



Constraining Cosmological Parameters with Type Ia Supernovae, the Cosmic Microwave Background, and Baryon Acoustic Oscillations: A Multi-Probe Analytical Review

Amritansh soni¹, Dr Avinash Singh²

¹Research Scholar, Department of Physics, Kalinga University, Raipur

²Research Supervisor, Department of Physics, Kalinga University, Raipur

Abstract- This conference paper examines how three major observational probes, Type Ia supernovae, the cosmic microwave background, and baryon acoustic oscillations, jointly constrain the central parameters of modern cosmology. The research problem addressed here is straightforward but fundamental: no single probe can independently determine the Hubble constant, matter density, spatial geometry, and dark-energy behavior without some level of degeneracy or model dependence. The paper therefore adopts a comparative analytical framework that evaluates the physical basis, redshift sensitivity, and systematic limitations of each probe before assessing their combined explanatory power. The review shows that Type Ia supernovae remain the most direct tracer of late-time acceleration, the cosmic microwave background provides the tightest early-universe anchor, and baryon acoustic oscillations supply an essential geometric bridge between them. Recent joint analyses continue to support a spatially flat cosmological model close to LambdaCDM, with dark energy still broadly consistent with a cosmological constant. At the same time, residual tensions, especially around H_0 and the possible evolution of dark energy, indicate that precision has outpaced complete physical consensus. The paper argues that the strongest current insight is not the dominance of one probe, but the methodological necessity of combining all three.

Keywords- cosmological parameters, Type Ia supernovae, cosmic microwave background, baryon acoustic oscillations, dark energy, observational cosmology.

I. Introduction

A central task in modern cosmology is to determine a small set of parameters that describe the large-scale structure and expansion history of the universe. These include the Hubble constant (H_0), the matter density parameter (Ω_m), spatial curvature, and the dark-energy equation-of-state parameter (w). The difficulty is that each parameter is inferred indirectly through observations, and every observational probe is sensitive to only part of the underlying model. The modern phase of this problem began when high-redshift Type Ia supernova studies showed that the universe is undergoing accelerated expansion, implying either a cosmological constant or some other dark-energy component (Riess et al., 1998; Perlmutter et al., 1999).

Since then, measurements of the cosmic microwave background (CMB) by Planck and distance constraints from baryon acoustic oscillations (BAO) have transformed cosmology into a precision science. Yet precision has not eliminated interpretation problems. Instead, it has exposed tensions between early- and late-universe inferences



and renewed debate over whether the standard LambdaCDM model is complete. This paper addresses that problem by asking how far the joint use of Type Ia supernovae, CMB, and BAO can robustly constrain cosmological parameters, and where the remaining limitations still lie.

II. Literature Review

The literature on cosmological parameter estimation is built on three interlocking traditions. The first concerns Type Ia supernova cosmology. The original acceleration results by Riess et al. (1998) and Perlmutter et al. (1999) established supernovae as effective standardizable candles for tracing luminosity distance across cosmic time. Later compilations improved sample size, calibration, and control of systematics. The Joint Light-curve Analysis by Betoule et al. (2014) became a major benchmark, and the Pantheon+ analysis by Brout et al. (2022) expanded the data set to 1,701 light curves from 1,550 spectroscopically confirmed supernovae over a wide redshift range. The second tradition is CMB cosmology.

The final Planck parameter analysis remains the most precise broad-scale test of the base LambdaCDM model and reports strong internal consistency for a spatially flat six-parameter framework (Planck Collaboration, 2020). The third tradition concerns BAO as a standard ruler. The first clear detection in Sloan Digital Sky Survey data was reported by Eisenstein et al. (2005), and later large-scale analyses from BOSS and DESI substantially improved the redshift coverage and statistical power of BAO constraints (Alam et al., 2017; DESI Collaboration, 2025). Taken together, this literature shows that the field has progressed from probe-specific evidence to probe-combination inference. The crucial issue is no longer whether the universe accelerates, but how different probes encode complementary information about the same cosmological model.

III. Methodology or Conceptual Approach

This paper adopts a conceptual analytical review rather than a new numerical parameter fit. That choice is appropriate for a conference paper aimed at clarifying the structure of current evidence rather than reproducing collaboration-level pipelines. The method proceeds in three steps. First, each probe is examined in terms of its physical observable: luminosity distance for Type Ia supernovae, anisotropy power spectra for the CMB, and the acoustic standard ruler for BAO. Second, each probe is evaluated according to its dominant redshift leverage and its main systematic uncertainties.

Third, the paper analyzes how combining the probes reduces degeneracies in H_0 , Ω_m , curvature, and w . The framework assumes that the value of a multi-probe approach lies not simply in statistical averaging, but in the way distinct observables test different epochs of cosmic history. This allows the paper to move beyond descriptive summary and toward a critical question: whether current agreement among probes indicates a settled cosmological model or only a temporary convergence under shared assumptions.



IV. Results or Analysis

Type Ia supernovae constrain the late-time expansion history because they provide relative distance measurements over a broad redshift range. Their major strength is direct sensitivity to cosmic acceleration. Their weakness is that they do not independently fix an absolute distance scale without calibration input, and their precision depends on light-curve standardization, host-galaxy corrections, selection effects, and possible population evolution. Even so, recent supernova analyses are remarkably informative. Brout et al. (2022) report that Pantheon+ alone yields $\Omega_m = 0.334 \pm 0.018$ for flat Λ CDM and $w_0 = -0.90 \pm 0.14$ for flat w CDM, while the combination with CMB and BAO gives w_0 close to -1. The analytical implication is important: supernovae are powerful for mapping the recent expansion history, but they become far more decisive when tied to complementary probes that anchor the absolute scale and early-universe physics.

The CMB provides a radically different kind of constraint. Rather than tracing late-time distances directly, it measures the physical conditions of the early universe and the geometry encoded in the angular size of acoustic features at recombination. This makes it extraordinarily efficient at constraining combinations of $\Omega_b h^2$, $\Omega_c h^2$, n_s , and the acoustic scale, and it provides a strong indirect estimate of late-time parameters once a cosmological model is specified. Planck Collaboration (2020) finds $H_0 = 67.4 \pm 0.5$ km/s/Mpc, $\Omega_m = 0.315 \pm 0.007$, and $n_s = 0.965 \pm 0.004$ within base Λ CDM, while also reporting no compelling evidence for model extensions. The strength of the CMB is therefore precision. Its limitation is interpretive dependence: the inferred late-universe parameters are only as secure as the early-universe model used to translate the anisotropies into present-day quantities. In practical terms, the CMB is the most powerful single anchor in cosmology, but it is not methodologically self-sufficient.

BAO occupies an intermediate and highly strategic position. The acoustic scale imprinted in the matter distribution acts as a standard ruler, allowing measurements of the expansion rate and comoving distance at multiple redshifts. Historically, the first detection by Eisenstein et al. (2005) established BAO as a viable cosmological observable, while BOSS and DESI turned it into a precision geometric test. The BOSS DR12 analysis by Alam et al. (2017) synthesized galaxy clustering measurements across three effective redshifts, and the DESI first-year cosmology analysis extended the scope further through galaxies, quasars, and Lyman-alpha forest tracers. The analytical value of BAO lies in its comparatively clean large-scale physics and its ability to bridge the observational gap between the CMB and supernovae. At the same time, BAO still relies on the sound horizon as a physical scale, so its strongest late-time conclusions are often sharpened when combined with CMB information. In that sense, BAO is neither redundant with the CMB nor merely supportive of supernovae. It is the geometric mediator that allows the three-probe system to function coherently.

The strongest result emerging from the literature is therefore the complementarity of the probes. Supernovae track relative luminosity distance at low to intermediate redshift. The CMB fixes the early-universe baseline and tightly constrains the physical matter content. BAO links these two domains through a standard-ruler measurement of the expansion history. When used jointly, they break parameter degeneracies that none



of them can fully resolve alone. This is evident in the way Pantheon+ constraints on w tighten significantly when combined with CMB and BAO, and in the way Planck results gain interpretive robustness when cross-checked against late-time distance probes. The combined evidence continues to favor a spatially flat cosmology close to Λ CDM, with dark energy broadly consistent with a constant equation of state near $w = -1$. However, the convergence should not be overstated. It is more accurate to say that the standard model remains highly successful under current data combinations than to say that all cosmological tensions have been solved.

V. Discussion

The discussion turns on one central point: multi-probe precision is not equivalent to final theoretical closure. The current cosmological model performs impressively because the three probes reinforce one another across different redshift regimes, but the apparent stability of the result depends on careful treatment of calibration, covariance, and model assumptions. Supernova cosmology still faces questions about standardization and population drift. CMB inference remains sensitive to assumptions about pre-recombination physics. BAO is robust on large scales, yet its interpretive force increases substantially when connected to the sound horizon established by early-universe modeling. For that reason, current cosmological parameter estimation is best understood as a structured inference problem rather than a direct measurement problem. The contribution of this paper is to make that structure explicit. The most important insight is not that one probe has become dominant, but that each probe compensates for the epistemic weaknesses of the others. This is precisely why multi-probe cosmology has become the standard strategy in the field.

A second point concerns unresolved tensions. The most widely discussed is the discrepancy between local and early-universe estimates of H_0 , but broader questions also remain about whether dark energy is exactly constant or only approximately so within present uncertainties. Recent large-survey analyses have intensified attention to that issue, even though the evidence for evolving dark energy remains suggestive rather than decisive. The analytical lesson is that contemporary cosmology is in a transitional moment. The standard model is empirically resilient, yet the residual discrepancies are too persistent to dismiss as mere noise without further scrutiny. A cautious reading of the literature therefore supports neither a triumphalist claim that Λ CDM is closed, nor a premature claim that it has already failed. The stronger position is methodological: future progress depends on better cross-calibration, larger low-systematic samples, and joint analyses that treat consistency itself as an observable feature of the cosmological model.

VI. Conclusion and Future Work

This paper has argued that constraining cosmological parameters is fundamentally a multi-probe problem. Type Ia supernovae reveal the late-time acceleration of the universe, the CMB supplies the most precise early-universe anchor, and BAO connects these regimes through a stable geometric ruler. The main finding is that the combination of these probes continues to support a flat universe dominated by matter and a dark-energy component close to a cosmological constant. At the same time, the remaining tensions around H_0 and the open question of dark-energy evolution show that precision



does not automatically produce conceptual finality. The paper contributes a concise analytical synthesis suitable for conference presentation by showing why the strength of current cosmology lies in complementarity rather than in any single observational method. Future work should focus on improved supernova calibration, expanded BAO measurements across redshift, and more rigorous joint inference frameworks that test not only best-fit parameters but also the stability of conclusions across alternative cosmological assumptions. Such work will determine whether current tensions are statistical residue, hidden systematics, or early signs of physics beyond the standard model.

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