Impact of Varying Dark Energy on Future Large-Scale Structure Studies

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The cosmos withholds multiple mysteries such as dark forms of matter and energy that are yet beyond human comprehension. In the standard cosmological model, ΛCDM, the cosmological constant Λ is thought to be responsible for the late accelerated expansion of the Universe. However, recent results from the Dark Energy Spectroscopic Instrument (DESI) suggest the possibility of evolving dark energy, which warrants further exploration. Future surveys such as the Rubin Observatory Legacy Survey of Space and Time (LSST) will map the large-scale structure (LSS) with unprecedented precision, giving us valuable statistical information about the cosmos. The goal of this research is to investigate the potential impact of an evolving dark energy scenario on cosmological parameters constrained by LSS probes, as will be mapped by the LSST. For this, we examine the power spectra of lens galaxies, source galaxies, and cross-power spectra between lens galaxies and source galaxies. The combination of these statistics is commonly referred to as '3 × 2 points'. For this investigation, we created a set of simulations resembling LSST data and used them to perform cosmological parameter inference in two scenarios: one in which the simulated data is based on the fiducial model and another on evolving dark energy. We then examined the degeneracy between the cosmological parameters and checked for potential shifts in the parametric space when the data contains dynamical dark energy but the modeling assumes ΛCDM. Our findings indicate that mismodeling the dark energy equation of state can significantly impact parameter inference, particularly affecting the total matter density, Ω_m, and the growth of structures, as represented by the S_8 parameter. These results highlight the importance of further exploring extensions of the ΛCDM model in future LSS studies.

I. INTRODUCTION

When Albert Einstein was developing his theory of General Relativity, he temporarily introduced a "cosmological constant" in his field equations to counterbalance the effect of gravity and achieve a static universe. However, when Edwin Hubble discovered the universe was expanding in 1929, Einstein abandoned the concept, deeming it his biggest mistake. It was later found that the cosmological constant actually added a repulsive energy throughout the universe. This concept was revived in modern cosmology as part of the ΛCDM model to account for the observed accelerated expansion of the universe. Notably, Einstein's original constant differs from the lambda in the ΛCDM model, which specifically explains this accelerated expansion of the Universe.

Astronomical observations also indicate that most of the matter in the universe is composed of non-luminous matter, known as dark matter, being almost five times more abundant than baryonic matter. Despite years of research, the true nature of Dark Matter and Dark Energy is still an open question in Cosmology. The study of large-scale structure (LSS) with various cosmic probes has proven to be a significant way to comprehend the nature of these cosmic mysteries. In particular, the two-point correlation function or its Fourier transform, the power spectrum, has been widely implemented to study the LSS and their properties. The galaxy power spectrum, so-called galaxy clustering, determined from galaxies' angular positions and redshifts, allows direct measurement of the cosmic expansion history (H(z)) via baryon acoustic oscillations (BAO) and the growth of large-scale cosmic structures (fg(z)) through redshift-space distortions (RSD) and the estimate of the σ_8 parameter. Similarly, weak gravitational lensing, which refers to the subtle distortion of the images of distant galaxies due to the gravitational influence of large-scale structures such as galaxy clusters lying between the observer and these distant galaxies, can be statistically analyzed with the power spectrum across many galaxies. This analysis enables mapping the distribution of dark matter and studying the overall structure and evolution of the universe.

Future LSS surveys will have to consider the subtle influence of cosmic mysteries and parameters during data analysis and interpretation. The Rubin Observatory Legacy Survey of Space and Time (LSST) will be one of those significant projects to shed light on the nature of our cosmos. LSST is a decade-long survey of the southern sky, set to be conducted at the Vera C. Rubin Observatory, which is being built on Cerro Pachón's El Peñon peak in northern Chile. The survey's data will help global researchers explore numerous critical questions about dark energy and dark matter, the Milky Way's formation, characteristics of small solar system bodies, trajectories of potentially dangerous asteroids, and the potential discovery of unknown explosive events. Currently, the ΛCDM model of the universe accounts for the accelerating expansion, which is built on three main principles: general relativity accurately models gravitational interactions at cosmological scales; the Universe at these scales is homogeneous, isotropic, and spatially flat; and at later times, the Universe's composition is primarily non-relativistic, pressureless cold dark matter (CDM) and the cosmological constant Λ is responsible for a late-time accelerated expansion of the universe.

Recent analyses of the first-year data from the Dark Energy Spectroscopic Instrument (DESI) survey indicate a possible evolving dark energy scenario[1], where the parameter of the equation of state that relates the pressure and density of the dark energy component, w, is not constant and differs from -1, differently from what we expect in the ΛCDM scenario. These results require further exploration and LSS probes can provide valuable insights into this. Indeed, these recent DESI results motivated our study to understand the impact of LSS probes if the data is consistent with an evolving dark energy but we do not account for this in the model, instead assuming the ΛCDM scenario. For that, we study the "3×2pt" analysis, which combines three types of projected two-point correlation functions—cosmic shear measurements, galaxy clustering measurements, and galaxy shear to extract information. In simple terms, the analysis consists of a set of measurements describing the angular correlation of lens galaxy positions and source galaxy shapes for several redshift bins. With this analysis, we aim to better comprehend the nature of Dark energy by measuring the growth and evolution of the LSS. Finally, we compare the results from the model fixed in ΛCDM scenario and with the 3x2pt data simulated using an evolving dark-energy scenario.

II. METHOD

A. Power Spectrum

The angular power spectrum of the LSS probes provides a statistical measure of the density fluctuations in the universe, which are essential for understanding the formation and evolution of cosmic structures like galaxies, clusters of galaxies, and the cosmic web. In particular, we use the power spectrum of the lens galaxies (galaxy power spectrum- C_ℓ^{gg}), source galaxies (galaxy weak lensing- $C_\ell^{\kappa\kappa}$), and lens-source (galaxy-galaxy lensing- $C_\ell^{\kappa g}$). These measurements encode the properties of the large-scale structure, the processes of galaxy formation and evolution, and the fundamental contents of the cosmos.

We used **pyccl**[2,3] package in Python to generate the theoretical power spectra according to the cosmological model. In most general cases, assuming Limber approximation[4], the angular power spectrum between two tracers, X and Y is given by

$$C_\ell^{XY} = \int_0^\infty \frac{dz}{c}\frac{H(z)}{\chi^2(z)}[W^X(z)W^Y(z)]P\left(k=\frac{\ell}{\chi(z)},z\right); \quad (1)$$

where $\chi(z)$ is the comoving distance to redshift z, $H(z)$ is the Hubble factor at redshift z, $P(k,z)$ is the matter power spectrum. The function $W(z)$ denotes the kernel of the tracer[5]. For lens galaxies, assuming linear, deterministic galaxy bias, we have

$$W^g(z) = b(z)\frac{dn}{dz}, \quad (2)$$

where dn/dz is the normalized redshift distribution. For source galaxies, the weak lensing kernel W^κ is

$$W^\kappa = \frac{3H_0^2\Omega_{\mathrm{m},0}}{2H(z)c}\frac{\chi(z)}{a(z)}\int_z^{z_H} dz' n(z')\frac{\chi(z')-\chi(z)}{\chi(z')}, \quad (3)$$

where $n(z)$ is the redshift distribution of the sample, Ω_m is the total matter density and H_0 is the Hubble constant today, and $a(z)$ is the scale factor.

B. LSST like mocks

In order to predict the observations by LSST, we produced a set of 2000 lognormal correlated LSST-like mocks to compute the covariance of the data. We consider the redshift distributions of the tomographic bins for the lens and source galaxy samples for the first year of LSST operation, as expected according to the LSST-DESC Science Requirements Document (SRD)[6]. We show in Fig. 1 the corresponding redshift distributions for the lens (solid lines) and source (dashed lines) galaxies. We created random realization maps of shot and source noises to the lens and source maps respectively by accounting for the specifics shown in Table I. The shot-noise power spectra are computed by taking $1/\mathrm{n_{gal}}$ for lens maps and $\sigma_e^2/\mathrm{n_{gal}}$ for source maps. We use the python package **healpy**[7,8], which handles pixelated data on the sphere, to perform harmonic transform operations and facilitate visualization of our models as HEALPix maps.

Figure 2 shows the Healpix Maps of an individual realization of the fields Galaxy Overdensity (left) and Galaxy Weak Lensing(right). We produced these mocks considering the redshift distribution of the lens and source galaxies in the LSST mock as shown in Figure 1.

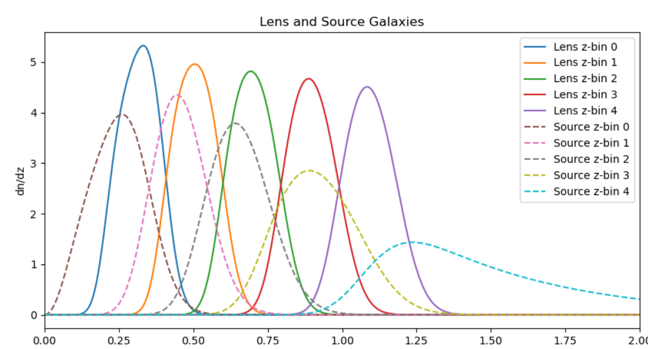

FIG. 1: Redshift distributions ($\frac{dN}{dZ}$) of the Lens and source galaxies for a survey like- LSST first year[6].

We computed the power spectrum of the 2000 simulated realizations for each redshift bin using the `anafast` routine in healpy. We then used these noisy mock power spectra to

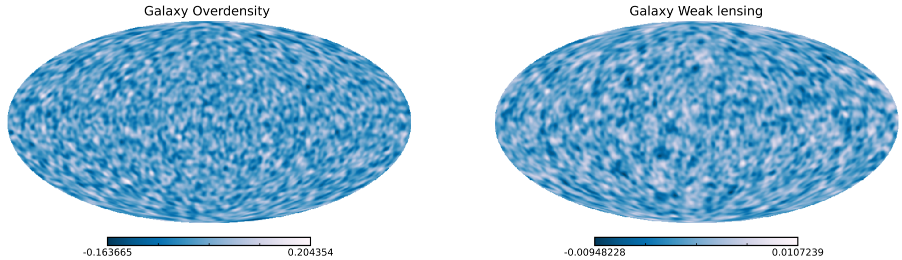

FIG. 2: Example of the galaxy overdensity (left) and galaxy weak lensing (right) simulated maps considered in our study. The maps are smoothed with a Gaussian beam with a 3-degree width for visualization purposes only.

Lens z-bin	**<z>**	**Number density (ngal)**	**Galaxy Bias**
1	0.30	2.25	1.0
2	0.50	3.11	1.1
3	0.70	3.09	1.2
4	0.90	2.61	1.5
5	1.10	2.00	2.0
Source z- bin	**<z>**	**Number density (ngal)**	**Shape noise σ_e**
1	0.31		
2	0.49		
3	0.69	1.78	0.26
4	0.96		
5	1.59		

TABLE I: The specifications for the LSST Y1 DESC sample are outlined according to[9]. The number densities are given in units of 1/arcmin^2, and σ_e represents the shape noise. The same number density and shape noise are assumed for all source redshift bins. The noise levels for the lens and source samples are defined based on these specifications. Specifically, the galaxy shot noise is defined as $1/\text{ngal}$ and the lensing noise is defined as σ_e^2/ngal.

compute the covariance matrix (C) expected for the measurements,

$$C_{ij} = \frac{1}{N-1}\sum_{n=1}^{N}(d_i^n - \bar{d}_i)(d_j^n - \bar{d}_j), \tag{4}$$

where $N = 2000$ is the number of simulations, d is the data array (e.g., C_ℓ^{gg}, $C_\ell^{\kappa\kappa}$, $C_\ell^{\kappa g}$ or the combination of them), and $\bar{d}$ is the average of the statistics over the 2000 realizations.

C. Time dependent Dark Energy

In cosmology, the components of the universe are characterized by its equation of state parameter w, which relates to pressure P of the fluid to its density ρ via $w = \frac{P}{\rho}$. For the dark energy component in the ΛCDM model, w is assumed to be constant and equal to -1, causing a negative pressure responsible for accelerated expansion. However, some alternative cosmological models consider different parameterizations for the dark energy equation of state[10]. A common parameterization for this evolving dark energy is given by a model so-called CPL:

$$w(a) = w_0 + w_a(1-a)$$

where w_0 is the present value of w, w_a describes the rate of change of w with the scale factor a, and $a = \frac{1}{1+z}$ (where z is the redshift).

In this research, we perform parameter inference using the ΛCDM cosmology model. However, we base our simulated "data" on two scenarios: one following the ΛCDM model and another incorporating $w_a \neq 0$ and $w \neq 1$. In particular, we considered the w_0 and w_a values from the latest DESI + Cosmic Microwave Brackgroud (CMB) results[1], where $w_0 = -0.45$ and $w_a = -1.79$. Our goal is to understand if neglecting a consistent modeling of evolving dark energy when the data is consistent with it, would impact the inferred values of cosmological parameters.

III. RESULTS AND DISCUSSION

Firstly, we study the sensitivity of probes with a "3×2pt" analysis. To achieve this, we use pyccl to produce the theoretical power spectra, C_ℓ^{gg}, $C_\ell^{\kappa\kappa}$, and $C_\ell^{\kappa g}$, by varying each of the cosmological parameters while keeping the rest fixed at the fiducial cosmology (Table II). These parameters include Ω_m, n_s, A_s, H_0, w_0, w_a, and σ_8. Ω_m is the matter density of the universe, which can be further divided into the baryonic matter density, Ω_b, and the dark matter density, Ω_c. n_s is the scalar spectral index, a parameter derived from the primordial power spectrum. A_s represents the normalization or amplitude of fluctuations in the primordial power spectrum. H_0 is the Hubble parameter, describing the expansion rate of the universe through the velocity of galaxies one megaparsec away. For this analysis, we use the dimensionless version of the Hubble parameter, h, defined as $H_0/100$ km/s/Mpc. σ_8 describes the amplitude of density fluctuations in the late universe and can be mathematically defined as the normalization of the late-time matter power spectrum. Combining σ_8 and Ω_m yields $S_8 \equiv \sigma_8\sqrt{(\Omega_m/0.3)}$, a parameter sensitive to growth of the structures.

Figure 3 shows the expected sensitivity of the C_ℓ^{gg} (top row), $C_\ell^{\kappa\kappa}$ (mid-row), and $C_\ell^{\kappa g}$ (bottom row) to variations of

w_0, w_a, and Ω_b, respectively. For visual clarity, we present the results for only three parameters and two redshift bins of the lens and source galaxies, specifically bin-2 and bin-3. The colored gradient illustrates that the probes are significantly affected by changes in the cosmological parameters. Some probes exhibit similar scale-dependent variations, suggesting that these parameters are likely highly degenerate with one another.

Finally, we examined the degeneracy between cosmological parameters and assessed the potential impact on our analysis when the data suggest a dynamical dark energy scenario, but our modeling assumes a static dark energy component. In order to perform the parameter inference we use Bayesian statistic[11] and evaluate the posterior of the parameters conditional on the data by assuming a Gaussian likelihood, $\mathscr{L}$ of the form

$$\ln \mathscr{L}(\mathbf{d}|\boldsymbol{\theta}) = -\frac{1}{2}[\mathbf{d} - x(\boldsymbol{\theta})]^{\mathrm{T}} \mathrm{C}^{-1} [\mathbf{d} - x(\boldsymbol{\theta})], \quad (5)$$

where $\mathbf{d}$ is the measured data vector, C is the covariance matrix computed using mocks, $x(\boldsymbol{\theta})$ is the ΛCDM theoretical prediction at parameter values ($\boldsymbol{\theta}$) estimated using pyccl. Here, we consider data as C_ℓ^{gg}, $C_\ell^{\kappa\kappa}$, and $C_\ell^{\kappa g}$ combined in the fiducial scenario ($w_0 = -1.0, w_a = 0.0$) and also in the $w_0 = -0.45, w_a = -1.79$ scenario. We then, sample the likelihood using the Monte Carlo Markov Chain (MCMC) sampler, implemented in the publicly available code `Cobaya`[12][13]. Initially, in the plots shown in Fig 3, we varied only one parameter at a time. However, in the parameter inference process, we vary all parameters simultaneously to find the optimal solution for all of them, as detailed in the priors listed in Table II.

Figure 4 shows the cosmological constraints for the two scenarios we considered: the fiducial model and data (red contours) and the $w_a - w_0$ data (blue contours). As expected, the best-fit values of the fiducial case align with the input parameters (vertical dashed lines) because the modeling is consistent with the simulated data. In the $w_a - w_0$ case, the cosmological parameters deviate from the input values because the $w_a - w_0$ model is not accounted for, particularly affecting Ω_m, σ_8, and S_8. Our results indicate that there is a strong impact on the late-time parameters, such as the growth of the structures, even though we only change the parameter connected to the equation of the state of the dark energy. In light of the recent S_8 discrepancy, where CMB studies found higher values compared to LSS probes[10,14,15], our results point that a possibly unaccounted evolving dark energy scenario can produce a lower S_8 by the LSS probes. Therefore, exploring extensions to the ΛCDM model is essential for further understanding the consistency of cosmological parameters.

Table III shows the best-fit values with associated errors for various cosmic parameters in both scenarios. Lastly, we calculated the normalized shift for each parameter from fiducial to $w_a - w_0$ model in Table III by using the following

Parameter	Fiducial	Prior
Ω_c	0.25	(0.1, 0.9)
Ω_b	0.05	(0.03, 0.07)
n_s	0.96	(0.87, 1.07)
h	0.7	(0.55, 0.91)
$A_s \times 10^9$	2.1	(0.5, 5.0)
w_0	-1.0	–
w_a	0.0	–

TABLE II: Parameters and priors describing the baseline cosmology and nuisance parameters used in this analysis. We quote the lower and upper limits of flat priors. In the fiducial case, we assume $w_0 = -1$ and $w_a = 0.0$ based on ΛCDM values. When considering the evolving dark energy scenario, we simulate data with $w_0 = -0.45$ and $w_a = -1.79$, according to BAO+CMB data from DESI+Planck[1] results, but keep the modeling assuming the ΛCDM scenario.

Parameter	Fiducial	$w_a - w_0$	Parameter Shift(Δ)
Ω_m	0.3000 ± 0.0017	0.2593 ± 0.0015	13.56σ
σ_8	0.8255 ± 0.0015	0.8575 ± 0.0014	11.42σ
$S8$	0.8254 ± 0.0020	0.7972 ± 0.0020	7.05σ

TABLE III: The table depicts the difference in peak values of some important cosmological parameters that we're trying to study like Ω_m, σ_8, and $S8$

equation:

$$\Delta P = \frac{P_{\text{fiducial}} - P_{(\mathrm{w_a - w_0})}}{\sqrt{\sigma_{upper}^2 + \sigma_{lower}^2}}$$

where P is any parameter, and σ_{upper} and σ_{lower} are upper and lower bounds of 1 σ error in $w_a - w_0$ case. Our results show a clear shift from the input values when considering our simulated data consistent with an evolving Dark Energy model.

IV. CONCLUSIONS

In our research, we examine the cosmological sensitivity of future LSS probes, as will be measured by the LSST survey. In particular, we aimed to understand the possible impact of unaccounted evolving dark energy in the 3×2pt analysis. Firstly, using the python package pyccl to generate theoretical cosmological power spectra, we checked the sensitivity of the individual power spectrum to various cosmological parameters. To estimate the expected error bars (and corresponding covariance) of the measurements, we use a set of 2000 lognormal correlated LSST-like mocks. Finally, we use MCMC to perform the parameter inference of two cosmological scenarios: one with the simulated data with the same input cosmology (ΛCDM parameters), and another with a dark energy equation of state parameters different from the ΛCDM case, specifically $w_0 = -0.45$ and $w_a = -1.79$, consistent with recent DESI+CMB results[1].

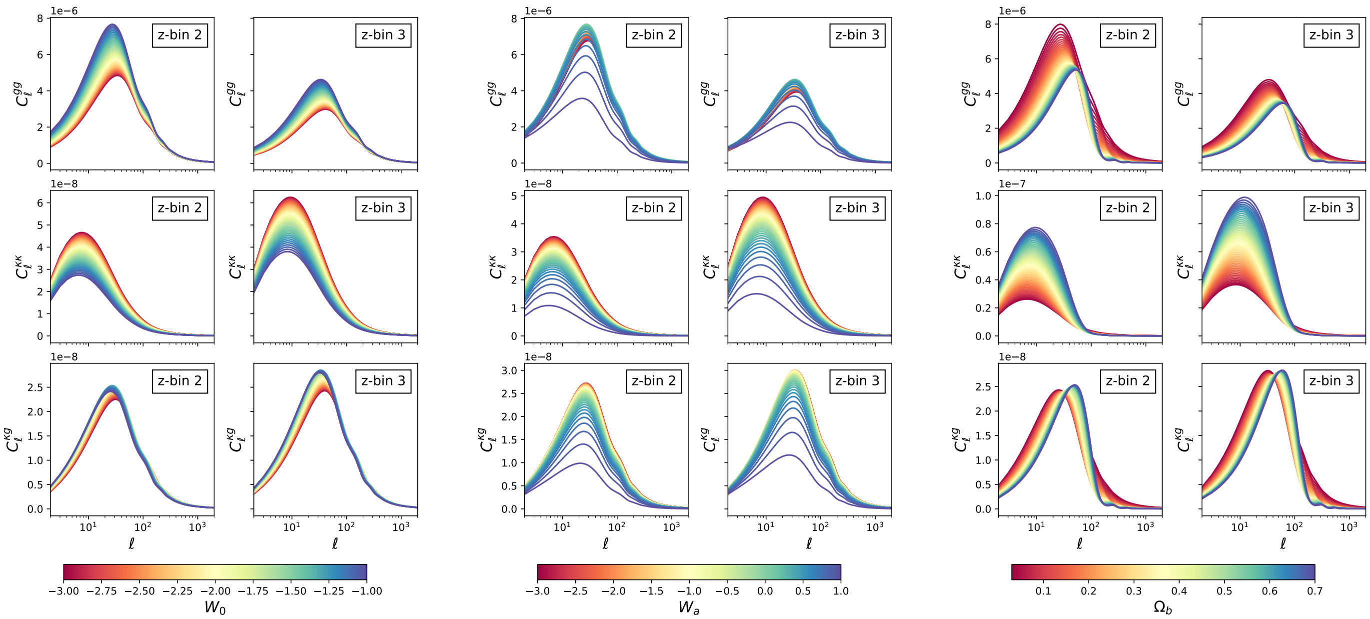

FIG. 3: Theoretical sensitivity of C_l^{gg} (upper row), C_l^{kk} (mid-row), and C_l^{kg} (bottom-row) to variations in w_0, w_a, and Ω_b, from left to right.

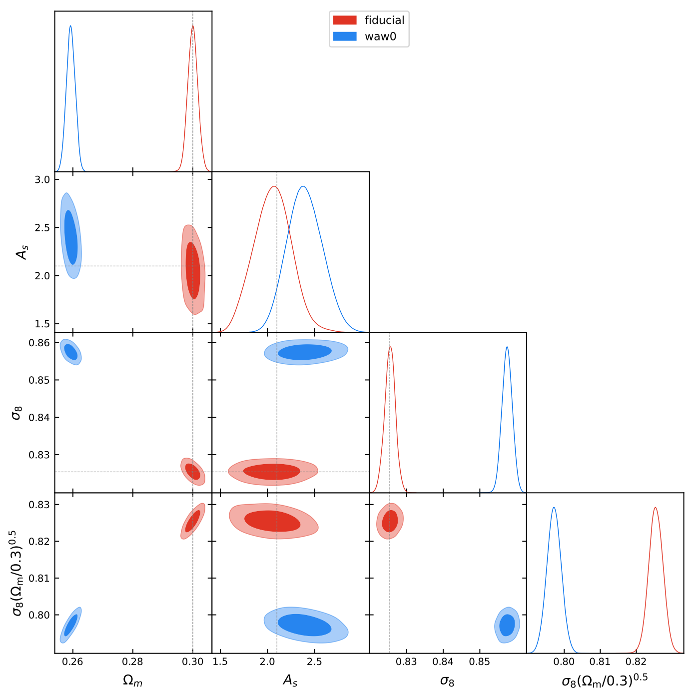

FIG. 4: Cosmological constraints from the MCMC analysis considering different simulated data: one based on the fiducial ΛCDM model (red) and another on evolving dark energy with $w_0 = -0.45$ and $w_a = -1.79$ (blue). For the inference, we assume the ΛCDM model ($w_0 = -1, w_a = 0.0$), which explains the parameter shifts observed in the $w_0 - w_a$ case.

Our analysis has demonstrated the critical need to accurately model the dark energy equation of state on LSS analysis. By examining the parameter inference under the assumption of ΛCDM when the true data incorporates dynamical dark energy, we have shown significant shifts, particularly in the total matter density, Ω_m, and the growth of structures, as quantified by the S_8 parameter, as depicted in Table III. These findings underscore the necessity for continued investigation into extensions of the ΛCDM model in future LSS analyses, such as with future LSST data. The future high-quality and deep data will allow researchers to refine their models of the universe, leading to more precise measurements of critical parameters. In particular, our results suggest that further explorations of alternative scenarios might explain the current S_8 discrepancy between CMB and LSS data. A more comprehensive analysis will benefit from incorporating more realistic considerations to better understand the total impact of evolving dark energy. This includes not only considering different well-motivated dark energy models but also accounting for astrophysical and observational effects such as uncertainties in photometric redshifts, intrinsic alignment of galaxies, and baryonic feedback, among others.

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