International Conference on Science, Engineering
& Management Trends

International Journal of Science,
Engineering and Technology
ISSN: 2348-4098, P-ISSN: 2395-4752

Probing Dark Energy and the Hubble Tension through Multi-Probe Constraints from SNe Ia, CMB, and BAO

Amritansh soni[1], Dr Avinash Singh[2]
[1]Research Scholar, Department of Physics, Kalinga University, Raipur
[2]Research Supervisor, Department of Physics, Kalinga University, Raipur

Abstract- The current phase of precision cosmology is defined not only by increasingly accurate measurements, but by the need to interpret agreement and tension across fundamentally different probes. Type Ia supernovae (SNe Ia) trace the late-time luminosity distance relation, the cosmic microwave background (CMB) constrains the early-Universe acoustic scale and physical densities, and baryon acoustic oscillations (BAO) provide a robust standard ruler across a broad redshift range. The research problem addressed in this paper is whether the joint use of these probes strengthens the case for the baseline LambdaCDM model or instead points toward unresolved late-time physics, especially in relation to dark energy dynamics and the Hubble tension. This empirical conference paper develops a secondary-data synthesis of benchmark results from Pantheon+, Planck 2018, the completed SDSS/eBOSS analysis, DESI Year 1 BAO, and the SH0ES local distance-ladder determination. The analysis compares single-probe and joint constraints in flat LambdaCDM, wCDM, and w0waCDM, focusing on degeneracy breaking, uncertainty reduction, and residual inter-probe inconsistency. The findings show that multi-probe combinations sharply tighten constraints on Omega_m and w0 relative to supernova-only inference and continue to support flat LambdaCDM in the most precise CMB plus BAO combinations. However, the H0 tension remains unresolved, and recent DESI-era results indicate mild but not decisive pressure toward evolving dark energy when time variation is allowed. The paper argues that multi-probe cosmology is best understood as both a triumph of precision inference and a structured test of the limits of the standard model.

Keywords- Dark energy, Hubble tension, Type Ia supernovae, cosmic microwave background, baryon acoustic oscillations, cosmological parameters

I. INTRODUCTION

Modern cosmology is often described as a precision science, yet its most important conclusions do not emerge from any single dataset. They arise from combining probes that measure different physical processes at different epochs in cosmic history. SNe Ia map the relative late-time expansion history through luminosity distances, the CMB constrains the acoustic physics of the early Universe, and BAO connects primordial information to low-redshift geometry through a standard ruler. This multi-probe architecture has made it possible to estimate key parameters such as Omega_m, H0, and dark energy equation-of-state terms with far greater precision than any individual probe can achieve alone. At the same time, the increased precision has made disagreements harder to ignore, especially the persistent difference between local and early-Universe determinations of H0 and the emerging question of whether late-time data may favor a dark energy sector more complex than a cosmological constant.

The empirical problem addressed here is therefore twofold. First, how much additional information is gained when SNe Ia, CMB, and BAO are interpreted jointly rather than separately? Second, does the resulting joint inference reinforce the baseline flat LambdaCDM model, or does it expose patterns that are difficult to reconcile with a constant dark energy component? These questions have become more pressing after Pantheon+ improved supernova constraining power relative to the original Pantheon sample, Planck 2018 reaffirmed the six-parameter LambdaCDM fit with high internal consistency, and DESI Year 1 delivered percent-level BAO measurements across seven redshift bins from more than 6 million objects. In other words, the debate is no longer whether these probes are mature. It is how their maturity should be interpreted when they converge in some sectors and diverge in others.

This paper argues that multi-probe cosmology should not be framed as a simple choice between confirmation and crisis. The strongest joint combinations still support flat LambdaCDM at high precision, particularly in the CMB plus BAO sector. Yet the Hubble tension remains substantial, and the latest DESI-based analyses suggest a mild preference for w0 > -1 and wa < 0 when time-varying dark energy is allowed, with significance that depends on the supernova compilation used. The contribution of this paper is to synthesize these developments in a concise empirical framework suitable for conference proceedings, showing how probe complementarity simultaneously sharpens parameter inference and clarifies where the standard model remains under pressure.

II. LITERATURE REVIEW

The basic theoretical rationale for multi-probe inference is well established. SNe Ia are standardizable candles that directly constrain the luminosity distance-redshift relation and therefore the late-time expansion history. Pantheon+ contains 1701 light curves of 1550 distinct SNe Ia over the redshift range 0.001 to 2.26 and reports roughly a factor-of-two improvement in cosmological constraining power relative to the original Pantheon compilation. In flat LambdaCDM, Pantheon+ finds Omega_m = 0.334 +/- 0.018 from supernovae alone, while in flat wCDM it finds w0 = -0.90 +/- 0.14 from supernovae alone. These results confirm that supernova cosmology is no longer only the route by which acceleration was first identified. It is now a precise late-time testbed for dark energy inference, although its standalone leverage on the absolute expansion scale still depends on calibration.

The CMB literature occupies a different evidential role. Planck 2018 remains the benchmark early-Universe analysis and reports strong consistency with the standard spatially flat six-parameter LambdaCDM model. Its combined temperature, polarization, and lensing analysis gives H0 = 67.4 +/- 0.5 km s^-1 Mpc^-1, Omega_m = 0.315 +/- 0.007, Omega_c h^2 = 0.120 +/- 0.001, Omega_b h^2 = 0.0224 +/- 0.0001, and n_s = 0.965 +/- 0.004. The importance of the Planck result lies not only in the small error bars, but in the fact that these parameters remain stable across many commonly considered model extensions, with no compelling evidence for physics beyond baseline LambdaCDM in the core fit. This stability is one reason why any proposed solution to late-time anomalies faces a high bar: it must relieve the anomaly without spoiling the overall success of the early-Universe model.

BAO studies provide the essential bridge between these two regimes. The completed SDSS/eBOSS cosmological analysis showed that the inverse distance ladder yields H0 = 68.20 +/- 0.81 km s^-1 Mpc^-1 in ow0waCDM and that precision on Omega_Lambda, H0, and sigma_8 remains near the 1 percent level across a range of cosmological models. DESI Year 1 extends that program with BAO measurements from galaxy, quasar, and Lyman-alpha forest tracers across 0.1 < z < 4.2. DESI BAO alone are consistent with flat LambdaCDM with Omega_m = 0.295 +/- 0.015. Paired with a big-bang nucleosynthesis prior and the acoustic angular scale from the CMB, DESI requires H0 = 68.52 +/- 0.62

km s^-1 Mpc^-1. Combined with Planck anisotropies and Planck plus ACT lensing, DESI gives Omega_m = 0.307 +/- 0.005 and H0 = 67.97 +/- 0.38 km s^-1 Mpc^-1. These results make BAO central to the present debate because they independently reinforce the low-H0, early-Universe route rather than drifting toward the local ladder value.

The main late-time debate now concerns whether dark energy is observationally consistent with a cosmological constant or whether recent data are beginning to prefer time variation. Pantheon+ combined with CMB and BAO yields w0 = -0.978^(+0.024)_(-0.031), still fully consistent with w = -1, and wa = -0.65^(+0.28)_(-0.32), which does not constitute decisive evidence for evolution. However, the DESI Year 1 cosmology paper reports that in w0waCDM, combinations of DESI with CMB or with SNe Ia individually prefer w0 > -1 and wa < 0. The stated level of discrepancy from LambdaCDM is 2.6 sigma for DESI plus CMB and rises to 2.5 sigma, 3.5 sigma, or 3.9 sigma when Pantheon+, Union3, or DES-SN5YR supernova data are added, respectively.

The recent DES 5-year supernova analysis is relevant here because it provides the tightest supernova-only cosmological constraints to date, with Omega_m = 0.352 +/- 0.017 in flat LambdaCDM and supernova-only evidence for acceleration at more than 5 sigma, while still finding dark energy broadly consistent with a cosmological constant at about the 2 sigma level when combined with external data. Together, these results suggest that the dark energy sector is no longer empirically featureless, even if the evidence does not yet support a definitive departure from LambdaCDM.

The other major debate is the Hubble tension. The SH0ES collaboration reports a local Cepheid-calibrated result of H0 = 73.04 +/- 1.04 km s^-1 Mpc^-1 and describes a 5 sigma difference with the Planck prediction under LambdaCDM. Pantheon+ also reports H0 = 73.5 +/- 1.1 km s^-1 Mpc^-1 when Cepheid host distances are included and finds that systematic uncertainties in the supernova distance ladder account for less than one third of the total uncertainty, which the authors argue cannot explain the present tension. The literature therefore points to a structured split rather than a general disagreement between all low-redshift and high-redshift probes. CMB and inverse-distance-ladder estimates cluster around 68 km s^-1 Mpc^-1, while the local Cepheid ladder remains near 73 km s^-1 Mpc^-1. This is precisely why a multi-probe framing is necessary: the problem is not just a number, but the relationship between distinct observational routes to that number.

III. METHODOLOGY OR CONCEPTUAL APPROACH

This paper adopts a secondary empirical design based on published observational constraints rather than a de novo likelihood analysis of raw supernova light curves, CMB maps, or galaxy clustering catalogs. That choice is methodological rather than merely practical. The aim of the paper is not to claim a new chain analysis, but to compare how benchmark probe combinations shape inference about dark energy and H0 across the most relevant current datasets. For a conference paper, this approach is defensible because it allows the analysis to remain transparent about its evidentiary basis while still producing an original synthesis of the present literature. The study is empirical in that its conclusions are built from observational results, and analytical in that it reorganizes those results around a common interpretive question.

The evidence base is purposively sampled. Five sources define the core dataset: Pantheon+ for the contemporary supernova benchmark; Planck 2018 for the baseline CMB solution; the final SDSS/eBOSS cosmology paper for the mature pre-DESI BAO baseline; DESI Year 1 for the most important recent BAO update; and SH0ES for the current local-ladder H0 benchmark. Two supplementary sources are used to assess robustness in the supernova sector: the DES 5-year supernova cosmology paper and the Union3 analysis, both relevant because DESI reports that the significance of w0waCDM deviations depends on which supernova compilation is added. This sampling strategy is appropriate because these papers collectively define the current parameter-estimation debate and provide directly comparable constraints in flat LambdaCDM, wCDM, and w0waCDM.

The conceptual framework is degeneracy breaking. Each probe constrains a different projection of the same cosmological parameter space. SNe Ia strongly constrain relative late-time distances but only weakly fix the absolute expansion scale without calibration. The CMB tightly constrains early-Universe physical densities and the acoustic scale, but its late-time parameters are model-dependent extrapolations. BAO links the primordial sound horizon to the late-time geometry and H(z), supplying a low-systematics standard ruler that is especially valuable in adjudicating between early and late inference routes. Joint estimation works because these probes are not redundant. Their parameter degeneracies intersect at different angles, and the overlap of their allowed regions compresses the posterior volume. The key question is whether that overlap compresses cleanly around LambdaCDM or reveals consistent directional pressure toward extensions.

To make this comparison explicit, the paper uses two simple empirical devices. The first is a precision-gain ratio, defined as the 1-sigma uncertainty from a single probe divided by the corresponding uncertainty from a joint probe combination. This indicates how much information is gained through combination. The second is a simple Gaussian tension estimate, defined as the difference between two central values divided by the quadrature sum of their reported uncertainties. This is not a substitute for a full posterior-overlap statistic, but it provides a transparent conference-level summary of the severity of inter-probe disagreement where the measurements are sufficiently distinct, especially for Planck versus SH0ES. Because the paper works from published summaries, these tools are used conservatively and only for interpretive comparison. No attempt is made to reconstruct the full covariance structure of overlapping datasets.

IV. RESULTS OR ANALYSIS

The first result is that supernovae alone now provide a stronger late-time cosmological constraint than was common only a few years ago, but they do not by themselves settle the broader model question. Pantheon+ yields Omega_m = 0.334 +/- 0.018 in flat LambdaCDM and w0 = -0.90 +/- 0.14 in flat wCDM from SNe Ia alone. DES 5-year supernova cosmology yields Omega_m = 0.352 +/- 0.017 from supernovae alone and reports that supernova data now require acceleration at more than 5 sigma. These results show that SNe Ia have become powerful standalone late-time probes. Yet the w0 uncertainty from supernovae alone remains much broader than the uncertainty obtained once CMB and BAO information are added, which means the supernova sector is highly informative but not self-sufficient for precision model discrimination.

The second result is that the CMB plus BAO sector remains strikingly stable around the baseline model. Planck 2018 finds H0 = 67.4 +/- 0.5 km s^-1 Mpc^-1 and Omega_m = 0.315 +/- 0.007 in base LambdaCDM, while DESI BAO alone find Omega_m = 0.295 +/- 0.015. When DESI is paired with BBN and the CMB acoustic angular scale, H0 becomes 68.52 +/- 0.62 km s^-1 Mpc^-1, and when DESI is combined with Planck anisotropies and CMB lensing, the result is Omega_m = 0.307 +/- 0.005 and H0 = 67.97 +/- 0.38 km s^-1 Mpc^-1. These values cluster closely with the Planck prediction and reinforce the long-standing inverse-distance-ladder picture already seen in eBOSS, where H0 = 68.20 +/- 0.81 km s^-1 Mpc^-1 in ow0waCDM. The empirical implication is clear: low-systematics geometric inference has not moved toward the local high-H0 value. It has instead consolidated the early-Universe route.
The third result is that joint constraints substantially tighten the dark energy sector. Pantheon+ alone gives w0 = -0.90 +/- 0.14 in flat wCDM, whereas Pantheon+ combined with CMB and BAO gives w0 = -0.978^(+0.024)_(-0.031). If one uses an average joint uncertainty of about 0.028, the effective precision gain relative to supernovae alone is approximately 5.0. A similar pattern appears for Omega_m: the

uncertainty shrinks from 0.018 in Pantheon+ alone to 0.005 in DESI plus Planck, a precision gain of about 3.6. These reductions are too large to be treated as incremental. They are direct evidence that multi-probe estimation changes the quality of cosmological inference by breaking the principal degeneracies that remain in single-probe fits.

The fourth result is more ambiguous and therefore more interesting. In constant-w fits, the evidence remains conservative. DESI BAO alone require w = -0.99^(+0.15)_(-0.13), and Pantheon+ plus CMB plus BAO yield w0 consistent with -1. However, once time variation is allowed, the posterior shifts directionally. DESI reports that in w0waCDM, DESI plus CMB prefer w0 > -1 and wa < 0 at 2.6 sigma, and that the discrepancy with LambdaCDM persists or grows when supernova compilations are added, reaching 2.5 sigma with Pantheon+, 3.5 sigma with Union3, and 3.9 sigma with DES-SN5YR. This does not amount to discovery-level evidence for evolving dark energy, but it does mean the late-time sector is no longer observationally indifferent to extension space. The pressure is mild, model-dependent, and compilation-dependent, yet it is coherent enough to warrant sustained follow-up.

The fifth result is that the Hubble tension remains unresolved under joint inference. Using the published Planck value of 67.4 +/- 0.5 and the SH0ES value of 73.04 +/- 1.04, a simple Gaussian tension estimate gives roughly 4.9 sigma, which is consistent with SH0ES's own description of the discrepancy as 5 sigma. Pantheon+ with Cepheid host distances gives H0 = 73.5 +/- 1.1 km s^-1 Mpc^-1, which is likewise far from the Planck and DESI plus BBN values. This means that the most precise multi-probe combinations do not soften the tension by drifting toward the local ladder. On the contrary, they sharpen the contrast between the inverse-distance-ladder route and the Cepheid-calibrated local route. That is one of the most important substantive conclusions of the present synthesis.

V. DISCUSSION

Three interpretive conclusions follow from the analysis. First, multi-probe cosmology is successful in exactly the way the standard framework predicts. The large reduction in uncertainty for Omega_m and w0 shows that SNe Ia, CMB, and BAO are not simply overlapping measurements of the same thing. They constrain different projections of a common parameter space, and their combination sharply contracts the allowed region. In this sense, the precision era is not merely an era of larger surveys. It is an era in which the geometry of parameter degeneracies has become as important as the raw size of the data.

Second, the strongest available combinations still support a conservative reading of the baseline model. Planck remains stable under the six-parameter LambdaCDM fit, DESI BAO alone remain consistent with flat LambdaCDM, and DESI plus Planck plus lensing tighten the standard-model solution rather than destabilizing it. This matters because public discussion of cosmology often jumps too quickly from "tension exists" to "the model has failed." The current evidence does not justify that leap. A viable alternative must explain not only the H0 discrepancy or late-time directional shifts, but also the striking consistency of the CMB plus BAO sector. At present, no single extension has clearly achieved that across the full data landscape.

Third, the late-time dark energy sector has become more diagnostically interesting than it was during the earlier post-Planck period. The DESI-era preference for w0 > -1 and wa < 0 is still below the threshold that would justify a claim of evolving dark energy, and its significance depends on the supernova compilation used. Even so, it would be misleading to describe the evidence as entirely null. The pattern now has structure. The real question is no longer whether some extension can fit subsets of the data slightly better, but whether the same directional preference survives future DESI releases, improved supernova calibration, and cross-compilation harmonization. If it does, the case for revisiting the cosmological-constant assumption will become materially stronger. If it does not, the present signal will likely be interpreted as a transient interaction between parameterization choice and residual survey systematics.

The Hubble tension illustrates the same broader lesson. Greater precision has not produced automatic consensus. Instead, it has clarified the architecture of disagreement. CMB and inverse-distance-ladder estimates remain close to one another, while local Cepheid-calibrated values remain significantly higher. This makes the tension more informative than a simple mismatch between two numbers. It suggests that future progress will depend on genuinely independent routes to H0, such as gravitational-wave standard sirens, improved lensing time-delay measurements, or further refinement of local calibration methods, rather than on simply repeating the same two inference chains with modestly smaller errors. The precision era therefore forces cosmology to confront not just uncertainty reduction, but cross-method validation.

VI. CONCLUSION AND FUTURE WORK

This paper has examined how joint constraints from SNe Ia, CMB, and BAO bear on two of the central late-time issues in cosmology: dark energy and the Hubble tension. The empirical synthesis shows that multi-probe inference dramatically improves parameter precision relative to single-probe fits and continues to support flat LambdaCDM in the highest-precision CMB plus BAO combinations. At the same time, the analysis shows that the H0 tension remains unresolved and that recent DESI-based results create mild but non-negligible pressure toward time-varying dark energy in w0waCDM. The central conclusion is therefore balanced rather than binary. Multi-probe cosmology is a clear success in precision parameter estimation, but it is also a disciplined way of identifying where the standard model may be incomplete.

Future work should proceed along three connected lines. First, the dark energy question needs retesting with larger DESI releases and with continued supernova cross-calibration, especially because the apparent significance of evolving-dark-energy signals changes across Pantheon+, Union3, and DES-SN5YR. Second, the H0 problem requires additional independent high-precision routes that are not anchored in the same calibration chains as the current local and inverse ladders. Third, comparative analyses should increasingly move beyond headline best-fit parameters and incorporate richer covariance-aware consistency tests across probes. Only then will it become possible to determine whether the present late-time anomalies are transient statistical and systematic effects or early signs of physics beyond LambdaCDM.

REFERENCES

1. Alam, S., Aubert, M., Avila, S., Balland, C., Bautista, J. E., Bershady, M. A., et al. (2021). The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory. Physical Review D, 103(8), 083533. doi:10.1103/PhysRevD.103.083533
2. Brout, D., Scolnic, D., Popovic, B., Riess, A. G., Zuntz, J., Kessler, R., et al. (2022). The Pantheon+ analysis: Cosmological constraints. The Astrophysical Journal, 938(2), 110. doi:10.3847/1538-4357/ac8e04
3. DES Collaboration. (2024). The Dark Energy Survey: Cosmology results with approximately 1500 new high-redshift Type Ia supernovae using the full 5-year dataset. The Astrophysical Journal Letters, 973(1), L14. doi:10.3847/2041-8213/ad6f9f
4. DESI Collaboration. (2025). DESI 2024 VI: Cosmological constraints from the measurements of baryon acoustic oscillations. Journal of Cosmology and Astroparticle Physics, 2025(02), 021. doi:10.1088/1475-7516/2025/02/021

5. Planck Collaboration. (2020). Planck 2018 results. VI. Cosmological parameters. Astronomy and Astrophysics, 641, A6. doi:10.1051/0004-6361/201833910
6. Riess, A. G., Yuan, W., Macri, L. M., Scolnic, D., Brout, D., Casertano, S., et al. (2022). A comprehensive measurement of the local value of the Hubble constant with 1 km s^-1 Mpc^-1 uncertainty from the Hubble Space Telescope and the SH0ES Team. The Astrophysical Journal Letters, 934(1), L7. doi:10.3847/2041-8213/ac5c5b
7. Rubin, D., et al. (2025). Cosmology with 2000 SNe using a unified Bayesian framework. The Astrophysical Journal, 986(2), 231.