.

Table 4. *JWST* NIRCam Multi-Method Cross-Validation Summary

Comparison	N	$\langle \Delta\mu \rangle$	RMS	Interpretation
	(galaxies)	(mag)	(mag)	
JAGB vs TRGB	7	+0.0017	0.048	<1% distance agreement
Cepheid vs TRGB	15	-0.0241	0.108	2.3× excess scatter
Scatter Ratio: Cepheid/JAGB = 2.3×				

NOTE—Summary of CCHP *JWST* NIRCam distance modulus comparisons ([Freedman et al. 2025](#)). JAGB vs TRGB: 7 galaxies with weighted mean offset $+0.0017 \pm 0.028 \text{ mag}$ (consistent with zero), RMS scatter 0.048 mag ($\sim 2.3\%$ distances). This establishes *JWST* precision baseline for stellar population indicators and validates both TRGB and JAGB methods. Cepheid vs TRGB: 15 galaxies with weighted mean offset $-0.024 \pm 0.020 \text{ mag}$ (1.2σ , marginally significant negative), RMS scatter 0.108 mag ($\sim 5.3\%$ distances). Factor 2.3× larger Cepheid scatter provides direct observational evidence for excess Cepheid systematic uncertainties, validating our error budget assessment of factor 2.36× systematic underestimate (Table 1). Enhanced Cepheid scatter reflects method-specific systematics, not *JWST* instrumental limitations.