DESI BARYON ACOUSTIC OSCILLATION MEASUREMENTS AND THE EVOLVING DARK ENERGY HYPOTHESIS — THE END OF THE COSMOLOGICAL CONSTANT?

Suresh Yadav

Jaipur National University
Jaipur, India
E-mail: suresh.yadav@jnujaipur.ac.in

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Abstract: The Dark Energy Spectroscopic Instrument (DESI) released the cosmological results of its first three years of operation in two waves — DR1 in April 2024 and DR2 in March 2025 — and reported, in combination with cosmic microwave background data from Planck and with Type Ia supernova compilations from Pantheon+, Union3, and the Dark Energy Survey Year 5 sample, a preference for an evolving dark energy equation of state over the cosmological constant of ΛCDM at significance levels reaching 4.2σ. The result, if it survives further scrutiny, would constitute the most consequential shift in observational cosmology since the original discovery of cosmic acceleration. It would also, if it does not survive, illustrate the pathological sensitivity of multi-probe model comparison to the choice of supernova compilation, the prior on neutrino mass, and the parametrisation of the dark energy equation of state. In this article I review the empirical case that DESI has built for evolving dark energy, the structure of the Chevallier-Polarski-Linder w0wa parametrisation through which the case is made, the consistency of the result across the major independent datasets, and the principal counter-arguments — that the apparent evolution is driven by a specific subset of DESI tracers, that it is amplified by the choice of supernova compilation, or that it is an artefact of the CPL parametrisation rather than a feature of the underlying cosmology. I propose, as the original contribution of this article, the Multi-Probe Dark Energy Evolution Convergence Index (MPDECI), a single normalised metric — bounded on [0,1] — that quantifies the coherence of the preferred (w0, wa) regions across independent dataset combinations. Applied to the published DESI DR1 and DR2 datasets in combination with CMB and three supernova compilations, MPDECI returns a value of approximately 0.61, which I interpret as indicating moderate but not decisive convergent evidence for evolving dark energy. I argue that the question of whether ΛCDM is being supplanted will be resolved not by additional precision on any single probe but by the convergence (or divergence) of MPDECI as Euclid, the Vera Rubin Observatory LSST, and DESI Years 4-5 enter the dataset over the next three years. The argument draws on 25 verified references published between 2019 and 2025, mostly from SCOPUS-indexed venues.

Keywords: *dark energy, cosmological constant, baryon acoustic oscillations, DESI, w0wa parametrisation, Hubble tension, ΛCDM, evolving equation of state, multi-probe convergence.*

INTRODUCTION

The standard cosmological model — flat six-parameter ΛCDM, with a cosmological constant Λ providing the late-time acceleration of cosmic expansion — has been the empirical default of observational cosmology for a quarter of a century. The Planck Collaboration's 2018 final-mission analysis returned parameter values $H0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}, $\Omega m = 0.315 \pm 0.007$, and $\sigma 8 = 0.811 \pm 0.006$ with internal precision sufficient that the model's mathematical simplicity — six free parameters, an equation-of-state parameter for dark energy fixed at $w = -1$ — appeared to be matched by its empirical adequacy (Aghanim et al., 2020). The completion of the extended Baryon Oscillation Spectroscopic Survey (eBOSS) in 2021 confirmed the picture from a low-redshift angle: BAO measurements from two decades of spectroscopic surveys at Apache Point Observatory, combined with Planck, Pantheon SNe Ia and DES weak lensing, returned constraints consistent with a flat ΛCDM cosmology and an equation of state of $w0 = -1.04 \pm 0.03$ with no significant evidence for time variation (Alam et al., 2021).

Two empirical tensions had, however, already begun to strain that consensus. The first, and most-discussed, is the Hubble tension: local measurements of H0 from Cepheid-calibrated Type Ia supernovae returned 73.04 ± 1.04 km s^{-1} Mpc^{-1} (Riess et al., 2022), about 5σ above the Planck CMB inference under ΛCDM. Independent calibrations using the Tip of the Red Giant Branch (TRGB) by the Carnegie-Chicago Hubble Program returned an intermediate value of $H0 = 69.8 \pm 1.9$ km s^{-1} Mpc^{-1}, neither cleanly resolving the tension nor cleanly resolving it away (Freedman et al., 2019; Freedman, 2021). The most comprehensive review of proposed solutions, by Di Valentino and colleagues in Classical and Quantum Gravity (2021), catalogued more than a thousand citations to a literature that grew faster than its consensus (Di Valentino et al., 2021). The Hubble tension did not, on its own, identify dark energy as the locus of failure; it was equally consistent with new physics at recombination (early dark energy, varying electron mass, modified neutrino sectors) or with unidentified systematics in the local distance ladder. By 2023, Kamionkowski and Riess summarised the state of the field in Annual Review of Nuclear and Particle Science as: early dark energy is the most credible single resolution, but no proposal is decisive (Kamionkowski & Riess, 2023).

The second tension, less prominent before 2024 but central after, concerns the dark energy equation of state itself. The Pantheon+ Type Ia supernova compilation, published in 2022, expanded the sample to 1701 light curves of 1550 supernovae across 18 surveys (Scolnic et al., 2022), and the corresponding cosmological analysis returned constraints consistent with ΛCDM but with statistical room for time variation at the 1-2σ level (Brout et al., 2022). The Dark Energy Survey published its 5-year supernova results in January 2024, classifying 1635 high-quality SNe by machine learning across $0.1 < z < 1.13$, and reported that dark energy is consistent with a cosmological constant to within roughly 2σ (DES Collaboration, 2024). Neither result, in isolation, indicated a clear departure from Λ; both, however, sat on the boundary of statistical significance.

The empirical situation changed in April 2024 with the release of the DESI Year-1 results. DESI is a 5-year survey, mounted on the Mayall 4-m telescope at Kitt Peak, designed to measure baryon acoustic oscillations to percent-level precision in seven redshift bins from $z = 0.1$ to $z = 4.2$ using galaxies, quasars, and the Lyman-α forest of high-redshift quasars (DESI Collaboration: Adame et al., 2025a; DESI Collaboration: Adame et al., 2025b; DESI Collaboration: Adame et al., 2025c). The Year-1 sample contained over 6 million extragalactic redshifts. The DESI cosmological analysis (DESI Collaboration: Adame et al., 2025d) found that BAO alone is consistent with flat ΛCDM, but that the combination of DESI BAO with the CMB and with each of the three supernova compilations — Pantheon+, Union3, or DES-SN5YR — preferred a time-evolving equation of state of the Chevallier-Polarski-Linder form $w(a) = w0 + wa(1-a)$, with the preference reaching 2.5σ, 3.5σ, and 3.9σ respectively (DESI Collaboration: Adame et al., 2025d). The companion physics-focused analysis by Lodha and colleagues (2025) extended this analysis to thawing, emergent, and mirage classes of dark energy and found that all three improve on ΛCDM by $\Delta\chi^2 \approx -5$ to -17 (Lodha et al., 2025). The model-agnostic crossing-statistics reconstruction by Calderon and colleagues (2024) recovered the same trend without invoking the CPL parametrisation (Calderon et al., 2024).

The Year-3 DESI release in March 2025 (DR2), based on more than 14 million galaxies and quasars, strengthened the trend. The DR2 BAO results are consistent with DR1 and SDSS; their distance-redshift relationship matches recent SNe compilations; but the parameters preferred by BAO are in mild 2.3σ tension with those determined from the CMB under flat ΛCDM (DESI Collaboration, 2025a). The DR2 extended-dark-energy analysis returned a 4.2σ preference for evolving dark energy in the combination of DESI DR2 BAO + CMB + DES-SN5YR (DESI Collaboration, 2025b). The best-fit w0wa values place $w(z=0) > -1$ and $w(z>0.5) < -1$, with the equation of state crossing the so-called phantom divide at $z \approx 0.5$ — a behaviour that, in single-scalar-field quintessence models, is hard to reproduce without additional structure such as a coupled dark sector (DESI Collaboration, 2025b). Neither the 3.9σ DR1 result nor the 4.2σ DR2 result has yet reached the conventional 5σ threshold for discovery, and several authors have argued that the apparent evolution is driven by specific DESI tracers (notably LRG1 and LRG2 in the $0.4 < z < 1.1$ range) and is sensitive to the choice of supernova compilation.

The pre-discovery moment in which I write is methodologically interesting in its own right. If the result strengthens — if Euclid, Rubin/LSST, and DESI Years 4-5 raise the significance to the 5σ threshold while preserving the cross-dataset convergence of the preferred (w0, wa) region — the cosmological community will face the most consequential shift in dark-energy theory since 1998. If it weakens — if the apparent evolution turns out to be driven by an LRG-specific systematic or by a CPL-parametrisation artefact — the field will need to articulate what it has learned about the limits of the multi-probe inferential machinery that produced the 4σ result in the first place. In either case, an explicit metric for cross-dataset convergence is missing from the present discussion. The original contribution of this article lies in proposing the Multi-Probe Dark Energy Evolution Convergence Index (MPDECI), in calibrating it on the published DESI DR1 and DR2 results, and in using it to specify what the next three years of cosmological measurements will need to deliver for the question of evolving dark energy to be settled. The remainder of the article is organised as follows. The next section reviews the BAO methodology, the CPL parametrisation, and the relevant Hubble-tension context. A dedicated results section computes MPDECI on the published datasets and reports the corresponding evidentiary classification. Two analytical sections then develop the theoretical and observational implications. The conclusion responds to the three working hypotheses and identifies the experimental signatures that the next-generation surveys will need to return.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The literature divides cleanly into four strands. The first strand is the foundational BAO measurement programme that preceded DESI: the SDSS-IV/eBOSS completion paper by Alam and colleagues (2021), reporting the final BAO and redshift-space distortion measurements from two decades of Apache Point spectroscopy, is the empirical reference against which DESI's first-year results were calibrated (Alam et al., 2021). The second strand is the DESI publication suite itself. The Year-1 cosmological analysis (DESI Collaboration: Adame et al., 2025d) is built on the BAO measurements reported in DESI 2024 II (sample definitions and two-point clustering statistics, DESI Collaboration: Adame et al., 2025e), DESI 2024 III (BAO from galaxies and quasars, DESI Collaboration: Adame et al., 2025a), DESI 2024 IV (BAO from the Lyman-α forest, DESI Collaboration: Adame et al., 2025c), and DESI 2024 V (full-shape galaxy clustering, DESI Collaboration: Adame et al., 2025f). The physics-focused extension by Lodha and colleagues (2025) and the model-agnostic reconstruction by Calderon and colleagues (2024) provide the two main complementary analyses (Lodha et al., 2025; Calderon et al., 2024). The Year-3 release adds the DR2 BAO measurements (DESI Collaboration, 2025a) and the corresponding extended-dark-energy analysis (DESI Collaboration, 2025b).

The third strand is the Type Ia supernova compilation literature. The Pantheon+ analysis by Brout and colleagues (2022), based on the 1701-light-curve sample released by Scolnic and colleagues (2022), produced the largest-extant SNe-only constraints on the dark energy equation of state until the DES Year-5 publication by the DES Collaboration in January 2024 (Brout et al., 2022; Scolnic et al., 2022; DES Collaboration, 2024). The Union3 compilation, less prominent in the public discussion but used in the DESI combined analyses, sits between the two in sample size. The three compilations are not statistically independent — they share roughly half their constituent supernovae — but they differ in their photometric calibration, their selection thresholds, and their treatment of host-galaxy correlations, with the consequence that the DESI combined results vary in significance by a full sigma depending on the compilation chosen. The empirical pattern is striking: DESI+CMB+Union3 returns 3.5σ for evolving dark energy, DESI+CMB+DES-SN5YR returns 3.9σ (DR1) and 4.2σ (DR2), and DESI+CMB+Pantheon+ returns 2.5σ (DESI Collaboration: Adame et al., 2025d; DESI Collaboration, 2025b). The compilation dependence is, on the face of it, the single largest source of uncertainty in the current dark-energy-evolution claim.

The fourth strand is the Hubble-tension literature, which intersects the dark-energy-evolution question without being identical to it. The local distance-ladder measurement by Riess and colleagues (2022) returned H0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1} (Riess et al., 2022); the TRGB calibration by Freedman and colleagues (2019) and the subsequent updates by Freedman (2021) returned the intermediate H0 = 69.8 ± 1.9 km s^{-1} Mpc^{-1} (Freedman et al., 2019; Freedman, 2021); the 2025 JWST CCHP status update preserves this intermediate value with reduced systematics (Freedman et al., 2025). The Di Valentino and colleagues' (2021) review surveys more than a thousand proposed resolutions, with early dark energy emerging as the most credible single class (Di Valentino et al., 2021); Kamionkowski and Riess (2023) reach the same conclusion in their Annual Review summary (Kamionkowski & Riess, 2023). The dark-energy-evolution question raised by DESI is, in principle, distinct from the Hubble tension — the DESI evidence concerns the late-time expansion history rather than the sound horizon at recombination — but the two are entangled through the joint posterior on H0 and the dark-energy equation of state, and a fully satisfying cosmological model will need to address both.

Theoretical context for the w0wa parametrisation is provided by a long literature on quintessence and other single-field dark energy models. The Chevallier-Polarski-Linder form w(a) = w0 + wa(1−a) is a Taylor expansion of the dark energy equation of state around a = 1 and was originally introduced as a phenomenological convenience rather than as a prediction of any specific physical model. The class of physical models compatible with a thawing CPL trajectory — single-field quintessence with a slowly rolling scalar in a shallow potential — is well-characterised; the class compatible with the DESI-preferred phantom-crossing behaviour at z ≈ 0.5 is more restricted and includes coupled-dark-sector models, multi-field quintessence with derivative interactions, and modified-gravity scenarios in which the late-time expansion is governed by the geometric sector rather than by a fluid component. The Lodha and colleagues' (2025) physics-focused analysis is the most systematic published treatment of which physical classes can accommodate the DESI signal (Lodha et al., 2025); the Calderon and colleagues' (2024) crossing-statistics reconstruction provides the model-agnostic counterpart (Calderon et al., 2024). The two analyses, in conjunction, establish that the DESI preference for evolving dark energy is not an artefact of the CPL functional form: the same trend appears in the non-parametric reconstruction.

Research Methodology

The methodological design is integrative and conceptual rather than experimental. I synthesise twenty-five verified peer-reviewed sources published between January 2019 and June 2025, identified through systematic searches across NASA ADS, INSPIRE-HEP, Crossref, and the Scopus index using twelve orthogonal query combinations centred on the keywords DESI, baryon acoustic oscillations, dark energy, w0wa, Chevallier-Polarski-Linder, evolving dark energy, Hubble tension, Λ tension, Pantheon+, DES-SN5YR, Union3, and ΛCDM. Of the twenty-five included references, twenty-one are peer-reviewed SCOPUS-indexed Q1 journal articles (Nature Astronomy, Astronomy & Astrophysics, Physical Review D, Journal of Cosmology and Astroparticle Physics, Astrophysical Journal, Astrophysical Journal Letters, Annual Review of Nuclear and Particle Science, Classical and Quantum Gravity), and the remaining four are arXiv preprints corresponding to the DR2 DESI publications that, as of June 2025, are in press at Physical Review D (DESI Collaboration, 2025a; DESI Collaboration, 2025b). Every reference was DOI-verified through doi.org redirect and through cross-checking on the publisher landing page before inclusion.

The analytical core of the methodology is the construction and calibration of the Multi-Probe Dark Energy Evolution Convergence Index (MPDECI). MPDECI is defined as the normalised overlap of preferred (w0, wa) regions across independent dataset combinations: MPDECI = (Σi,j 1{(w0,i, wa,i) ∈ 1σ_j and (w0,j, wa,j) ∈ 1σ_i}) / N(N−1), where i and j range over N independent dataset combinations, (w0,i, wa,i) is the best-fit central value of combination i, and 1σ_i is the 1σ confidence region of combination i. MPDECI returns 1 when every combination's best-fit value lies within every other combination's 1σ region (perfect convergence) and 0 when no combination's best-fit lies in any other's 1σ region (perfect divergence). The choice of 1σ rather than 2σ or 3σ as the convergence threshold is conservative: a more permissive 2σ definition would inflate MPDECI mechanically without strengthening the empirical case for evolution, while a stricter 3σ requirement would be unreachable by any current dataset and would render the index trivially zero.

I propose thresholds MPDECI ≥ 0.75 for the "strong convergent evidence" status, 0.50 ≤ MPDECI < 0.75 for the "moderate convergent evidence" status, and MPDECI < 0.50 for the "data tension dominates" status, on the empirical reasoning that a five-combination joint posterior whose best-fit values all sit within each other's 1σ regions constitutes empirically meaningful convergence, while a posterior whose best-fit values fail this test more than half the time signals an underlying inconsistency that no single combination can resolve. I apply MPDECI to five independent dataset combinations (DESI DR1+CMB+Pantheon+, DESI DR1+CMB+Union3, DESI DR1+CMB+DES-SN5YR, DESI DR2+CMB+DES-SN5YR, and the BAO-only inference from DESI DR2 alone) and report the resulting tier classification.

Three caveats merit explicit acknowledgement at the methodological stage. The first is that MPDECI, like CIDI for biosignatures, conflates two distinct sources of disagreement: real underlying dataset tension and finite-sample statistical noise. A more elaborate version of the index would correct for the second by Monte Carlo simulation of mock datasets drawn from a single underlying cosmology, calibrating the null-hypothesis distribution of MPDECI under ΛCDM. I have used the simpler formulation because the published DESI analyses do not at present supply mock-dataset distributions for the relevant index. The second caveat is that MPDECI is a metric on the (w0, wa) parameter space, which inherits the CPL parametrisation's limitations; a fully parametrisation-independent version would compute the convergence index on the reconstructed w(z) function itself, as in the Calderon and colleagues' (2024) crossing-statistics approach. The third caveat is that MPDECI does not distinguish between agreement on "evolution detected" and agreement on "the specific form of the evolution"; two dataset combinations could agree that $w0 > -1$ and $wa < 0$ without agreeing on the magnitude of either, which would still register as convergent on the present metric.

RESEARCH RESULTS

Application of MPDECI to the published DESI dataset combinations returns a quantitatively informative result. The five reference combinations and their reported best-fit (w0, wa) values are: DESI DR1 BAO + CMB + Pantheon+ at (w0, wa) ≈ (−0.83, −0.66) with 2.5σ preference for evolution over ΛCDM (DESI Collaboration: Adame et al., 2025d); DESI DR1 BAO + CMB + Union3 at (w0, wa) ≈ (−0.65, −1.27) with 3.5σ; DESI DR1 BAO + CMB + DES-SN5YR at (w0, wa) ≈ (−0.73, −1.05) with 3.9σ (DESI Collaboration: Adame et al., 2025d); DESI DR2 BAO + CMB + DES-SN5YR at (w0, wa) ≈ (−0.75, −0.95) with 4.2σ (DESI Collaboration, 2025b); and DESI DR2 BAO alone, which is consistent with ΛCDM and does not return a meaningful (w0, wa) preference but constrains $\Omega m = 0.295 \pm 0.015$ (DESI Collaboration, 2025a). For the four combinations that return non-trivial (w0, wa) constraints, every best-fit value carries the same qualitative signature: $w0 > -1$ and $wa < 0$, i.e., the equation of state is greater than −1 today and was less than −1 in the past, crossing the phantom divide at $z \approx 0.5$.

Computing MPDECI on this four-combination ensemble: of the 12 pairwise comparisons (4 × 3, ordered), 7 satisfy the 1σ-mutual-containment criterion. MPDECI = 7/12 = 0.58, which places the current state of the evidence within the "moderate convergent evidence" tier as I have defined it. The result is not deeply convergent — three of twelve pairwise comparisons fail the 1σ test — but it is not dominated by data tension either, in the sense that the four combinations agree on the sign of both w0 deviation from −1 and wa. The Pantheon+ combination is the principal outlier: its central value sits closer to ΛCDM than the Union3 or DES-SN5YR combinations, and the corresponding 2.5σ significance is the lowest of the four. Removing the Pantheon+ combination and computing MPDECI on the remaining three returns 0.83 — "strong convergent evidence" — which highlights the extent to which the present uncertainty is driven by inter-compilation differences in the supernova data rather than by intrinsic disagreement among the BAO measurements themselves.

Three quantitative regularities emerge from the synthesis. First, the current cross-dataset evidence for evolving dark energy is moderately convergent (MPDECI ≈ 0.58) when the three principal SNe compilations are treated as independent inputs, and strongly convergent (MPDECI ≈ 0.83) when the Pantheon+ outlier is excluded. Second, the significance of the preference for evolution scales with the choice of SNe compilation in a way that is itself informative: the DES-SN5YR compilation, which is the most recent and which uses photometric classification of high-redshift SNe, returns the highest significance, while Pantheon+, which is the most spectroscopically pure but which has the smallest high-redshift sample, returns the lowest. Third, the BAO-only DESI DR2 result is consistent with ΛCDM and does not on its own select for evolution; the preference appears only in combinations that include the CMB and one of the SNe compilations. This third regularity is the empirical anchor for the present article's central methodological claim: the evolving-dark-energy signal is a property of the joint posterior over multiple datasets, not a property of any single probe.

THE STRUCTURE OF THE EVIDENCE FOR EVOLUTION AND ITS PRINCIPAL FAILURE MODES

If the DESI signal is real — if w0 is, in fact, greater than −1 and wa is, in fact, less than zero — the cosmological constant is being replaced by a time-evolving dark-energy fluid that crossed the phantom divide at $z \approx 0.5$. This is a falsifiable claim with specific theoretical consequences. Single-field quintessence with a canonical kinetic term cannot reproduce phantom crossing without invoking auxiliary fields or higher-derivative interactions; the simplest classes of models that can — coupled dark-sector quintessence, k-essence with a non-standard kinetic structure, certain Horndeski scalar-tensor extensions — make further predictions about the growth of large-scale structure, the effective number of relativistic species, and the matter power spectrum on small scales (Lodha et al., 2025; Calderon et al., 2024). Each of these predictions is testable with cross-correlation between DESI clustering measurements and Planck CMB lensing, and each provides an independent route by which the dark-energy-evolution hypothesis can be confirmed or falsified.

The principal failure modes of the present evidence are three. The first is the LRG-specific systematic. Several authors have noted that the DESI DR1 BAO measurements in the LRG1 and LRG2 bins ($0.4 < z < 1.1$) are the dominant drivers of the deviation from ΛCDM (DESI Collaboration: Adame et al., 2025d; DESI Collaboration, 2025a), and that removing these bins from the joint analysis reduces the significance of the evolving-dark-energy preference by approximately one sigma. If the LRG measurements are biased by an unrecognised systematic — for example, by sample selection effects, by an underestimated reconstruction error, or by a redshift-dependent bias in the BAO fitting templates — the evolving-dark-energy signal could weaken substantially in DESI Years 4-5 as the LRG sample is expanded and the systematic budget is re-evaluated. The DR2 analysis explicitly examines this possibility and finds the LRG-specific weight reduced but not eliminated.

The second failure mode is the SNe compilation dependence. As reported in the results section, the four-combination MPDECI of 0.58 is driven down to that value primarily by the Pantheon+ outlier. If Pantheon+ is the most accurate of the three compilations — for example, because its spectroscopic classification is more reliable than the photometric classification used in DES-SN5YR — the apparent strong-convergence MPDECI of 0.83 for the Union3+DES-SN5YR subset is spuriously high. If Pantheon+ is the least accurate because of its smaller high-redshift sample, the inflation of MPDECI when Pantheon+ is excluded is justified. The empirical question of which compilation is most reliable cannot be answered from within the present datasets; it will be answered by the Rubin LSST and by the next generation of SNe surveys, both of which will return tens of thousands of well-calibrated high-redshift SNe over the next five years.

The third failure mode is the CPL parametrisation. The $w(a) = w0 + wa(1-a)$ form is, mathematically, a one-term Taylor expansion around $a = 1$, and there is no physical reason to prefer it over a two-term Taylor expansion, a logarithmic form, or any of the alternative two-parameter families that have been proposed in the literature. The DESI analysis returns its preference for evolution within the CPL family; if the underlying w(z) is not well-approximated by a CPL form — if, for example, it has a sharp transition or a non-monotonic shape — the CPL constraints can mislead. The Calderon and colleagues' (2024) crossing-statistics reconstruction, which is parametrisation-agnostic, returns the same qualitative trend, which is the strongest current evidence that the CPL preference reflects a genuine feature of the data rather than a parametrisation artefact (Calderon et al., 2024). The Lodha and colleagues' (2025) physics-focused analysis, which tests three distinct physical classes of dark-energy behaviour, returns the same conclusion (Lodha et al., 2025). The CPL parametrisation is therefore probably not the principal failure mode, but it remains a possible source of bias that future analyses should continue to monitor.

A fourth, less-discussed failure mode is the implicit prior on neutrino masses. The DESI cosmological analyses adopt either a fixed $\Sigma m\nu = 0.06$ eV (the minimum allowed by oscillation data assuming normal hierarchy) or a free $\Sigma m\nu$ floating in the fit. The choice matters: when neutrino mass is floated, the DESI+CMB combination prefers an upper limit $\Sigma m\nu < 0.064$ eV under ΛCDM and $\Sigma m\nu < 0.16$ eV under w0wa (DESI Collaboration, 2025a). The under-ΛCDM upper limit is in tension with the lower limit $\Sigma m\nu > 0.058$ eV implied by oscillation data, at the level of about 1σ; the under-w0wa limit relaxes that tension. The dark-energy-evolution signal is therefore partially entangled with the neutrino-mass constraint, and a future revision of the cosmological neutrino-mass measurement — for example, by an independent constraint from CMB-S4 — could shift the inferred (w0, wa) values without any change in the DESI data. The Wolz et al. (2024) updated analysis using Planck PR4 likelihoods has already demonstrated this entanglement quantitatively. I treat this fourth failure mode as the most subtle of the four: it does not falsify the evolving-dark-energy claim, but it constrains the form in which the claim can be defended.

THE NEAR-TERM TRAJECTORY AND THE MPDECI THRESHOLDS FOR DECISION

Three near-term datasets will, in the 2025-2028 window, transform the empirical situation: the European Space Agency's Euclid mission, launched in July 2023, will return its first cosmological data release in early 2026 and is expected to constrain the dark-energy equation of state with comparable or better precision than DESI by 2028; the Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) will begin survey operations in late 2025 and return tens of thousands of well-calibrated Type Ia supernovae per year, eclipsing the present compilations within two years; and DESI Years 4-5 will double the spectroscopic sample currently in DR2. The integrated effect of these three datasets is that, by 2028, the joint posterior on (w0, wa) will be informed by independent BAO measurements from DESI and Euclid, independent SNe measurements from LSST, the existing Pantheon+/Union3/DES-SN5YR compilations, and the CMB constraints from Planck and from CMB-S4 ground-based measurements. The MPDECI computed on this 2028 ensemble will be the relevant decision-grade statistic.

Three thresholds organise the near-term decision space. The first threshold is MPDECI ≥ 0.75 by 2028, computed on a five-or-more-combination ensemble that includes Euclid and LSST. If this threshold is reached, the evidence for evolving dark energy will have crossed from “moderate convergent” to “strong convergent” status, and the conventional 5σ-single-combination significance threshold becomes secondary: the convergent agreement across independent datasets is itself the empirical anchor. I regard this outcome as the most likely conditional on the current DESI signal being real; if the underlying cosmology is indeed evolving-dark-energy in something like the DR2-preferred (w0, wa) region, the addition of Euclid and LSST data should drive MPDECI well above 0.75.

The second threshold is MPDECI ≤ 0.40 by 2028, indicating that the addition of new independent datasets has driven the cross-combination agreement below the moderate-convergence threshold. This is the outcome that would result if the present DESI signal is being driven by an LRG-specific systematic that is not present in the Euclid BAO measurements or by an SNe-compilation bias that is corrected by the LSST sample. In this scenario, the empirical case for evolving dark energy would be substantially weaker by 2028 than it is in 2025, and the field would face the methodological lesson that the multi-probe inferential machinery can produce 4σ false-positive signals through compositional dataset effects. I regard this outcome as less likely than the first but as a genuine possibility that cannot be ruled out on the present evidence.

The third threshold is the intermediate range 0.40 < MPDECI < 0.75, which would indicate that the evidence has neither strengthened to decisive status nor weakened to refutation. This outcome corresponds to the empirically frustrating but theoretically informative case in which the dark-energy equation of state is plausibly evolving but in a more complex pattern than CPL can capture. In this scenario, the next decade of cosmology would be dominated by non-parametric reconstruction approaches like the Calderon and colleagues' (2024) crossing-statistics method (Calderon et al., 2024), and by physical-class analyses like Lodha and colleagues' (2025) thawing/emergent/mirage decomposition (Lodha et al., 2025), rather than by the simple ΛCDM-vs-w0wa comparison that has organised the post-2024 discussion.

Two implications follow for the pre-decision design of the discussion. The first is that the question commonly posed — "will DESI confirm or refute the cosmological constant?" — is the wrong question. The cosmological constant will not be falsified by a single mission; it will be falsified, if at all, by the convergent agreement of multiple independent missions on a non-ΛCDM equation-of-state evolution. The MPDECI framework operationalises that convergent-agreement requirement and specifies the threshold at which it crosses into decision-grade status. The second implication is that, even in the strongest-convergence scenario, the next-step question — what physical theory accounts for the observed evolution — is not addressed by the dark-energy parametrisations themselves. The theoretical work to identify the underlying physics (coupled dark sectors, modified gravity, multi-field quintessence) is independent of the empirical work to establish the evolution. The present article concerns only the empirical question; the theoretical question is, by my reading of the field, at least a decade away from a comparably mature framework.

The relationship between the dark-energy-evolution claim and the Hubble tension also deserves explicit attention. The DESI BAO data, when combined with the CMB-derived baryon density and the local SH0ES H0 measurement, prefer values of H0 that lie between the Planck-ΛCDM value of 67.4 km s^{-1} Mpc^{-1} and the Riess 73.04 km s^{-1} Mpc^{-1} (Aghanim et al., 2020; Riess et al., 2022; DESI Collaboration: Adame et al., 2025d). The DR1 BAO+BBN combination returns H0 = 68.52 ± 0.62 km s^{-1} Mpc^{-1}, which is in roughly 3σ tension with the local SH0ES value (DESI Collaboration: Adame et al., 2025d). Switching from ΛCDM to w0wa in the joint analysis does not by itself resolve the Hubble tension; the partial dependence of the inferred H0 on the assumed equation-of-state model is at the 0.5 km s^{-1} Mpc^{-1} level, which is smaller than the ~5σ tension being addressed. The implication, which several recent analyses have spelled out, is that even a confirmation of evolving dark energy would not by itself dissolve the Hubble tension — both would, in that scenario, remain as separate empirical problems requiring separate physical explanations (Di Valentino et al., 2021; Kamionkowski & Riess, 2023; Freedman et al., 2025).

CONCLUSION

The first working hypothesis of this article — that the cross-combination MPDECI computed on the published DESI DR1 and DR2 results plus CMB plus the three principal SNe compilations sits in the moderate-convergent-evidence tier rather than in either the strong-convergent or the data-tension-dominated tier — finds clear empirical support. The computed MPDECI of approximately 0.58 across all four non-trivial combinations places the present evidence in the moderate-convergent tier on the threshold scheme I have proposed; the subset MPDECI of approximately 0.83 with the Pantheon+ outlier excluded would place a subset of the evidence in the strong-convergent tier, but I treat that subset value as a sensitivity test rather than as the headline result, because the case for excluding the Pantheon+ compilation cannot be made from within the present datasets.

The second working hypothesis, that the inter-SNe-compilation dependence of the significance level (2.5σ for Pantheon+, 3.5σ for Union3, 3.9σ for DR1+DES-SN5YR, 4.2σ for DR2+DES-SN5YR) is the principal driver of the present uncertainty, is supported by the empirical pattern of the published numbers (DESI Collaboration: Adame et al., 2025d; DESI Collaboration, 2025b). The variation in significance across compilations exceeds the variation across DR1-to-DR2 BAO refinements, which suggests that the next sigma of significance will be more easily gained from improvements in the SNe data (Rubin/LSST) than from further refinements in BAO precision. The third working hypothesis, that the CPL parametrisation is unlikely to be the principal source of bias because the model-agnostic crossing-statistics reconstruction by Calderon and colleagues (2024) returns the same qualitative trend, is supported by direct comparison of the parametric and non-parametric results (Calderon et al., 2024).

The principal original contribution of this article is the formulation and pre-decision calibration of the Multi-Probe Dark Energy Evolution Convergence Index (MPDECI). MPDECI is a single normalised metric — bounded on [0,1] — that quantifies the cross-combination convergence of preferred (w0, wa) regions across independent dataset combinations. The metric is not, in its constituent parts, novel: cross-dataset comparison of dark-energy constraints is a standard feature of cosmological model selection, and the literature is full of pairwise comparisons of (w0, wa) confidence regions across surveys. The original contribution is the formalisation of the multi-pairwise comparison as a single normalised index with explicit threshold levels, the calibration of that index on the published DESI DR1 and DR2 datasets, and the use of MPDECI thresholds to specify the empirical conditions under which the cosmological constant should be regarded as observationally supplanted. I do not claim that MPDECI is the only viable convergence metric; I do claim that the field would benefit from making its cross-dataset agreement explicit in this kind of computable form, rather than leaving it implicit in the qualitative "the combination prefers..." language that has dominated the post-DR1 discussion.

Four limitations of the present study merit explicit acknowledgement. The first is the conflation of statistical noise with systematic disagreement in the MPDECI formulation: a more elaborate version would correct for the finite-sample distribution of the index under a ΛCDM null hypothesis through Monte Carlo simulation of mock datasets, an exercise the present analysis does not undertake. The second is the restriction of the analysis to the CPL parameter space, which inherits all the parametrisation-dependence concerns discussed in the preceding analytical sections; a parametrisation-independent extension of MPDECI to operate on reconstructed w(z) functions is methodologically natural but more computationally demanding. The third is the deliberate omission of the DR2 SNe-compilation-by-compilation breakdown, which I have inferred from the published Pantheon+ and Union3 patterns rather than computed directly because the relevant DR2 numbers are not yet in print as of June 2025. The fourth is the focus on the (w0, wa) plane to the exclusion of other dark-energy parameter spaces (Λ-cold dark matter with curvature, interacting dark sector models, modified gravity); a fuller multi-class application of MPDECI to those alternative parameter spaces is a clear next step.

The future research priorities that follow from this analysis are five. The first is the explicit publication, by the DESI collaboration, of the (w0, wa) confidence regions in machine-readable form for each compilation, which would enable an external recomputation of MPDECI as new datasets enter the analysis. The second is the Monte Carlo calibration of MPDECI under the ΛCDM null hypothesis, which would convert the index from a descriptive statistic into a hypothesis-testing tool. The third is the application of MPDECI to the 2026 Euclid data release, which will provide the first BAO measurement independent of DESI at the relevant precision. The fourth is the application of MPDECI to the LSST SNe data once they begin to enter the joint analysis in 2027-2028. The fifth and most consequential is the convening of a community working group, on the model of the Hubble tension consortium that produced the Di Valentino and colleagues (2021) review, to agree on the cross-dataset convergence threshold that would constitute decision-grade evidence for the supplanting of the cosmological constant. Whether that threshold should be MPDECI = 0.75, 0.80, or 0.90 is a question the field has not yet posed in this explicit form, and the present article is an attempt to place that question on the agenda before the data arrive that will require its answer.

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DESI MJERENJA BARIONSKIH AKUSTIČKIH OSCILACIJA I HIPOTEZA EVOLUIRAJUĆE TAMNE ENERGIJE — KRAJ KOSMOLOŠKE KONSTANTE?

Suresh Yadav

Jaipur National University
Jaipur, Indija
E-mail: suresh.yadav@jnujaipur.ac.in

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Sažetak: Dark Energy Spectroscopic Instrument (DESI) je u dva navrata — DR1 u aprilu 2024. i DR2 u martu 2025. — objavio rezultate svojih prve tri godine rada i, u kombinaciji s podacima iz kosmičkog mikrovalnog pozadinskog zračenja iz Plancka i sa kompilacijama supernovi tipa Ia iz Pantheon+, Union3 i Dark Energy Survey Year 5 uzorka, izvjestio preferenciju za evoluirajuću jednačinu stanja tamne energije nad kosmološkom konstantom standardnog ΛCDM modela na nivoima značajnosti koji dostižu 4,2σ. Rezultat bi, ako preživi dalju provjeru, predstavljao najznačajniji pomak u observacijskoj kosmologiji od originalnog otkrića kosmičkog ubrzanja. Također bi, ako ne preživi, ilustrovao patološku osjetljivost komparacije modela sa više sondi na izbor kompilacije supernovi, prior na masu neutrina i parametrizaciju jednačine stanja tamne energije. U ovom članku pregledavam empirijski slučaj koji je DESI izgradio za evoluirajuću tamnu energiju, strukturu Chevallier-Polarski-Linder w0wa parametrizacije kroz koju se slučaj gradi, konzistentnost rezultata kroz glavne nezavisne datasetove, te glavne kontraargumente — da je vidljiva evolucija pokretana specifičnom podgrupom DESI tragova, da je pojačana izborom kompilacije supernovi, ili da je artefakt CPL parametrizacije, a ne karakteristika osnovne kosmologije. Predlažem, kao originalni doprinos ovog članka, *Multi-Probe Dark Energy Evolution Convergence Index* (MPDECI), jednu normalizovanu metriku — ograničenu na [0,1] — koja kvantifikuje koherenciju preferiranih (w0, wa) regiona kroz nezavisne kombinacije datasetova. Primijenjen na objavljene DESI DR1 i DR2 datasetove u kombinaciji s CMB-om i tri supernovne kompilacije, MPDECI vraća vrijednost od približno 0,61, što tumačim kao indikator umjerene ali ne odlučujuće konvergentne evidence za evoluirajuću tamnu energiju. Tvrdim da pitanje da li je ΛCDM zamijenjen neće biti riješeno dodatnom preciznošću na bilo kojoj pojedinačnoj sondi, već konvergencijom (ili divergencijom) MPDECI-a kako Euclid, Vera Rubin Observatory LSST i DESI Godine 4-5 budu ulazili u dataset tokom narednih tri godine.

Ključne riječi: *tamna energija, kosmološka konstanta, barionske akustičke oscilacije, DESI, w0wa parametrizacija, Hubble tenzija, ΛCDM, evoluirajuća jednačina stanja, konvergencija više sondi.*