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The Hubble Tension: A Review of Early- and Late-Universe Determinations of the Cosmic Expansion Rate and Proposed Theoretical Resolutions

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FULL ABSTRACT

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The Hubble Tension: A Review of Early- and Late-Universe Determinations of the Cosmic Expansion Rate and Proposed Theoretical Resolutions

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Abstract

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Keywords: *cosmic chronometers, cosmic distance ladder, cosmic microwave background, Cosmology, Dark energy, gravitational lensing, Hubble constant, Hubble tension, standard sirens, ΛCDM*

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1. Introduction

1.1. Historical background

Edwin Hubble's 1929 discovery that the recession velocity of galaxies scales linearly with distance established the expansion of the universe and defined the constant of proportionality, H0, that bears his name; Hubble's original estimate, roughly 500 km s^{-1} Mpc^{-1}, was later found to be too large by nearly an order of magnitude because of systematic errors in his distance calibration, a reminder that the history of H0 measurement is itself a history of identifying and correcting subtle systematics. Through the mid-to-late twentieth century, the value of H0 was the subject of a prolonged and often personal dispute, most famously between Allan Sandage, who favored values near 50 km s^{-1} Mpc^{-1}, and Gérard de Vaucouleurs, who favored values near 100 km s^{-1} Mpc^{-1}. This factor-of-two disagreement was substantially resolved by the HST Key Project in the early 2000s, which used Cepheid variables to calibrate multiple secondary distance indicators and converged on H0 = 72 ± 8 km s^{-1} Mpc^{-1}. It is against this backdrop that the modern tension, at the ~7% level between early- and late-universe probes, should be judged: it is a far smaller discrepancy than the Sandage–de Vaucouleurs dispute, but the measurements on each side are now individually precise enough that the discrepancy is statistically much more significant.

1.2. The modern tension

Over the last decade a statistically significant discrepancy has re-emerged between two broad classes of H0 determination. Measurements that rely on the physics of the early universe — the acoustic oscillations imprinted in the CMB and in the large-scale distribution of galaxies — combined with the assumption that the universe is well described by the flat ΛCDM model, consistently return H0 ≈ 67–68 km s^{-1} Mpc^{-1}. Measurements that instead build a distance ladder through the local universe, or that measure distances geometrically and independently of any ladder, cluster in the range H0 ≈ 70–75 km s⁻¹ Mpc⁻¹. Taken together, the two regimes now disagree at a level reported between 4σ and 6σ depending on the specific datasets combined, a discrepancy widely termed the "Hubble tension." Unlike earlier cosmological disputes that were resolved by additional data revealing a systematic error on one side, the Hubble tension has hardened as measurement precision has improved on both sides, which is one of the principal reasons it is now taken seriously as a possible signal of physics beyond ΛCDM rather than as a transient calibration problem.

This review has five aims: to place the tension in historical context and summarize the theoretical framework relating H0 to the sound horizon and cosmic expansion history; to summarize the principal early-universe and late-universe methods for determining H0, including several less commonly reviewed techniques; to tabulate and compare the resulting values directly; to review the systematic-error investigations that have progressively closed off mundane explanations for the tension; and to survey and critically assess the leading theoretical proposals advanced to reconcile the two regimes.

2. Scope and method of this review

This review synthesizes results from the primary cosmological literature published between approximately 2002 and 2026, prioritizing measurements from large collaborations (Planck, DESI, SH0ES, H0LiCOW/TDCOSMO, the Megamaser Cosmology Project) and recent independent cross-checks, including JWST-based recalibrations of the distance ladder. It is restricted to determinations of the present-day Hubble parameter, H0, and does not attempt to cover the related but distinct S8/σ8 tension in the amplitude of matter clustering, except where a proposed resolution explicitly links the two. Numerical values are quoted as reported in the cited sources, generally at 68% confidence, and readers requiring the most current figures are directed to the original works, since this remains an actively evolving field in which central values shift by fractions of their quoted uncertainty from one data release to the next.

3. Theoretical framework

In the standard Friedmann-Lemaître-Robertson-Walker (FLRW) cosmology, the expansion rate at redshift z is governed by the Friedmann equation,

$$H(z)^2 = H_0^2[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda] \quad \text{(flat ΛCDM)},$$

where Ω_m, Ω_r, and Ω_Λ are the present-day fractional densities of matter, radiation, and dark energy. $H_0 = H(z = 0)$ is therefore not an independent free parameter of the theory in the same sense as Ω_m; rather, it is the normalization that fixes the absolute scale of distances and times once the shape of $H(z)$ has been determined.

Early-universe methods measure H_0 indirectly, via the sound horizon at the drag epoch,

$$r_s = \int [c_s(z)/H(z)]\, dz, \quad \text{integrated from } z = z_{\text{drag}} \text{ to } z \to \infty,$$

where $c_s(z)$ is the sound speed of the pre-recombination photon-baryon fluid. The CMB and BAO observations measure the angular or comoving scale of this standard ruler on the sky; since r_s itself is fixed by well-understood early-universe microphysics (the baryon and photon densities), converting an observed angular scale into H_0 requires assuming a specific expansion history, $H(z)$, between the drag epoch and today — which is precisely the ΛCDM assumption under scrutiny. Any new physics that changes r_s, or that changes $H(z)$ at low redshift relative to ΛCDM, will change the inferred H_0 without requiring any flaw in the CMB or BAO data themselves.

Late-universe, distance-ladder methods instead measure H_0 directly and locally, via the Hubble-Lemaître law in its differential form,

$$v = H_0 d$$

(in the limit of small z, after correcting for peculiar velocities),

using a luminosity distance, d, established through a chain of geometric and standard-candle calibrators. This route requires no assumption about the expansion history at high redshift, but it does require that each rung of the distance ladder — geometric parallax or maser distances, the Cepheid (or TRGB/JAGB) period–luminosity or luminosity-cutoff relation, and the SN Ia standardization relation — be free of unrecognized systematics. The theoretical asymmetry between the two routes is central to interpreting the tension: the early-universe route is precise but model-dependent, while the late-universe route is comparatively model-independent but depends on a longer chain of empirical calibrations.

4. Early-universe determinations of H0

The most precise early-universe determination of H0 comes from the CMB temperature and polarization anisotropy power spectra measured by the Planck satellite. Within the flat ΛCDM model, the physical scale of the sound horizon at recombination, rs, is fixed by the pre-recombination physics of the photon-baryon fluid, and its observed angular size on the sky, combined with the angular-diameter distance to the last-scattering surface, jointly determine H0. This chain yields H0 = 67.4 ± 0.5 km s⁻¹ Mpc⁻¹ (Planck Collaboration, 2020). Because this inference depends on extrapating the flat ΛCDM model from redshift z ≈ 1100 to the present day, it is properly described as an indirect, model-dependent measurement rather than a direct one: any new physics that alters the sound horizon or the late-time expansion history relative to ΛCDM would change the inferred H0 without requiring any error in the Planck data itself.

An independent early-universe route combines baryon acoustic oscillation (BAO) measurements of the three-dimensional galaxy distribution with the sound horizon calibrated by Big Bang nucleosynthesis (BBN), bypassing the CMB entirely. The Dark Energy Spectroscopic Instrument (DESI) has produced BAO measurements spanning a wide range of redshifts from its DR1 and DR2 releases; combined with BBN-calibrated physical baryon and matter densities, these measurements return an H0 consistent with the Planck result, reinforcing the early-universe value at approximately 67–68 km s⁻¹ Mpc⁻¹ (DESI Collaboration, 2025). The mutual agreement of two independent early-universe probes — CMB anisotropies and BAO+BBN — that rely on largely independent systematics is one of the strongest arguments that the tension does not simply reflect an error internal to the Planck analysis pipeline.

A further, still-developing early-universe channel uses the DESI BAO measurements themselves to test the flat ΛCDM assumption. Several DESI DR1/DR2 analyses report a mild statistical preference, at the 2–3σ level depending on the supernova compilation used, for a dark-energy equation of state that departs from w = −1 and evolves with redshift. If confirmed, this would mean that the "early-universe" H0 value is itself model-dependent in a way not previously appreciated, since it is derived assuming a specific, and possibly incorrect, late-time expansion history (DESI Collaboration, 2025).

5. Late-universe determinations of H0

5.1. Cepheid-calibrated distance ladder

The traditional route to a direct, local measurement of H0 is the three-rung cosmic distance ladder: geometric parallax and detached-eclipsing-binary (DEB) distances calibrate the Cepheid period–luminosity relation, Cepheids calibrate the peak luminosity of Type Ia supernovae (SNe Ia) in their host galaxies, and those supernovae are then observed out to distances where the smooth Hubble flow dominates over local peculiar velocities. The first rung is anchored primarily by DEB distances to the Large Magellanic Cloud (LMC), Milky Way Cepheid parallaxes from Gaia, and megamaser and DEB distances to NGC 4258. Using this method, the SH0ES (Supernovae and H0 for the Equation of State of dark energy) collaboration reports H0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1} (Riess et al., 2022), and an extended calibrator sample re-observed with JWST gives a consistent H0 = 72.6 ± 2.0 km s^{-1} Mpc^{-1} (Riess et al., 2024). The quoted 1.4% uncertainty on the SH0ES value is dominated by the combination of all four anchor distances and the SN Ia standardization scatter, rather than by any single rung.

5.2. TRGB and JAGB calibrations

Alternative first-rung calibrators give a more heterogeneous picture. The Tip of the Red Giant Branch (TRGB) method, applied by the Carnegie-Chicago Hubble Program, calibrates SN Ia hosts using the sharp luminosity cutoff of red giant stars rather than Cepheids, and returns a somewhat lower value, H0 = 69.6 ± 1.9 km s^{-1} Mpc^{-1} (Freedman et al., 2019, 2020), statistically consistent with both the Planck and SH0ES results within its larger uncertainty. The related J-region Asymptotic Giant Branch (JAGB) method gives comparable intermediate values when applied to the same calibrator hosts. Because TRGB and JAGB distances are measured in the outer haloes of galaxies and are largely insensitive to interstellar dust and to the Cepheid period-luminosity relation's known metallicity dependence, their intermediate placement suggests that at least part of the reported spread among late-universe measurements may trace to the choice of stellar distance indicator and its associated systematics, rather than to new physics.

5.3. Geometric and standard-candle methods independent of Cepheids

Several methods measure H0 without any Cepheid calibration. The Megamaser Cosmology Project uses the geometry of water-maser disks orbiting supermassive black holes to obtain purely geometric distances to the host galaxies, yielding H0 = 73.9 ± 3.0 km s^{-1} Mpc^{-1} (Pesce et al., 2020). The surface brightness fluctuation (SBF) method, which measures the pixel-to-pixel graininess of unresolved starlight in early-type galaxies, gives H0 = 73.3 ± 2.4 km s^{-1} Mpc^{-1} (Blakeslee et al., 2021). The Tully–Fisher relation between a spiral galaxy's rotation velocity and luminosity, calibrated with Cepheid-hosting galaxies, gives H0 = 75.1 ± 2.3 km s^{-1} Mpc^{-1} (Kourkchi et al., 2020). With the partial exception of TRGB, essentially all late-universe, non-CMB methods return values at or above H0 ≈ 70 km s^{-1} Mpc^{-1}, reinforcing the late-universe side of the tension using techniques with largely independent systematics from the Cepheid ladder.

5.4. Strong-lensing time-delay cosmography

Strong gravitational-lens time-delay cosmography, in which the time delay between multiple images of a lensed quasar or supernova is combined with a model of the foreground lens galaxy's mass distribution, offers a fully independent, one-step geometric route to H0 that requires no distance ladder at all. Assuming a simple power-law mass profile for the lens galaxies, the H0LiCOW collaboration reported H0 = 73.3 ± 1.8 km s^{-1} Mpc^{-1} from six lensed quasars, in agreement with SH0ES and in tension with Planck at the 5.3σ level (Wong et al., 2020). However, the successor TDCOSMO collaboration showed that relaxing the assumed lens mass profile and instead using spatially resolved stellar kinematics to constrain it directly, without an informative prior from external power-law-lens samples, substantially inflates the uncertainty and shifts the central value downward to H0 = 67.4 (+4.1/−3.2) km s^{-1} Mpc^{-1}, consistent with both Planck and SH0ES (Birrer et al., 2020). More recent TDCOSMO analyses using improved spatially resolved kinematics for individual lenses have sought to reduce this degeneracy while retaining physically motivated priors, generally recovering values intermediate between the original H0LiCOW result and the fully free Birrer et al. analysis (TDCOSMO Collaboration, 2023). This body of work demonstrates that the strong-lensing H0 value is more sensitive to assumptions about lens mass-density profiles than originally appreciated, and that its contribution to the overall tension should be weighted accordingly.

5.5. Gravitational-wave standard sirens

Gravitational-wave "standard sirens" offer a further, fully independent channel: the amplitude of a compact-binary merger's gravitational-wave signal gives a direct luminosity distance without any distance-ladder calibration, which, combined with an electromagnetic redshift measurement or a statistical host-galaxy association, yields H0. The landmark binary neutron star merger GW170817 gave H0 ≈ 70 km s^{-1} Mpc^{-1} with an uncertainty broad enough to be consistent with both the Planck and SH0ES values (Abbott et al., 2017). Subsequent events, including statistical "dark siren" analyses without electromagnetic counterparts, have tightened this constraint only modestly; standard sirens currently lack the precision to adjudicate the tension alone but are expected to reach percent-level precision as the LIGO-Virgo-KAGRA network and next-generation detectors accumulate a larger sample of well-localized events.

5.6. Cosmic chronometers

Cosmic chronometers estimate the expansion rate H(z) directly from the differential ages of pairs of massive, passively evolving galaxies at similar redshift, via $H(z) = -(1/(1+z))(dz/dt)$, without assuming any specific cosmological model (Jimenez & Loeb, 2002). Because this method constrains the shape of H(z) rather than its absolute normalization, it does not determine H0 in isolation; H0 must be obtained by extrapolating the reconstructed H(z) to z = 0 or by combining chronometer data with an external calibration such as SN Ia distances. When combined with supernova data in this way, cosmic-chronometer analyses have returned H0 = 67.4 ± 4.75 km s^{-1} Mpc^{-1} (Gomez-Valent & Amendola, 2018), a value with an uncertainty too large to discriminate strongly between the Planck and SH0ES results but broadly consistent with the lower, early-universe value. The chronometer method's principal appeal is its independence from both the cosmic distance ladder and the CMB sound horizon; it will become increasingly competitive as spectroscopic samples of quiescent galaxies grow and as ages are calibrated with improved stellar population synthesis models.

5.7. Quasar and high-redshift cosmography

A distinct approach exploits the nonlinear relation between the ultraviolet and X-ray luminosities of quasars to build a Hubble diagram extending to redshifts far beyond the reach of SNe Ia, z ≈ 5–7 (Risaliti & Lusso, 2019). Because quasars are not true standard candles in the same sense as SNe Ia — the luminosity relation must be calibrated and has intrinsic scatter — this method is generally used less as a direct H0 measurement than as a consistency test of ΛCDM at high redshift. The quasar Hubble diagram, together with related high-redshift compilations combining SNe Ia, quasars, and gamma-ray bursts, has been reported to show a deviation from the flat ΛCDM expansion history extrapolated from low-redshift SN Ia fits at a significance of several sigma, which some authors interpret as independent, redshift-dependent evidence consistent with an evolving dark-energy equation of state of the kind also hinted at by recent DESI BAO analyses (Risaliti & Lusso, 2019). This result remains actively debated, since it depends sensitively on the quasar sample selection and on corrections for intrinsic scatter, but it illustrates that evidence relevant to the Hubble tension is not confined to the traditional CMB-versus-distance-ladder comparison.

Table 1. Selected Determinations of H0

Method	H0 (km s^{-1} Mpc^{-1})	Reference
CMB (Planck, ΛCDM)	67.4 ± 0.5	Planck Collaboration (2020)
BAO + BBN (DESI)	≈ 68	DESI Collaboration (2025)
Cepheid + SNe Ia (SH0ES)	73.04 ± 1.04	Riess et al. (2022)
Cepheid + SNe Ia (JWST)	72.6 ± 2.0	Riess et al. (2024)
TRGB + SNe Ia	69.6 ± 1.9	Freedman et al. (2019, 2020)
Tully–Fisher (Cepheid-cal.)	75.1 ± 2.3	Kourkchi et al. (2020)
Megamasers (geometric)	73.9 ± 3.0	Pesce et al. (2020)
Surface Brightness Fluctuations	73.3 ± 2.4	Blakeslee et al. (2021)
Strong lensing (power-law profile)	73.3 ± 1.8	Wong et al. (2020)
Strong lensing (free mass profile)	67.4 (+4.1/−3.2)	Birrer et al. (2020)
GW standard sirens	≈ 70 (broad)	Abbott et al. (2017)
Cosmic chronometers + SNe Ia	67.4 ± 4.75	Gomez-Valent & Amendola (2018)

Uncertainties are as quoted in the original sources (statistical and, where reported, systematic terms combined). Values in the upper block are early-universe, model-dependent determinations; values in the lower block are late-universe, geometric, or model-independent determinations.

6. Assessing systematics

6.1. The role of JWST

Because the Cepheid-based distance ladder is the most precise late-universe route to H0, an early and widely discussed hypothesis was that the tension reflected an unrecognized systematic in Hubble Space Telescope (HST) Cepheid photometry — for example, contamination from crowded stellar fields or blending with unresolved companions in the crowded fields of the calibrator hosts, an effect to which HST's angular resolution is more susceptible than JWST's. JWST's superior resolution was expected to test this hypothesis directly. Re-observation of the SH0ES Cepheid calibrator hosts with JWST confirmed, rather than overturned, the HST photometry: the JWST magnitudes agree with the earlier HST measurements to within their quoted uncertainties, ruling out crowding and blending as the dominant source of the discrepancy (Riess et al., 2024). Rather than resolving the tension, this result has deepened it, since it removes the most widely discussed mundane explanation and strengthens the case that the discrepancy reflects either an unrecognized systematic elsewhere in the analysis chain or genuine physics beyond ΛCDM.

6.2. SN Ia standardization and the LMC anchor

Beyond Cepheid photometry, two further systematics are routinely scrutinized. First, SN Ia peak luminosities are standardized using empirical relations between light-curve shape, color, and host-galaxy properties; residual, unmodeled dependence of these relations on host-galaxy mass or star-formation history could in principle introduce a redshift-dependent bias between the nearby Cepheid-calibrator hosts and the more distant Hubble-flow sample, although current analyses find no evidence for a bias of the size needed to resolve the tension. Second, the absolute distance to the LMC, one of the primary geometric anchors of the first rung, is now known to better than 1% from a large sample of DEB systems; because this distance propagates directly into H0, continued refinement and independent cross-checks of the LMC distance remain an active priority.

6.3. Lens-modeling systematics

As discussed in Section V.D, the strong-lensing route to H0 is subject to a well-documented mass-sheet degeneracy between the lens galaxy's radial mass profile and the inferred H0; different, individually plausible assumptions about that profile can shift the central value by several km s^{-1} Mpc^{-1}, comparable to the full size of the tension. This is arguably the single largest identified systematic uncertainty among the methods reviewed here, and it argues for caution in treating early published lensing results as fully independent confirmations of the SH0ES value.

7. Quantifying the tension

The commonly quoted “5σ” figure typically refers to a direct comparison of the Planck and SH0ES central values and uncertainties, treating each as an independent Gaussian measurement: the tension in standard deviations is simply the difference in central values divided by the combined uncertainty added in quadrature. More sophisticated statistical treatments account for the fact that a simple Gaussian comparison can be sensitive to the specific pair of experiments chosen and to non-Gaussian tails in either posterior; metrics such as the difference-in-maximum-a-posteriori statistic (Q_DMAP) and Bayesian suspiciousness have been developed to test tension robustly across more complex, non-Gaussian, or correlated datasets.

Because a two-experiment comparison is potentially sensitive to the idiosyncrasies of either analysis, several groups have assembled larger compilations of independent, largely sound-horizon-free H0 measurements — spanning strong lensing, standard sirens, masers, surface-brightness fluctuations, cosmic chronometers, and distance-ladder-free SN Ia spectral modeling — to test whether the tension persists as a general feature of the data rather than a peculiarity of any single pair of experiments. Recent compilations of several dozen such measurements, updated through late 2025, find that the discrepancy between the distance-ladder ensemble and the distance-ladder-independent, sound-horizon-free ensemble persists at a comparable or greater significance than the traditional Planck-versus-SH0ES comparison, and is robust to the exclusion of any single measurement or methodological class, strengthening the case that the tension is a general feature of the data.

8. Theoretical proposals for resolution

With late-time photometric systematics increasingly disfavored by the JWST results, and with the strong-lensing tension shown to be sensitive to lens-modeling assumptions, attention has increasingly shifted to modifications of the standard cosmological model. Proposals broadly fall into five categories.

8.1. Early dark energy and modified pre-recombination physics

Early Dark Energy (EDE) models introduce an additional energy component that is dynamically significant only around the epoch of matter-radiation equality, briefly increasing the early-universe expansion rate and thereby shrinking the sound horizon, rs, imprinted in the CMB and BAO. Because the CMB-inferred H0 depends on rs through the fixed angular scale of the acoustic peaks, a smaller sound horizon raises the inferred H0, potentially reconciling it with the SH0ES value. EDE models can partially relieve the tension but generally require finely tuned parameters, and they are constrained by their effect on the CMB damping tail and on the growth of large-scale structure, which current data do not obviously favor (Poulin, Smith, & Karwal, 2023). Closely related proposals invoke modified recombination physics, primordial magnetic fields, or additional relativistic species (an increase in the effective number of neutrino species, ΔNeff) to alter rs by similar mechanisms; all such proposals face the same basic tension between resolving H0 and preserving the excellent fit of ΛCDM to the detailed shape of the CMB power spectrum.

8.2. Evolving dark energy and late-time modifications

Evolving dark-energy models relax the assumption that dark energy behaves as a strict cosmological constant. Recent DESI BAO results, when combined with CMB and supernova data, show a preference, at low-to-moderate statistical significance, for a dark-energy equation of state that evolves with redshift, often parameterized as w0waCDM, rather than the fixed w = −1 of ΛCDM. Several analyses find that allowing the effective H0 to decline smoothly with the redshift range probed — from values consistent with SH0ES at low redshift toward values consistent with Planck at high redshift — can substantially relieve the tension without introducing new early-universe physics (DESI Collaboration, 2025). Interacting dark-energy models, in which dark energy exchanges energy with dark matter at a rate that depends on redshift, have been proposed on similar grounds and can, in some parameterizations, simultaneously address the S8 tension.

8.3. Modified gravity

A smaller body of work explores departures from general relativity on cosmological scales, such as scalar-tensor or f(R) gravity, which can alter both the growth of structure and the effective expansion history in ways that partially mimic evolving dark energy. These models generally face tight constraints from solar-system tests, the observed near-equality of the speed of gravitational waves and light established by the electromagnetic counterpart to GW170817, and large-scale-structure data, which together limit the viable parameter space for a full resolution of the tension through modified gravity alone.

8.4. Ladder-wide and cross-cutting systematics

A further class of explanation asks whether an as-yet-unidentified systematic affects multiple, nominally independent late-universe methods coherently — for instance, through a shared dependence on the same small set of geometric anchor distances (such as the DEB-based distance to the LMC) or on common assumptions in SN Ia standardization. The general agreement among Cepheid, megamaser, SBF, and Tully–Fisher determinations, which do not share identical systematics, makes a single coherent ladder-wide error a less parsimonious explanation than it was several years ago, but it has not been definitively excluded, and ongoing work — including a JWST program to cross-calibrate the TRGB and SBF distance scales — is specifically designed to test it.

8.5. Other and combined proposals

A range of less mainstream proposals has also been explored, including spatial curvature departing from exact flatness, time-varying fundamental constants, decaying dark matter, and primordial non-Gaussianity affecting the CMB-inferred sound horizon indirectly. Several recent studies also combine elements of the above categories — for example, early dark energy together with a modestly evolving late-time equation of state — finding that hybrid models can relieve the tension further than either ingredient alone, at the cost of additional free parameters and reduced predictivity.

Table 2. Summary of Proposed Theoretical Resolutions

Proposal	Mechanism	Current status
Early Dark Energy (EDE)	Shrinks sound horizon rs before recombination, raising CMB-inferred H0	Partial relief; requires fine-tuning; constrained by CMB damping tail
Evolving dark energy ($w_0 w_a$CDM)	Late-time expansion history departs from w = −1	Mildly favored by DESI BAO; substantial relief possible
Modified gravity (e.g., f(R))	Alters growth of structure and effective H(z)	Tightly constrained by GW170817 and structure growth
Interacting dark energy	Energy exchange between dark energy and dark matter	Can address H0 and S8 tensions jointly; model-dependent
ΔN_{eff} / extra relativistic species	Increases early expansion rate, shrinks rs	Constrained by CMB and BBN light-element abundances
Ladder-wide systematic	Shared bias across Cepheid, TRGB, SBF, maser, lensing methods	Increasingly disfavored by mutual method agreement
Residual lens mass-profile bias	Power-law priors bias strong-lensing H0 high	Confirmed as a real, partial contributor (Birrer et al., 2020)

9. Discussion

The Hubble tension can usefully be framed as a cosmological trilemma: the reliability of the ΛCDM model, the reliability of early-universe (CMB/BAO) inferences of H0 within that model, and the reliability of late-universe determinations of H0 cannot all be simultaneously correct at face value. The JWST recalibration of the Cepheid distance ladder has substantially weakened the case that late-universe photometric systematics alone are responsible, while the mutual agreement between CMB and BAO+BBN early-universe probes weakens the case for an isolated Planck-specific error. The demonstration that strong-lensing H0 values are sensitive to lens mass-profile assumptions is an important cautionary result, showing that at least one late-universe method's contribution to the tension is more model-dependent than originally reported — a reminder that not every late-universe method is equally probative, and that the strength of the tension should be assessed from the full ensemble in Table I rather than from any single pairwise comparison. The mild, independent hints of evolving dark energy from DESI BAO and from the quasar Hubble diagram add a further, largely independent line of evidence that the late-time expansion history may genuinely depart from ΛCDM, which would naturally link the Hubble tension to changes already being discussed for other reasons. Taken together, the balance of current evidence leaves genuine physics beyond ΛCDM — whether in the pre-recombination era, in the dark-energy sector, or in a subtle systematic common to several distance indicators — as an increasingly plausible explanation, though no single proposal currently commands consensus support.

10. Future prospects

Several forthcoming observational programs are expected to materially sharpen this picture over the next decade. The Vera C. Rubin Observatory's Legacy Survey of Space and Time will discover and monitor large samples of SNe Ia and lensed quasars, improving both the distance-ladder and time-delay-cosmography routes to H0 and providing the statistics needed to average over individual lens-modeling systematics. The Euclid and Nancy Grace Roman Space Telescope missions will extend precise photometric and geometric distance measurements, including TRGB and Cepheid distances, to larger, more homogeneous samples of galaxies over a wider volume than currently accessible from the ground or with HST. A dedicated JWST program aims to establish a firm, TRGB-anchored zero point for the SBF distance scale, directly testing whether ladder-wide systematics can account for part of the tension. DESI's continuing data releases, together with forthcoming spectroscopic surveys, will sharpen constraints on any redshift evolution of the dark-energy equation of state. Finally, an expanding catalogue of gravitational-wave standard sirens from the LIGO-Virgo-KAGRA network and, in the following decade, from the Einstein Telescope and Cosmic Explorer, is expected to eventually deliver an H0 measurement with percent-level precision that is independent of both the CMB and the electromagnetic distance ladder, potentially providing a decisive arbitration of the tension.

11. Limitations of this review

This review is necessarily a synthesis rather than an exhaustive meta-analysis: it does not perform an independent joint statistical combination of the measurements in Table I, and the central values quoted are taken directly from the cited sources without re-analysis. Coverage of the theoretical-proposal literature, which is extremely large and rapidly evolving, is representative rather than complete, and some promising but more speculative proposals have been omitted for brevity. Readers seeking a fully quantitative, continuously updated meta-analysis are directed to the dedicated compilation papers cited in Section VII.

12. Conclusion

A century of increasingly precise measurement — from Hubble's original, order-of-magnitude estimate, through the Sandage–de Vaucouleurs controversy, to the sub-percent-level precision of the modern era — has hardened, rather than dissolved, the discrepancy between early- and late-universe determinations of H0. Early-universe probes anchored in ΛCDM converge tightly on H0 ≈ 67–68 km s^{-1} Mpc^{-1}, while a broad and methodologically diverse ensemble of late-universe measurements clusters around H0 ≈ 70–75 km s^{-1} Mpc^{-1}, and JWST observations have removed the leading purely photometric explanation for the gap. Reconciling the two regimes will likely require either a modification of early-universe physics, such as early dark energy or additional relativistic species; a modification of late-time physics, such as an evolving dark-energy equation of state; or the identification of a subtle systematic shared across several, only partially independent distance indicators. Forthcoming data from the Vera C. Rubin Observatory, Euclid, the Roman Space Telescope, and an expanding gravitational-wave standard-siren catalogue should provide the statistical power needed to distinguish between these possibilities within the next decade.

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