THE HUBBLE TENSION AS AN EPISTEMIC CRISIS OF THE STANDARD COSMOLOGICAL MODEL: MULTI-PROBE MEASUREMENT LANDSCAPE AND THE HTRPI RESOLUTION-PATHWAY EVALUATION FRAMEWORK

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Abstract: The Hubble tension — the persistent and now ≥5σ disagreement between the Hubble constant H_0 inferred from the cosmic microwave background under ΛCDM (H_0 = 67.4 ± 0.5 km s^{-1} Mpc^{-1}; Planck 2018, Aghanim et al., 2020) and the value from the local Cepheid–Type-Ia-supernova distance ladder (H_0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1}; SH0ES, Riess et al., 2022) — has, over 2016–2023, moved from a curiosity at the boundary of observational cosmology to one of the principal candidate signatures of physics beyond ΛCDM. Independent corroboration of the local high value by strong-lensing time delays (H0LiCOW: $73.3^{+1.7}_{-1.8}$; Wong et al., 2020) and megamaser distances (Megamaser Cosmology Project: 73.9 ± 3.0; Pesce et al., 2020), together with the intermediate Tip-of-Red-Giant-Branch value (69.8 ± 1.9; Freedman et al., 2019; Freedman, 2021) and the GW170817 standard-siren measurement ($70.0^{+12.0}_{-8.0}$; Abbott et al., 2017), have produced a multi-probe landscape that ΛCDM cannot simultaneously accommodate within its uncertainty budget. The Di Valentino et al. (2021) review catalogued the breadth of the theoretical response across more than a thousand proposals; the Kamionkowski–Riess (2023) synthesis identified early dark energy as the most credible single-class resolution; the Schöneberg et al. (2022) “H0 Olympics”provided the first systematic comparative ranking against multi-dataset constraints. The dialectical question remaining at the December 2023 boundary is which resolution pathway is best supported when CMB, BAO, supernova, structure-growth, and lensing constraints are jointly considered. The original contribution of this article is the Hubble Tension Resolution Pathway Index (HTRPI), a normalised composite metric bounded on [0,1] that integrates five evaluation dimensions — CMB compatibility, BAO compatibility, S_8/structure-growth compatibility, predictive distinctness from ΛCDM, and theoretical motivation strength — and returns a quantitative ranking of five canonical pathway classes (pre-recombination early dark energy, late-time dark-energy modifications, sound-horizon modifications, local-physics systematic resolutions, and new dark-sector interactions). Applied to the 2016–2023 data, HTRPI returns the highest value for early dark energy (≈0.50), intermediate values for sound-horizon modifications (≈0.42) and new dark-sector interactions (≈0.38), and lower values for late-time dark-energy modifications (≈0.32) and local-physics resolutions (≈0.28).

Keywords: *Hubble constant, H0 tension, ΛCDM, early dark energy, SH0ES, Planck CMB, distance ladder, sound horizon, modified gravity, multi-probe cosmology.*

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INTRODUCTION

The Hubble constant H0 — the present-day expansion rate of the universe — is the central scaling parameter of cosmological observation. The history of H0 measurements is, equivalently, the history of attempts to measure cosmic distances with sufficient precision to constrain the geometry and the matter-energy content of the universe. From the original Hubble (1929) value of approximately 500 km s^{-1} Mpc^{-1} through the multi-decade reduction to ≈ 100 km s^{-1} Mpc^{-1} in the 1960s, the further reduction to ≈ 70 km s^{-1} Mpc^{-1} by the Hubble Space Telescope Key Project of the 1990s and 2000s, and the modern precision-cosmology era anchored on the Planck Cosmic Microwave Background satellite (Aghanim et al., 2020) and the SH0ES Cepheid-Type-Ia-supernova distance ladder (Riess et al., 2022), the H0 measurement landscape has converged on a value in the range 67-74 km s^{-1} Mpc^{-1} — but with a persistent disagreement among the methods within that range that has, since the early 2010s, refused to converge despite substantial reductions in individual-method uncertainty budgets.

The modern Hubble tension is the empirical observation that this persistent disagreement is statistically inconsistent with measurement error in any of the contributing methods. The Planck 2018 final-mission analysis returned, under flat ΛCDM, H0 = 67.4 ± 0.5 km s^{-1} Mpc^{-1} with internal precision sufficient that further systematic-error budget would have to be qualitatively new to absorb the result (Aghanim et al., 2020). The Riess and colleagues (2022) SH0ES Cepheid-SN1a determination returned H0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1} from observations of 42 Type Ia supernova host galaxies in the redshift range $z \leq 0.01$, calibrated against geometric anchors including the parallax distance to NGC 4258, the Large Magellanic Cloud detached-eclipsing-binary distance, and Milky Way parallaxes (Riess et al., 2022). The disagreement between the two measurements is approximately 5σ on standard error-propagation assumptions, and the question of whether the disagreement reflects an unknown systematic in one of the methods or new cosmological physics has, over the 2016-2023 window, become the principal organising question of observational cosmology.

The independent corroboration of the local high value by methods that do not share the Cepheid-SN1a distance-ladder systematics is the strongest single empirical fact against the unknown-systematic interpretation. The H0LiCOW strong-lensing time-delay programme reported H0 = $73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1} from a joint analysis of six lensed quasars with measured time delays, with the formal 5.3σ tension with Planck calibrated at that time (Wong et al., 2020). The Megamaser Cosmology Project reported H0 = 73.9 ± 3.0 km s^{-1} Mpc^{-1} from water-maser observations in NGC 4258 and CGCG 074-064 (Pesce et al., 2020). The gravitational-wave standard-siren measurement from the binary-neutron-star merger GW170817 produced an early-stage H0 = $70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1} with much larger uncertainties but methodologically independent of the other approaches (Abbott et al., 2017). The simultaneous Tip-of-Red-Giant-Branch (TRGB) Carnegie-Chicago Hubble Program result returned an intermediate H0 = 69.8 ± 1.9 km s^{-1} Mpc^{-1} (Freedman et al., 2019; Freedman, 2021).

Two empirical patterns have emerged from this multi-probe landscape. First, the methods that anchor on the cosmic-microwave-background sound-horizon scale (Planck CMB, BAO-derived inverse distance ladder) consistently return the lower value of H0 ≈ 67-68 km s^{-1} Mpc^{-1}. Second, the methods that anchor on local geometric or astrophysical distance measurements (Cepheid-SN1a, strong-lensing time delays, megamasers, standard sirens) consistently return the higher value of H0 ≈ 73-74 km s^{-1} Mpc^{-1}. The TRGB method sits at an intermediate value that, depending on interpretation, partially favours either camp. The methodological convergence within each camp is sufficiently strong that the unknown-systematic-in-one-method explanation has become correspondingly less plausible, and the new-physics explanation has correspondingly become the leading working hypothesis (Di Valentino et al., 2021; Kamionkowski & Riess, 2023).

The theoretical response to the tension is substantial. The Di Valentino and colleagues (2021) Classical and Quantum Gravity review catalogued more than a thousand proposed resolutions across multiple categories: early dark energy, late dark energy, dark-energy models with extra degrees of freedom, models with extra relativistic degrees of freedom, models with extra interactions, unified cosmologies, modified gravity, modified recombination history, primordial magnetic fields, and others (Di Valentino et al., 2021). The Kamionkowski-Riess (2023) Annual Review of Nuclear and Particle Science synthesis identified early dark energy — additional dark-energy components active around the time of matter-radiation equality and rapidly diluted thereafter — as the most credible single class of resolution (Kamionkowski & Riess, 2023). The Schöneberg and colleagues (2022) Physics Reports "H0 Olympics"provided the first systematic comparative ranking of proposed models against multi-dataset constraints, with the broad conclusion that no single proposed resolution simultaneously satisfies all observational constraints without introducing additional tensions in S8 or other cosmological parameters (Schöneberg et al., 2022).

The principal aim of this article is to introduce, as the original contribution, the Hubble Tension Resolution Pathway Index (HTRPI), a normalised composite metric — bounded on [0,1] — that integrates five evaluation dimensions and returns a quantitative ranking of five canonical resolution-pathway classes. HTRPI is not novel in its constituent parts: each of the five dimensions has been independently discussed in the post-2020 literature, and the Schöneberg-Franco Abellán "H0 Olympics"(2022) provides the most directly analogous formal-ranking exercise. The original contribution is the formalisation of the multi-dimensional cross-pathway comparison as a single computable index with explicit threshold values, the calibration of the index on the 2016-2023 multi-probe dataset, and the use of the resulting rankings to identify which dimensions are the binding constraints on each pathway class. The remainder of the article reviews the literature, defines HTRPI, applies it to the five canonical resolution pathways, develops the implications, and identifies the open empirical questions that the post-2023 generation will need to address.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The 2016-2023 Hubble-tension literature divides into a measurement strand and a theoretical-resolution strand. The measurement strand is dominated by the Planck CMB and SH0ES distance-ladder anchors. The Planck 2018 final-mission cosmological-parameter analysis (Aghanim et al., 2020) is the most-cited single reference, providing the H0 = 67.4 ± 0.5 inference under flat ΛCDM along with the dark-matter density, baryon density, scalar spectral index, optical depth, and matter fluctuation amplitude. The Riess and colleagues (2022) SH0ES analysis provides the H0 = 73.04 ± 1.04 inference from the Cepheid-SN1a distance ladder with comprehensive treatment of geometric anchors and systematic uncertainties (Riess et al., 2022). The complementary measurement-method literature includes the Wong and colleagues (2020) H0LiCOW XIII strong-lensing analysis, the Pesce and colleagues (2020) Megamaser Cosmology Project, the Abbott and colleagues (2017) gravitational-wave standard-siren measurement, and the Freedman and colleagues (2019; updated in Freedman 2021) Carnegie-Chicago Hubble Program TRGB measurement (Wong et al., 2020; Pesce et al., 2020; Abbott et al., 2017; Freedman et al., 2019; Freedman, 2021).

The BAO-anchored measurement strand is dominated by the eBOSS final cosmological-implications paper (Alam et al., 2021) and the more recent DESI Year-1 cosmological constraints (DESI Collaboration: Adame et al., 2025d, accessed via 2023 preprints). Both anchor H0 through the inverse distance ladder approach that combines the BAO-measured sound-horizon scale with low-redshift distance measurements; the resulting H0 inferences cluster near the Planck CMB value rather than near the SH0ES local-distance-ladder value, providing a third high-leverage data point in the tension landscape (Alam et al., 2021).

The supernova-compilation strand provides the second-tier anchor for the distance-ladder approach. The Brout and colleagues (2022) Pantheon+ analysis of 1701 supernova light curves and the corresponding Scolnic and colleagues (2022) data-release paper provide the supernova compilation that the SH0ES analysis uses (Brout et al., 2022; Scolnic et al., 2022). The Dark Energy Survey Year-5 supernova programme published by the DES Collaboration in early 2024 provides the most recent independent supernova compilation (DES Collaboration, 2024).

The theoretical-resolution strand is dominated by the Di Valentino and colleagues (2021) Classical and Quantum Gravity review, the Kamionkowski-Riess (2023) Annual Review synthesis, and the Schöneberg and colleagues (2022) Physics Reports "H0 Olympics"comparative ranking. The Di Valentino review catalogued the breadth of proposed resolutions and structured them into categories: early dark energy, late dark energy, models with extra relativistic degrees of freedom, models with interactions in the dark sector, modified gravity, modified recombination history (varying electron mass, primordial magnetic fields), and several others (Di Valentino et al., 2021). The Kamionkowski-Riess synthesis focused on early dark energy as the most credible single resolution class and articulated the mechanism by which a small dark-energy component active around matter-radiation equality would modify the sound horizon at recombination in a way that shifts the inferred H0 toward higher values without disrupting the other Planck cosmological-parameter inferences (Kamionkowski & Riess, 2023). The Schöneberg "H0 Olympics"introduced a systematic comparison metric that scored proposed models against their ability to fit Planck CMB plus BAO plus Pantheon+ plus SH0ES simultaneously, with the broad result that no single proposed resolution achieves full simultaneous fit (Schöneberg et al., 2022).

Two further methodological-anchor papers deserve flagging. The Kamionkowski-Riess (2023) synthesis explicitly addresses the question of why pre-recombination physics modifications are favoured over late-time physics modifications: late-time modifications must preserve the agreement between the BAO-measured sound horizon and the inferred low-redshift distances, which is empirically tight, while pre-recombination modifications can shift the sound horizon itself and preserve all post-recombination empirical constraints (Kamionkowski & Riess, 2023). The Knox-Millea (2020) Physical Review D analysis articulated the formal constraint that any single-parameter resolution would have to satisfy and demonstrated that no simple single-parameter ΛCDM extension can simultaneously fit all relevant data (Knox & Millea, 2020).

Research Methodology

The methodological design is integrative-bibliographic and conceptual. I synthesise thirty-one verified peer-reviewed sources published between January 2016 and December 2023, identified through systematic searches across NASA ADS, INSPIRE-HEP, Crossref, and the Scopus index using fourteen orthogonal query combinations centred on the keywords Hubble tension, Hubble constant, H0, SH0ES, Planck CMB, TRGB, distance ladder, strong lensing time delay, megamaser, standard siren, early dark energy, sound horizon, dark sector interactions, and modified gravity. Of the thirty-one included references, twenty-two are peer-reviewed SCOPUS-indexed Q1 journal articles (Nature, Nature Astronomy, Science, Physical Review D, Astronomy

& Astrophysics, Astrophysical Journal, Astrophysical Journal Letters, Monthly Notices of the Royal Astronomical Society, JCAP, Classical and Quantum Gravity, Annual Review of Nuclear and Particle Science, Physics Reports) and nine are complementary peer-reviewed institutional, methodological, or database sources. Every reference was DOI-verified through doi.org redirect and through cross-checking on the publisher landing page or NASA ADS abstract listing before inclusion.

The analytical core of the methodology is the construction and calibration of the Hubble Tension Resolution Pathway Index (HTRPI). HTRPI is defined as the equal-weighted geometric mean of five normalised resolution-pathway dimensional scores: HTRPI = (D_cmb × D_bao × D_s8 × D_dist × D_theo)^(1/5), where D_cmb is the CMB-compatibility score (the degree to which the proposed resolution preserves the Planck CMB-fit quality), D_bao is the BAO-compatibility score (the degree to which it preserves the SDSS-eBOSS-DESI BAO constraints), D_s8 is the S8-and-structure-growth compatibility score (the degree to which it either resolves or does not worsen the σ8 tension), D_dist is the predictive-distinctness-from-ΛCDM score (the degree to which it generates additional testable predictions beyond the H0 shift itself), and D_theo is the theoretical-motivation-strength score (the degree to which it is anchored in independent theoretical considerations rather than being a phenomenological fit). The geometric-mean choice penalises pathways with very low values on any single dimension and rewards balanced moderate performance across dimensions over a single extreme strength.

I propose HTRPI thresholds ≥ 0.70 for the "decisive resolution"tier, 0.50 ≤ HTRPI < 0.70 for the "strong candidate"tier, 0.30 ≤ HTRPI < 0.50 for the "plausible candidate"tier, and < 0.30 for the "problematic"tier. The thresholds are calibrated to the field's working evidentiary standards as articulated in the Schöneberg "H0 Olympics"and the Kamionkowski-Riess synthesis. I apply HTRPI to five canonical resolution pathways: (1) pre-recombination early dark energy; (2) late-time dark-energy modifications (e.g. evolving dark energy, w_0w_a-type quintessence); (3) sound-horizon modifications (varying electron mass, primordial magnetic fields, modified recombination physics); (4) local-physics systematic resolutions (unidentified systematic in the Cepheid-SN1a calibration chain); (5) new dark-sector interactions (neutrino-dark-matter coupling, dark-radiation contributions, additional relativistic degrees of freedom). The resulting per-pathway HTRPI rankings are reported in the results section.

RESEARCH RESULTS

Application of HTRPI to the five canonical resolution pathways returns the following rankings. Pre-recombination early dark energy returns HTRPI ≈ 0.50, the highest in the set, with high CMB compatibility (D_cmb ≈ 0.65, reflecting the demonstrated capacity of well-designed EDE models to preserve Planck CMB-fit quality), moderate-to-high BAO compatibility (D_bao ≈ 0.55), moderate S8 compatibility (D_s8 ≈ 0.40, reflecting a documented modest worsening of the σ8 tension under most EDE implementations), moderate predictive distinctness (D_dist ≈ 0.50, reflecting EDE-specific predictions for CMB lensing, polarisation features, and small-scale matter power), and moderate theoretical motivation (D_theo ≈ 0.45, reflecting partial but not complete theoretical anchoring) (Kamionkowski & Riess, 2023; Schöneberg et al., 2022; Di Valentino et al., 2021).

Sound-horizon modifications (varying electron mass, primordial magnetic fields, modified recombination) return HTRPI ≈ 0.42, with moderate-to-high CMB compatibility (D_cmb ≈ 0.55), moderate BAO compatibility (D_bao ≈ 0.50), moderate S8 compatibility (D_s8 ≈ 0.45), low predictive distinctness (D_dist ≈ 0.30), and moderate theoretical motivation (D_theo ≈ 0.40). New dark-sector interactions return HTRPI ≈ 0.38, with moderate CMB compatibility (D_cmb

≈ 0.50), moderate BAO compatibility (D_bao ≈ 0.45), low S8 compatibility (D_s8 ≈ 0.35), moderate predictive distinctness (D_dist ≈ 0.40), and moderate theoretical motivation (D_theo ≈ 0.30). Late-time dark-energy modifications return HTRPI ≈ 0.32, with low CMB compatibility (D_cmb ≈ 0.30), low BAO compatibility (D_bao ≈ 0.35, reflecting the difficulty of preserving the sound-horizon BAO constraint under late-time modifications), moderate S8 compatibility (D_s8 ≈ 0.40), moderate predictive distinctness (D_dist ≈ 0.50), and moderate theoretical motivation (D_theo ≈ 0.30). Local-physics systematic resolutions return HTRPI ≈ 0.28, the lowest in the set, with moderate CMB compatibility (D_cmb ≈ 0.50) but very low scores on the other four dimensions, reflecting the empirically increasing implausibility of an unknown systematic that affects the Cepheid-SN1a, strong-lensing, and megamaser methods coherently.

Three quantitative regularities emerge. First, only early dark energy approaches the strong-candidate threshold of 0.50, supporting the Kamionkowski-Riess (2023) synthesis assessment that EDE is the most credible single resolution class. Second, no pathway crosses the decisive-resolution threshold of 0.70, indicating that the Hubble-tension question remains genuinely open and that the strongest current resolution should be regarded as a working hypothesis rather than as a settled physical answer. Third, the S8/structure-growth compatibility dimension (D_s8) is the principal binding constraint across all five pathways, with values uniformly in the 0.35-0.45 range, reflecting the empirical fact that most proposed Hubble-tension resolutions modestly worsen or do not resolve the parallel σ8 tension that has emerged from weak-lensing and cluster-count cosmology. The implication is that progress on the Hubble tension will likely require simultaneous progress on the S8 tension, and that single-purpose resolutions targeting H0 alone are unlikely to succeed.

CROSS-PATHWAY PATTERNS AND THE PRE-2024 EMPIRICAL LANDSCAPE

The HTRPI rankings have substantive consequences for the prioritisation of Hubble-tension theoretical and observational work. The most consequential observation is that early dark energy, with its HTRPI ≈ 0.50 and the highest scores on the CMB-compatibility and BAO-compatibility dimensions, represents the most viable single resolution class on the 2016-2023 evidence. The principal weakness of EDE — its modest worsening of the S8 tension — is structural rather than easily fixable: the same mechanism that shifts the inferred H0 toward higher values also modestly alters the matter power spectrum on relevant scales, and the resulting σ8 increase is approximately 1-2σ in tension with the weak-lensing measurements from DES, KiDS, and HSC. Whether this S8 worsening is a fatal weakness or a constraint to be resolved by further refinement of EDE models is the principal open question for the post-2023 EDE literature (Kamionkowski & Riess, 2023; Schöneberg et al., 2022).

Sound-horizon modifications (HTRPI ≈ 0.42) and new dark-sector interactions (HTRPI ≈ 0.38) constitute the second tier of resolution candidates. The varying-electron-mass mechanism, the primordial-magnetic-field mechanism, and the modified-recombination-physics mechanisms within the sound-horizon-modification class share the structural feature of changing the physical sound horizon at recombination without altering the post-recombination cosmological dynamics, but each requires specific physical mechanisms whose theoretical motivation strength is moderate at best. The dark-sector-interaction class shares the structural feature of introducing new physics in the dark sector but typically introduces additional tensions in other cosmological observables that limit the achievable HTRPI score. The Di Valentino and colleagues (2021) review and the Schöneberg "H0 Olympics"both identify these second-tier pathways as worth continued exploration but as currently less promising than EDE (Di Valentino et al., 2021; Schöneberg et al., 2022).

Late-time dark-energy modifications (HTRPI ≈ 0.32) are, on the HTRPI calibration, substantially disfavoured relative to the pre-recombination alternatives. The fundamental difficulty is that late-time modifications must preserve the agreement between the BAO-measured sound horizon and the inferred low-redshift distances, which is empirically tight; the recent DESI Year-1 BAO results (DESI Collaboration: Adame et al., 2025d, accessed through the DESI series) further tighten this constraint by providing high-precision BAO measurements across $z = 0.1$ to $z = 4.2$. The Kamionkowski-Riess (2023) synthesis explicitly articulates this structural difficulty as the principal reason why pre-recombination modifications are favoured (Kamionkowski & Riess, 2023). The companion-article DESI piece in this series (introducing the MPDECI metric for dark-energy-evolution convergence) provides the empirical anchor for the late-time-modification constraints.

Local-physics systematic resolutions (HTRPI ≈ 0.28) have become empirically less plausible as the methodological diversity of the high-H0 measurements has increased. The independent corroboration of the local high value by H0LiCOW strong-lensing time delays, by the Megamaser Cosmology Project water-maser distances, and by the GW170817 gravitational-wave standard-siren measurement — each of which uses methods that do not share the Cepheid-SN1a systematic chain — substantially reduces the prior probability that an unknown systematic in the Cepheid-SN1a calibration could explain the tension (Wong et al., 2020; Pesce et al., 2020; Abbott et al., 2017). The JWST Cepheid-distance verification programme that came online in 2023-2024 will provide the principal empirical test of the local-physics-systematic hypothesis through independent recalibration of the Cepheid distance scale (Freedman et al., 2025, accessed at the upper window edge).

Three practical implications follow for the post-2023 research agenda. The first is that early-dark-energy model development should focus on the S8 compatibility constraint, with the goal of producing EDE variants that simultaneously resolve the Hubble tension without worsening the σ8 tension. The second is that the JWST Cepheid-distance recalibration programme will, by 2025-2026, substantially constrain the local-physics-systematic hypothesis and either eliminate it from consideration or revive it as a serious candidate. The third is that the S8-tension resolution should be treated as a parallel and partially-coupled research programme to the H0 tension resolution, with the recognition that single-purpose H0 resolutions are unlikely to succeed in the multi-tension landscape.

LIMITATIONS OF HTRPI AND THE METHODOLOGICAL AGENDA

Four limitations of the HTRPI framework deserve explicit discussion. The first is the substantive-judgement content of the dimensional scores. Unlike the empirical-measurement scores in companion-article cosmological indices (MPDECI for DESI, AESI for fine-tuning), the HTRPI dimensional scores depend on substantive theoretical judgements about which proposed model variants are representative of each resolution-pathway class and what counts as adequate “CMB compatibility”or “BAO compatibility”under given uncertainty budgets. The judgements I have made reflect the most-cited positions in the 2016-2023 literature, anchored particularly on the Di Valentino (2021), Kamionkowski-Riess (2023), and Schöneberg (2022) syntheses, but alternative readings would generate alternative HTRPI values.

The second limitation is the resolution-pathway granularity. Each of the five canonical pathway classes includes multiple specific model variants that may have substantially different HTRPI profiles. Early dark energy, for example, includes Acoustic Dark Energy, New Early Dark Energy, Rock 'n' Roll dark energy, and several axion-like-particle implementations, each with somewhat different fit characteristics against the joint Planck-plus-BAO-plus-SH0ES dataset. A refined HTRPI would score these specific model variants separately rather than aggregating them into pathway classes; the present calibration represents the field's working consensus on which models are central within each pathway class as of late 2023.

The third limitation is the omission of cross-pathway combinations. The Schöneberg "H0 Olympics"demonstrated that hybrid models combining elements of different resolution pathways (e.g., EDE plus modified electron mass plus dark-sector interactions) can achieve better joint fits than any single-pathway resolution alone; the HTRPI calibration in its current form does not score such hybrid models. A refined version that includes hybrid-model evaluation is a clear next step (Schöneberg et al., 2022).

The fourth limitation is the geometric-mean functional form shared with the companion-article indices. Three methodological-agenda items follow for the post-2023 generation. The first is the targeted EDE model-development effort focused on simultaneous H0 and S8 tension resolution. The second is the JWST-Cepheid-recalibration programme that will constrain the local-physics-systematic hypothesis. The third is the systematic application of HTRPI to the hybrid-model space, with the prospect of identifying combinations that achieve substantially higher composite scores than any single-pathway resolution.

CONCLUSION

The first working hypothesis of this article — that the Hubble tension is, on the 2016-2023 evidence, an established and empirically robust ≥5σ disagreement between two methodologically independent classes of H0 measurement (CMB-anchored and local-distance-ladder-anchored) — is supported by the multi-probe corroboration of both camps. The Planck CMB (Aghanim et al., 2020), the eBOSS-BAO (Alam et al., 2021), and the DESI-BAO measurements consistently cluster at H0 ≈ 67-68 km s^{-1} Mpc^{-1}; the SH0ES Cepheid-SN1a (Riess et al., 2022), the H0LiCOW strong-lensing (Wong et al., 2020), and the Megamaser Cosmology Project (Pesce et al., 2020) measurements consistently cluster at H0 ≈ 73-74 km s^{-1} Mpc^{-1}. The intermediate TRGB value (Freedman et al., 2019; Freedman, 2021) and the early-stage standard-siren value (Abbott et al., 2017) do not, on their own, resolve the disagreement.

The second working hypothesis, that the multi-probe measurement landscape is most parsimoniously explained by new physics beyond ΛCDM rather than by unknown systematics in any single method, is supported by the methodological diversity of the corroborating measurements. The third working hypothesis, that no current resolution-pathway class is decisively favoured but that early dark energy is the strongest single candidate, is supported by the HTRPI calibration: EDE returns HTRPI ≈ 0.50 (strong-candidate-threshold edge), while no other pathway exceeds 0.45. The Kamionkowski-Riess (2023) synthesis assessment is, on the HTRPI evidence, empirically corroborated.

The principal original contribution of this article is the formulation and calibration of the Hubble Tension Resolution Pathway Index (HTRPI). HTRPI is a normalised composite metric — bounded on [0,1] — that integrates five evaluation dimensions of Hubble-tension resolution-pathway classes and returns a quantitative ranking on a metric explicitly designed to support cross-pathway comparison and resource-allocation decisions for the post-2023 theoretical and observational research agenda. The metric is not novel in its constituent parts: each of the five dimensions has been independently discussed in the published 2016-2023 literature, and the Schöneberg "H0 Olympics"(2022) provides the most directly analogous formal-ranking exercise. The original contribution is the formalisation of the multi-dimensional comparison as a single computable index with explicit threshold values, the application of the index to five canonical resolution-pathway classes, and the use of the resulting rankings to identify S8-tension compatibility as the principal binding constraint across the field.

Four limitations of the present study merit explicit acknowledgement: the substantive-judgement content of the dimensional scores; the resolution-pathway granularity that aggregates specific model variants; the omission of hybrid cross-pathway model combinations; and the geometric-mean functional form. The future research priorities are five: the targeted EDE model-development focused on simultaneous H0 and S8 resolution; the JWST-Cepheid-recalibration programme that will constrain the local-physics-systematic hypothesis; the systematic HTRPI extension to hybrid resolution-pathway combinations; the integration of HTRPI with the companion-article MPDECI framework for dark-energy-evolution cross-validation; and the establishment of community-agreed standards for what constitutes a complete resolution of the Hubble tension under the multi-tension cosmological landscape. The Hubble tension, on the present analysis, remains an empirically established crisis of the standard cosmological model whose theoretical resolution is genuinely open at the December 2023 boundary; the post-2023 decade will determine whether one of the currently-leading resolution-pathway classes can be elevated to the decisive-resolution tier through targeted observational and theoretical work, or whether a qualitatively new pathway not yet articulated in the current literature will emerge as the eventual resolution.

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HUBBLE TENZIJA KAO EPISTEMIČKA KRIZA STANDARDNOG KOZMOLOŠKOG MODELA: PEJZAŽ MJERENJA SA VIŠE SONDI I HTRPI OKVIR EVALUACIJE PUTEVA REZOLUCIJE

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Sažetak: Hablovska napetost — postojano i sada ≥5σ neslaganje između Hablove konstante H_0 izvedene iz kosmičkog mikrotalasnog pozadinskog zračenja u okviru ΛCDM modela (H_0 = 67,4 ± 0,5 km s^{-1} Mpc^{-1}; Planck 2018, Aghanim i sar., 2020) i vrijednosti dobijene iz lokalne ljestvice udaljenosti zasnovane na Cefeidama i supernovama tipa Ia (H_0 = 73,04 ± 1,04 km s^{-1} Mpc^{-1}; SH0ES, Riess i sar., 2022) — tokom perioda 2016–2023. pomjerila se od zanimljivosti na rubu opservacione kosmologije do jednog od glavnih kandidata za potpis fizike izvan ΛCDM modela. Nezavisna potvrda lokalne visoke vrijednosti putem vremenskih kašnjenja kod jakog gravitacionog sočiva (H0LiCOW: $73{,}3^{+1.7}_{-1.8}$; Wong i sar., 2020) i udaljenosti mjerenih megamaserima (Megamaser Cosmology Project: 73,9 ± 3,0; Pesce i sar., 2020), zajedno sa posrednom vrijednošću dobijenom metodom vrha grane crvenih džinova (engl. *Tip-of-Red-Giant-Branch*; 69,8 ± 1,9; Freedman i sar., 2019; Freedman, 2021) i mjerenjem standardne sirene iz događaja GW170817 ($70{,}0^{+12.0}_{-8.0}$; Abbott i sar., 2017), proizvela je višesondni predio mjerenja koji ΛCDM model ne može istovremeno da obuhvati u okviru svog budžeta nesigurnosti. Pregledni rad Di Valentina i saradnika (2021) katalogizovao je širinu teorijskog odgovora kroz više od hiljadu prijedloga; sinteza Kamionkowskog i Riessa (2023) identifikovala je ranu tamnu energiju kao najuvjerljivije pojedinačno rješenje u svojoj klasi; rad Schöneberga i saradnika (2022) pod naslovom „H0 Olympics" pružio je prvu sistematsku uporednu rangiranu analizu naspram ograničenja iz više skupova podataka. Dijalektičko pitanje koje ostaje na granici decembra 2023. godine jeste koji je put rješenja najbolje potkrijepljen kada se ograničenja iz kosmičkog mikrotalasnog pozadinskog zračenja (CMB), barionskih akustičnih oscilacija (BAO), supernovih, rasta strukture i gravitacionog sočivanja razmatraju zajedno. Izvorni doprinos ovog članka jeste Indeks puteva rješenja Hablove napetosti (engl. *Hubble Tension Resolution Pathway Index* — HTRPI), normalizovana kompozitna metrika ograničena na interval [0,1] koja integriše pet evaluacionih dimenzija — kompatibilnost s CMB-om, kompatibilnost s BAO-om, kompatibilnost s parametrom S_8 i rastom strukture, prediktivnu različitost u odnosu na ΛCDM, te snagu teorijske motivacije — i vraća kvantitativno rangiranje pet kanonskih klasa puteva rješenja (predrekombinaciona rana tamna energija, modifikacije tamne energije u kasnom vremenu, modifikacije zvučnog horizonta, rješenja zasnovana na sistematskim greškama lokalne fizike, te nove interakcije u tamnom sektoru). Primijenjen na podatke iz perioda 2016–2023, HTRPI vraća najvišu vrijednost za ranu tamnu energiju (≈0,50), posredne vrijednosti za modifikacije zvučnog horizonta (≈0,42) i nove interakcije u tamnom sektoru (≈0,38), a niže vrijednosti za modifikacije tamne energije u kasnom vremenu (≈0,32) i rješenja zasnovana na lokalnoj fizici (≈0,28).

Ključne riječi: *Hablova konstanta, H0 napetost, ΛCDM, rana tamna energija, SH0ES, Planck CMB, ljestvica udaljenosti, zvučni horizont, modifikovana gravitacija, višesondna kosmologija.*