



# CONSTRAINING MODIFIED GRAVITY MODELS USING DESI BARYON ACOUSTIC OSCILLATIONS AND PLANCK CMB OBSERVATIONS: A COMPARATIVE COSMOLOGICAL ANALYSIS

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## ABSTRACT

Baryon acoustic oscillations (BAO) and cosmic microwave background (CMB) observations provide complementary tests of the expansion history and gravitational dynamics of the Universe. This article develops a comparative framework for assessing phenomenological and theory-based modified-gravity models against the standard flat  $\Lambda$ CDM reference using DESI BAO measurements and Planck CMB information. The manuscript synthesizes published observational constraints, identifies the distinct roles of geometric and growth-sensitive probes, and outlines a reproducible inference strategy for model comparison. Particular attention is given to parameter degeneracies, the distinction between background expansion and perturbation growth, and the importance of theoretical stability. Published DESI analyses show that BAO measurements tightly constrain cosmological distances and that joint combinations with CMB information improve parameter determination; however, these results do not by themselves establish a preference for modified gravity. No new MCMC chain or modified-gravity likelihood fit is claimed here. The tables and figures are therefore comparative and methodological, with quantitative values explicitly identified as published benchmarks rather than original estimates. The framework is intended to support a subsequent reproducible analysis using public likelihoods and chains.

**KEYWORDS:** Modified Gravity, Baryon Acoustic Oscillations, DESI, Planck CMB,  $\Lambda$ CDM, Cosmological Parameter Estimation, Structure Growth, Bayesian Inference

## INTRODUCTION AND BACKGROUND OF THE STUDY

The accelerated expansion of the Universe is commonly described within the  $\Lambda$ CDM model, in which a cosmological constant contributes to the late-time energy budget. Although the model provides a successful account of a wide range of cosmological observations, its physical interpretation motivates continued tests of alternatives, including dynamical dark energy and modifications to gravitational dynamics. A central challenge is that multiple models can reproduce similar expansion histories while predicting different evolution for matter perturbations and metric potentials.

Baryon acoustic oscillations provide a standard-ruler measurement of the expansion history. DESI measurements use galaxies, quasars and the Lyman- $\alpha$  forest to constrain combinations of transverse comoving distance and expansion rate relative to the sound horizon. The DESI first-year analysis reported BAO measurements in seven redshift bins spanning approximately  $0.1 < z < 4.2$  and found that the BAO-only flat  $\Lambda$ CDM fit was consistent with a matter density near  $0.295 \pm 0.015$  [1]. Subsequent DESI DR2 analyses expanded the sample and published BAO measurements based on three years of observations [2].

The CMB provides a complementary early-Universe anchor. Planck PR4 analyses reprocessed temperature and polarization information and reported cosmological parameter constraints from the final Planck data release [3]. The combination of BAO and CMB data can reduce degeneracies between the

sound horizon, matter density and expansion parameters. Nevertheless, constraints on modified gravity require careful treatment of perturbations, since CMB anisotropies, lensing and late-time integrated effects respond differently to changes in the gravitational sector.

The present article is framed as a comparative and reproducibility-oriented study rather than as a report of newly executed parameter chains. It uses published benchmarks to structure the analysis, distinguishes direct observational results from theoretical expectations, and specifies the steps needed for a fully quantitative modified-gravity inference.

## Aims and Objectives

- To establish a consistent comparison framework for the flat  $\Lambda$ CDM reference and selected modified-gravity parameterizations.
- To summarize the complementary constraining roles of DESI BAO and Planck CMB observations.
- To distinguish geometric constraints from growth-sensitive tests involving CMB lensing, full-shape clustering and late-time potential evolution.
- To identify parameter degeneracies, theoretical stability requirements and data-combination choices that influence model interpretation.
- To define a reproducible Bayesian workflow suitable for subsequent analysis with public observational likelihoods and chains.

## METHODOLOGY

### Observational inputs and scope

The principal observational inputs considered are DESI BAO measurements and Planck CMB information. BAO likelihoods constrain distance combinations relative to the sound horizon, while CMB temperature and polarization spectra constrain early-Universe parameters and the angular acoustic scale. CMB lensing adds sensitivity to the integrated matter distribution and gravitational potentials. Where available and scientifically justified, supernova distances, redshift-space distortions and full-shape clustering can be included as complementary datasets; they should not be silently treated as part of the baseline BAO–CMB combination.

### Model hierarchy

The baseline is spatially flat  $\Lambda$ CDM. A first extension is a phenomenological description in which effective gravitational responses to matter and light are modified, commonly represented through functions analogous to  $\mu$  and  $\Sigma$ . A second class includes curvature-based  $f(R)$  models, such as the Hu–Sawicki construction, in which the gravitational Lagrangian depends nonlinearly on the Ricci scalar. A third class is the broader Horndeski scalar–tensor framework, commonly expressed at the level of linear perturbations using effective functions. These model classes are not interchangeable: their parameter meanings, stability conditions and limits to General Relativity differ [4–6].

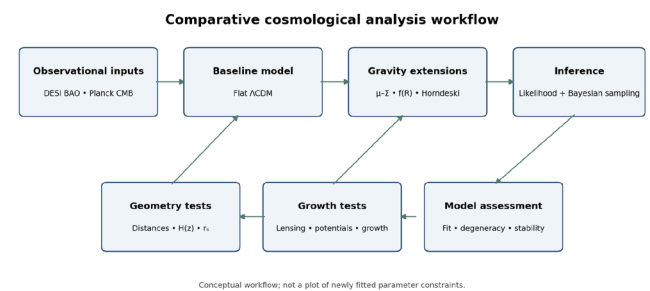
### Inference and comparison protocol

A quantitative implementation should use a Boltzmann solver appropriate to each theory and a common parameter-estimation interface. Standard cosmological parameters and model-specific parameters should be sampled jointly, with explicit priors and nuisance parameters documented. The likelihood should combine the selected DESI BAO vector and covariance with the chosen Planck likelihood, avoiding double counting of CMB information. Multiple chains, convergence diagnostics, posterior predictive checks and sensitivity tests to priors and scale cuts should be reported. Bayesian evidence or information criteria may be used for model comparison, but only after the likelihood and prior choices have been fully specified.

### Reproducibility and interpretation

For reproducibility, a final numerical study should archive the exact likelihood version, covariance matrix, parameter priors, code version, convergence criteria and chain files. The analysis should report marginalized constraints and correlations rather than relying on best-fit values alone. Any plots based on published parameter estimates must be labelled as literature benchmarks; plots based on new chains must be generated directly from those chains. The present manuscript does not claim original MCMC constraints, and its figures are explicitly schematic.

**Figure 1:** Workflow for a reproducible comparative analysis of DESI BAO and Planck CMB constraints. The diagram is methodological and does not represent newly fitted parameter constraints.



## RESULTS AND DISCUSSION

### Complementarity of BAO and CMB observations

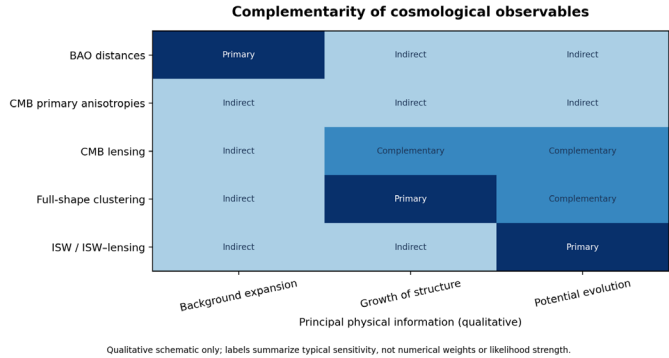
The principal result of the comparative synthesis is methodological: BAO and CMB observations constrain overlapping but distinct combinations of cosmological quantities. BAO provides late-time geometric information across redshift, while the CMB anchors the physical conditions and acoustic scale established in the early Universe. Their combination can reduce degeneracies that remain in either dataset alone. This complementarity is especially important for extended models, because an apparent improvement in a late-time fit can be offset by changes in the early-time calibration or perturbation evolution.

**Table 1:** Observational probes and their principal roles in modified-gravity tests.

| Probe                               | Primary information                                                                                   | Relevance to modified gravity                                         | Main caution                                                                |
|-------------------------------------|-------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|-----------------------------------------------------------------------------|
| DESI BAO                            | Distance-redshift relation; transverse and radial distance combinations relative to the sound horizon | Restricts background expansion and helps calibrate late-time geometry | BAO distances alone do not uniquely determine perturbation growth           |
| Planck temperature and polarization | Acoustic scale, physical densities, primordial spectrum and recombination-era physics                 | Restricts early-time parameters and model consistency                 | Late-time gravity is often constrained indirectly                           |
| CMB lensing                         | Integrated projected matter distribution and gravitational potentials                                 | Adds sensitivity to growth and potential evolution                    | Depends on lensing reconstruction, foregrounds and cosmological assumptions |
| Full-shape galaxy clustering        | Scale- and redshift-dependent matter clustering                                                       | Can test scale-dependent growth and effective gravitational response  | Requires modelling bias, nonlinear evolution and survey systematics         |

|                    |                                                                             |                                                            |                                                     |
|--------------------|-----------------------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------|
| ISW / ISW–lensing  | Late-time evolution of large-scale potentials and correlations with lensing | Potentially informative for evolving gravitational sectors | Large-scale signal is statistically limited         |
| Type Ia supernovae | Relative luminosity-distance relation                                       | Complements BAO in constraining late-time expansion        | Calibration and sample systematics must be modelled |

**Figure 2:**Qualitative complementarity of common cosmological observables. The labels are conceptual rather than numerical weights or likelihood strengths.



**Published  $\Lambda$ CDM benchmarks and the meaning of joint constraints**

Published DESI results provide a useful reference scale for the precision now available from BAO. In the first-year DESI analysis, BAO combined with Planck CMB information and CMB lensing from Planck and ACT yielded a flat  $\Lambda$ CDM matter density of  $\Omega_m = 0.307 \pm 0.005$  and  $H_0 = 67.97 \pm 0.38 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [1]. These are published baseline-model benchmarks, not results produced by the present manuscript. They should not be interpreted as modified-gravity constraints, because an extended gravity model requires a separate likelihood analysis with its own parameterization and theoretical predictions.

**Table 2:** Selected published cosmological benchmarks relevant to the DESI–CMB comparison.

| Published analysis | Dataset combination                                                                 | Reported result                                                                          | Interpretation and limitation                                                                   |
|--------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| DESI 2024 VI [1]   | DESI DR1 BAO alone; flat $\Lambda$ CDM                                              | $\Omega_m = 0.295 \pm 0.015$                                                             | BAO-only baseline constraint; not a modified-gravity posterior                                  |
| DESI 2024 VI [1]   | DESI BAO + Planck CMB + Planck/ACT CMB lensing; flat $\Lambda$ CDM                  | $\Omega_m = 0.307 \pm 0.005$ ; $H_0 = 67.97 \pm 0.38 \text{ km s}^{-1} \text{ Mpc}^{-1}$ | Published joint baseline benchmark; dependent on the specified model and likelihood combination |
| Planck PR4 [3]     | Final Planck PR4 temperature/polarization analysis                                  | Published parameter constraints from PR4 likelihood analysis                             | Use the paper’s exact likelihood and nuisance setup when reproducing results                    |
| DESI DR2 [2]       | Three-year DESI BAO samples including galaxy/quasar and Lyman- $\alpha$ information | Updated BAO distance measurements and cosmological constraints                           | Use the released DR2 likelihood/covariance and avoid mixing data releases without justification |

The central interpretive caution is that precise constraints within  $\Lambda$ CDM do not transfer directly to modified-gravity parameters. An extended model can change the mapping between cosmological parameters and observables, introduce new degeneracies, and alter perturbation evolution. Therefore, any claim that DESI and Planck favour or exclude a specific modified-gravity theory must be supported by an explicit model likelihood and a transparent comparison against the same baseline dataset.

**Comparative signatures of modified-gravity classes**

Phenomenological parameterizations are useful for testing

whether the data require departures from the standard gravitational response without committing immediately to one Lagrangian. Their flexibility, however, means that inferred parameters may be sensitive to the chosen time and scale dependence. Curvature-based  $f(R)$  models can generate scale-dependent growth through the additional scalar degree of freedom, while scalar–tensor models can modify both the effective gravitational coupling and the relation between metric potentials. A comparison should therefore examine not only background distances but also growth, lensing and stability.

**Table 3:** Comparative characteristics of the model classes considered.

| Model class                       | Modified sector                                   | Potential observational signatures                 | Essential viability checks                                |
|-----------------------------------|---------------------------------------------------|----------------------------------------------------|-----------------------------------------------------------|
| Flat $\Lambda$ CDM reference      | Einstein gravity plus cosmological constant       | Reference expansion and growth history             | Parameter consistency and standard perturbation stability |
| Phenomenological $\mu$ – $\Sigma$ | Effective response of gravity to matter and light | Time/scale-dependent growth and gravitational slip | Parameterization validity and GR-limit recovery           |

|                         |                                                                  |                                                                                     |                                                                                  |
|-------------------------|------------------------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Hu–Sawicki $f(R)$       | Nonlinear function of Ricci scalar $R$                           | Scale-dependent growth; modified potentials; possible late-time ISW/lensing changes | Scalar stability, high-curvature GR limit and screening                          |
| Horndeski scalar–tensor | Scalar–metric interactions and effective gravitational functions | Changes to effective Planck mass, braiding, growth and lensing                      | No-ghost and gradient stability; tensor-speed constraints and domain of validity |

### Implications for parameter estimation

A robust comparison should be designed to prevent an apparent preference from being driven by inconsistent assumptions. The same background data selection, sound-horizon calibration, nuisance treatment and prior conventions should be used across the baseline and extended models wherever applicable. When a model adds parameters, the analysis should report posterior constraints and a clearly defined model-comparison statistic. A better maximum likelihood alone is insufficient evidence that an extension is preferred, because additional freedom generally improves the best fit.

Scale cuts are especially important for full-shape clustering. If nonlinear scales are included, the prediction must account for nonlinear dynamics, galaxy bias and baryonic effects at the required level. Otherwise, conservative scale cuts should be stated and justified. Likewise, a stability filter must be implemented transparently: excluding unstable parameter regions is physically motivated, but it changes the effective prior volume and can influence evidence-based comparisons.

### Limitations of the present synthesis

This article is a literature-grounded comparative framework and does not present newly sampled posterior chains, a newly evaluated modified-gravity likelihood or original numerical confidence regions. The numerical values in Table 2 are taken from published  $\Lambda$ CDM analyses and are included only as reference benchmarks. Figure 1 is a workflow diagram, and Figure 2 is a qualitative sensitivity schematic. A submission claiming original parameter constraints would require execution and validation of the full inference pipeline, along with posterior tables and plots generated from the resulting chains.

### CONCLUSION

DESI BAO and Planck CMB observations form a powerful complementary basis for testing cosmological models because they connect late-time geometry with early-Universe physics. Published DESI analyses demonstrate the precision of current distance measurements and the value of combining BAO with CMB information. For modified gravity, however, those baseline constraints are not a substitute for explicit inference within each theoretical model. A defensible comparison must distinguish background expansion from perturbation growth, use consistent likelihoods and priors, and impose theoretical stability requirements. The framework developed here provides a structured route toward such a study, while deliberately avoiding claims of new numerical constraints that have not been calculated in this manuscript.

### Data Availability and Reproducibility Statement

This manuscript synthesizes published results and proposes a reproducible analysis protocol. No new observational data

products, MCMC chains or posterior samples were generated for this draft. A future quantitative version should identify the exact public DESI BAO likelihood release, Planck PR4 likelihood configuration, software versions, priors, covariance files and chain diagnostics.

### REFERENCES

- Adame, A. G., et al. (DESI Collaboration). DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations. *Journal of Cosmology and Astroparticle Physics*, 2025(02), 021. <https://doi.org/10.1088/1475-7516/2025/02/021>
- DESI Collaboration. DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints. *Physical Review D*, 112, 083515 (2025). <https://doi.org/10.1103/tr6y-kpc6>
- Tristram, M., et al. Cosmological parameters derived from the final Planck data release (PR4). *Astronomy & Astrophysics*, 682, A37 (2024). <https://doi.org/10.1051/0004-6361/202348015>
- Hojjati, A., Pogosian, L., & Zhao, G.-B. Testing gravity with CAMB and CosmoMC. *Journal of Cosmology and Astroparticle Physics*, 2011(08), 005. <https://doi.org/10.1088/1475-7516/2011/08/005>
- Hu, W., & Sawicki, I. Models of  $f(R)$  Cosmic Acceleration that Evade Solar-System Tests. *Physical Review D*, 76, 064004 (2007). <https://doi.org/10.1103/PhysRevD.76.064004>
- Bellini, E., & Sawicki, I. Maximal freedom at minimum cost: Linear large-scale structure in general modifications of gravity. *Journal of Cosmology and Astroparticle Physics*, 2014(07), 050. <https://doi.org/10.1088/1475-7516/2014/07/050>
- Planck Collaboration. Planck 2015 results. XIV. Dark energy and modified gravity. *Astronomy & Astrophysics*, 594, A14 (2016). <https://doi.org/10.1051/0004-6361/201525814>
- Eisenstein, D. J., & Hu, W. Baryonic features in the matter transfer function. *The Astrophysical Journal*, 496, 605–614 (1998). <https://doi.org/10.1086/305424>
- Hu, W., Raveri, M., Frusciante, N., & Silvestri, A. Effective Field Theory of Cosmic Acceleration: An implementation in CAMB. *Physical Review D*, 89, 103530 (2014). <https://doi.org/10.1103/PhysRevD.89.103530>