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Robust preference for Dynamical Dark Energy in DESI BAO and SN measurements

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ABSTRACT: Recent Baryon Acoustic Oscillation (BAO) measurements released by DESI, when combined with Cosmic Microwave Background (CMB) data from Planck and two different samples of Type Ia supernovae (Pantheon-Plus and DESY5) reveal a preference for Dynamical Dark Energy (DDE) characterized by a present-day quintessence-like equation of state that crossed into the phantom regime in the past. A core *ansatz* for this result is assuming a linear Chevallier-Polarski-Linder (CPL) parameterization $w(a) = w_0 + w_a(1 - a)$ to describe the evolution of the DE equation of state (EoS). In this paper, we test if and to what extent this assumption impacts the results. To prevent broadening uncertainties in cosmological parameter inference and facilitate direct comparison with the baseline CPL case, we focus on 4 alternative well-known models that, just like CPL, consist of only two free parameters: the present-day DE EoS (w_0) and a parameter quantifying its dynamical evolution (w_a). We demonstrate that the preference for DDE remains robust regardless of the parameterization: w_0 consistently remains in the quintessence regime, while w_a consistently indicates a preference for a dynamical evolution towards the phantom regime. This tendency is significantly strengthened by DESY5 SN measurements. By comparing the best-fit χ^2

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obtained within each DDE model, we notice that the linear CPL parameterization is not the best-fitting case. Among the models considered, the EoS proposed by Barboza and Alcaniz consistently leads to the most significant improvement.

KEYWORDS: baryon acoustic oscillations, dark energy theory

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1 Introduction

One of the most undoubtedly fascinating and unforeseen discoveries of the past three decades is that the Universe is undergoing an accelerated phase of expansion. This was first argued in 1998 through observations of distant Type Ia Supernovae [1, 2], and has since been corroborated by a wide variety of other probes [3–62].¹

Since all known forces and components in nature would decelerate the expansion rate of the Universe, acceleration itself requires a physical mechanism beyond the Standard Model of fundamental interactions, able to counteract deceleration, inducing instead a Dark Energy (DE) phase where the dynamics is characterized by negative pressure with an effective Equation of State (EoS) $w < -1/3$, a condition that directly follows from the second Friedmann equation (also known as the acceleration equation) [75–82].

In the theoretical framework described by the standard Λ CDM model of cosmology, DE is parametrized by a positive cosmological constant term (Λ) in the Einstein equation with

¹For a few caveats, objections, and discussions surrounding this conclusion raised over the years, see refs. [63–74].

its energy density comprising the vast majority of the Universe’s energy budget. Despite its apparent simplicity, this interpretation is not free from conceptual problems and limitations [75, 78, 83–92]. Foremost, plugging a positive cosmological constant component into the gravitational field equations described by General Relativity (GR) implies living in an asymptotically de Sitter universe, which seems to contrast with several theories/models of quantum gravity proposing instead an asymptotically anti-de Sitter universe [93–97]. Secondly, it seems quite natural to question what made us so lucky to live precisely in the cosmic epoch when such a constant component came to be not only relevant but even dominant compared to other contributions such as matter, altering the expansion history of the Universe so prominently as to allow us to become easily aware of its existence and implications [82, 98–100]. Finally, and most importantly, when it comes to the physical interpretations, anything that contributes to the energy density of the vacuum behaves akin to a cosmological constant, summing up within the energy-momentum tensor as $T_{\mu\nu} \propto g_{\mu\nu}\rho$ due to Lorentz invariance. Based on standard quantum field theory calculations, one would expect a zero-point energy density contribution of ρ_{vac} , which, depending on the ultraviolet wavelength cutoff scale, is found to be somewhere between 10^{50} to 10^{120} orders of magnitude larger than what is inferred by cosmological data [83]. This leads to one of the biggest disagreements between theoretical predictions and observations, arguably requiring a level of fine-tuning that appears to be well beyond what any current theories can realistically explain [78, 83, 101–103]. As a result, from a theoretical perspective, the nature of DE remains one of the biggest puzzles in modern physics, sustaining significant research interest in the high-energy physics community.²

From an observational standpoint, investigating the nature of DE has sparked research interest comparable to that driven by the theoretical problems surrounding its physical interpretation [143, 165, 168–268]. Increasingly precise observations of the Cosmic Microwave Background (CMB) radiation, obtained from experiments such as WMAP [20, 21] and, more recently, the Planck satellite [39, 40], as well as the Atacama Cosmology Telescope (ACT) [43, 44, 56, 269] and the South Pole Telescope (SPT) [51, 270, 271], have provided extremely accurate measurements of the angular power spectra of temperature and polarization anisotropies, revealing a precise snapshot of the Universe at the last scattering surface $z \sim 1100$.³ Concurrently, progress in observational astronomy and astrophysics has culminated in a series of present surveys aimed at determining the properties of the Universe at low redshift through a multitude of probes, including — but not limited to — Baryon Acoustic Oscillations (BAO) and Type Ia Supernovae (SN) measurements.⁴ These collective efforts

²This diffuse interest is reflected in the wide range of models — both within and beyond the standard cosmological constant — that have been proposed over the years. These include, for example, new (ultra)light fields and modifications to gravity. With no claims to completeness see, e.g., refs. [92, 104–167].

³Notably, the gravitational deflection, or lensing, experienced by CMB photons due to their interactions with the large-scale structure of the Universe imprints a distinctive non-Gaussian four-point correlation function (trispectrum) in both temperature and polarization anisotropies [272]. This signal provides complementary information about late-time processes affecting structure formation, from neutrinos and thermal relics [273–277] to dark energy and its dynamical properties [56, 278–284].

⁴Excitingly, upcoming Stage-IV astronomical surveys such as future data releases from DESI, Euclid [285], the Large Synoptic Survey Telescope (LSST) [286], the Wide-Field InfraRed Survey Telescope (WFIRST) [287], and the Square Kilometre Array (SKA) [288], are expected to improve upon current sensitivity and are forecasted to constrain DE parameters to near-percent precision, offering new insights into the dark sector of the Universe.

have ushered in a new era of precision cosmology, eventually allowing percentage-level precision in cosmological parameter inference and enabling precise tests of physics within and beyond the Λ CDM framework [289–291].

Despite these remarkable achievements, it is no exaggeration to say that at the time of writing, observations are inconclusive about the physical nature of DE. While too far-away deviations from the canonical Λ CDM model appear severely constrained [292], several alternative theoretical frameworks and phenomenological avenues featuring new physics in the dark sector of the model remain at the very least plausible.

Trying to summarize an otherwise very articulated debate, we can adhere to Occam’s razor principle and start considering one of the simplest hypotheses beyond the cosmological constant. This involves assuming that DE can be modeled as a generic fluid with a constant EoS, w_0 . By leaving w_0 as a free parameter in the theoretical model, cosmological observations can constrain deviations from the cosmological constant value ($w_0 = -1$).⁵ In this regard, focusing exclusively on the Planck CMB data one might speculate about a preference for a phantom-like DE component ($w_0 < -1$) [40, 245].⁶ However, as extensively documented in the literature, this preference is not confirmed by independent CMB experiments such as ACT and SPT [44, 51, 271, 340], and — most importantly — it lacks consistent support from observations of the local universe. When combining CMB, BAO and SN data altogether, no convincing deviation from $w_0 = -1$ is seen, possibly lending weight to the cosmological constant interpretation [245].

However, one may argue that simplicity may not always be a prerogative of nature. Pushing this approach forward, we can relax the assumption of a constant EoS and consider models where $w(a)$ varies with the universe’s expansion — here and after known as Dynamical Dark Energy (DDE). This possibility, along with the various proposed physical realizations, has also undergone extensive testing; see, e.g., refs. [194, 195, 313, 319, 341–353]. From an observational standpoint, CMB data alone have limited capacity to constrain DDE models due to minimal effects left at the epoch of the last scattering surface and the increased number of cosmological parameters [354–356].⁷ Even in simple parametrizations aimed at minimizing the number of free degrees of freedom, CMB experiments produce constraints that are typically too broad to provide informative results. Therefore, local universe observations acquire primary importance.

A significant turning point in the study of DDE models is marked by the very recent BAO release from the Dark Energy Spectroscopic Instrument (DESI) [58, 59], and — albeit to a lesser extent — by SN distance moduli measurements from the Union3 compilation [357] first and, more recently, from the five-year observations of the Dark Energy

⁵See, e.g., refs. [32, 38, 40, 45, 50, 53, 54, 215, 245, 293–336] for recent and not-so-recent discussions and constraints on the DE EoS from a variety of astrophysical and cosmological probes.

⁶In recent years, the possibility that the DE EoS can be phantom in nature has gained substantial interest, as in principle a shift of $\sim 20\%$ towards $w_0 < -1$ could already be enough to address the well-known Hubble tension [289–291, 337, 338] — see, e.g., refs. [197, 339] for an overview, as well as for caveats surrounding this possibility.

⁷This difficulty is often referred to as geometrical degeneracy. At its core, the problem is that different combinations of late-time cosmic parameters can be adjusted in such a way that the acoustic angular scale θ_s — determined by the ratio of the comoving sound horizon at recombination to the comoving distance to last scattering — remains constant if both quantities change proportionally. Consequently, measurements based solely on this scale cannot provide strong constraints on (dynamical) DE parameters by themselves, unless perturbation-level effects and late-time data are also incorporated to break this degeneracy.

Survey (DESY5) [60–62]. Before these updated data, no significant preference had ever emerged in favor of DDE models, certainly not to the extent required to challenge the baseline cosmological constant interpretation [292]. Excitingly, when DESI BAO observations are combined with Planck CMB data and SN distance moduli measurements (whether from the Pantheon-plus catalog [55, 358], the Union3 compilation [357], or DESY5 [60–62]), they produce strong indications for DDE. Specifically, within the linear Chevallier-Polarski-Linder (CPL) parameterization of the DE EoS, $w(a) = w_0 + w_a(1 - a)$ [170, 172] — where w_0 represents the present-day DE EoS and w_a quantifies the dynamical evolution — we observe a preference for $w_0 > -1$ and $w_a < 0$ at a statistical level ranging between 2.5 and 3.9σ , depending on the specific combination of SN data used [336].

Unexpectedly, these results have heated up the recent debate, fueling a multitude of re-analyses and re-interpretations [59, 253, 264, 266, 267, 359–375]. As “extraordinary claims require extraordinary evidence”, we certainly advise and exercise caution. However, even taking in mind all the possible caveats and limitations surrounding the first DESI data release, it is undeniable that a high statistical preference for DDE holds intrinsic interest — if confirmed, this would represent the first concrete evidence of new physics beyond the standard model of cosmology.

Given the potential implications of this result, it is natural to question its robustness. Barring any possible systematic issues in these datasets,⁸ we examine if and to what extent assuming a linear parameterization for the DE EoS might impact the current findings. Although the CPL parameterization has been demonstrated to match the background evolution of distances arising from exact DE equations of motion to an accuracy of approximately 0.1% for viable cosmologies over a wide range of physics, including scalar fields, modified gravity, and phase transitions (see, e.g., refs. [172, 378]), other parameterizations proposed over the years (which may deviate from CPL at both $z \ll 1$ and $z \gtrsim 1$) remain allowed by current observations. Testing these alternative models against new data can certainly represent a useful exercise to shed light on the role played by the parameterization itself. To be fair, the process has already begun with several independent groups actively engaged in this activity [364, 379–384].

Given the vast number of parameterizations proposed over the years and recently analyzed in relation to the DESI data, a few warnings are in order. First and foremost, alternative parameterizations often introduce extra parameters compared to CPL. This is both a blessing and a curse: on the one hand, accounting for more degrees of freedom allows more flexibility in $w(a)$. On the other hand, this typically implies relaxing the overall constraining power due to the combined effects of degeneracies and correlations among parameters. Secondly, the physical interpretations of the parameters involved may differ from the two employed in the CPL model. This further compounds the comparison of the results, making it difficult to derive general guidelines on the preference towards DDE.

To overcome these difficulties, in this article, we test different DDE models while allowing for a fair comparison of the results. We restrict our attention to five well-known parameterizations that satisfy the following criteria: *(i)* they consist of two parameters to describe the evolution of $w(a)$, w_0 and w_a ; *(ii)* these two parameters retain the same physical

⁸As argued in various recent works, the DESI BAO measurement at $z = 0.71$ (which is in $\sim 3\sigma$ tension with Planck) can play a crucial role in deriving many of the DESI signals for new physics, partially including the preference for DDE [369, 376, 377].

meaning as in the CPL parameterization; *(iii)* for the same combinations of pairs w_0 - w_a , the resulting shape of $w(a)$ deviates from CPL either near the present epoch or in the past, depending on the specific case.

The paper is organized as follows. In section 2 we sketch the theoretical set-up of the gravitational equations and propose the DE parametrizations we wish to study. In section 3 we describe the observational data and the methodology to constrain the proposed DE parametrizations. In section 4 we present the constraints on the resulting DE scenarios. Finally, in section 5 we draw our general conclusions.

2 Dynamical Dark Energy models

Considering a DDE component in cosmological models produces changes both in the background dynamics and in the dynamics of cosmological perturbations.

Focusing on flat Friedmann-Lemaître-Robertson-Walker cosmology and models where the DE EoS $w(a)$ can be described by a continuous function of the scale factor, the first Friedman equation reads

$$H^2(a) = \frac{8\pi G}{3} \left[\rho_{r,0} a^{-4} + \rho_{m,0} a^{-3} + \rho_{\text{DE},0} a^{-3} \exp\left(-3 \int_{a_0=1}^a \frac{w(a')}{a'} da'\right) \right]. \quad (2.1)$$

Here $H(a) = \dot{a}/a$ is the Hubble parameter, the dot denotes the derivative with respect to physical time t , the subscript 0 indicates quantities evaluate at present while ρ_r , ρ_m , and ρ_{DE} are the energy densities in radiation, matter, and DE, respectively.

When it comes to cosmological perturbations, diffeomorphism invariance of GR requires fixing a gauge. In the synchronous gauge, the line element reads [385]

$$ds^2 = a^2(\tau) \left[-d\tau^2 + (\delta_{ij} + h_{ij}) dx^i dx^j \right], \quad (2.2)$$

where $d\tau = dt/a(t)$ is the conformal time, δ_{ij} and h_{ij} are the unperturbed and perturbed spatial part of the metric tensors. For a fluid component i , the equations governing the dimensionless density perturbations $\delta_i = \delta\rho_i/\rho_i$ and the divergence of the i -th fluid velocity $\theta_i = i\kappa^j v_j$ in the Fourier space are [385]:

$$\begin{aligned} \delta'_i &= -(1 + w_i) \left(\theta_i + \frac{h'}{2} \right) - 3\mathcal{H} \left(\frac{\delta P_i}{\delta\rho_i} - w_i \right) \delta_i \\ &\quad - 9\mathcal{H}^2 \left(\frac{\delta P_i}{\delta\rho_i} - c_{a,i}^2 \right) (1 + w_i) \frac{\theta_i}{\kappa^2}, \end{aligned} \quad (2.3)$$

$$\theta'_i = -\mathcal{H} \left(1 - 3 \frac{\delta P_i}{\delta\rho_i} \right) \theta_i + \frac{\delta P_i / \delta\rho_i}{1 + w_i} \kappa^2 \delta_i - \kappa^2 \sigma_i, \quad (2.4)$$

where the primes denote the derivative with respect to conformal time τ , h is the usual synchronous gauge metric perturbation, $\mathcal{H}(a) = a'/a$ is the conformal Hubble parameter, κ is the wavenumber in Fourier space, σ_i stands for the anisotropic stress of the i -th fluid, and $c_{a,i}^2$ represents the adiabatic sound speed of the i -th fluid defined as $c_{a,i}^2 = \dot{P}_i/\dot{\rho}_i$. In this work, we fix the squared sound speed of the DE component in the rest frame $c_{s,\text{DE}}^2 = \frac{\delta P_{\text{DE}}}{\delta\rho_{\text{DE}}} = 1$

as broadly expected for the simplest DE models based on a single light minimally coupled scalar field with a canonical kinetic term.

Having outlined the background and perturbation dynamics, we now list and describe the five different two-parameter models employed for $w(a)$.

2.1 Chevallier-Polarski-Linder parametrization

The model proposed by Chevallier, Polarski and Linder [170, 172] (CPL hereafter) can be regarded as the baseline parameterization used in most analyses focusing on DDE, including this work. In this scenario, the DE EoS reads

$$w(a) = w_0 + w_a \times (1 - a). \quad (2.5)$$

As already mentioned in the introduction, its advantages include a manageable 2-dimensional phase space, reduction to linear redshift behavior at low redshift, bounded behavior at high redshift, high accuracy in reconstructing various scalar field equations of state and the resulting distance-redshift relations up to 0.1% accuracy, good sensitivity to observational data, and a straightforward physical interpretation. The latter arises from its representation as the Taylor expansion of $w(a)$ around the present epoch $a \simeq a_0 \equiv 1$ up to the first order: $w_0 = w(a_0)$ and $w_a = -\left.\frac{dw(a)}{da}\right|_{a=a_0}$ which is the coefficient for the dynamical term.

2.2 Exponential parametrization

As a next step, we consider the exponential form for the DE EoS [386, 387]

$$w(a) = (w_0 - w_a) + w_a \times \exp(1 - a). \quad (2.6)$$

Up to the first order of the Taylor expansion, this description reduces to the CPL parameterization around $a \simeq a_0 \equiv 1$. However, as a moves far away from 1, the exponential form can introduce (small) deviations from the linear CPL regime without increasing the dimensionality of the parameter space [259].

2.3 Jassal-Bagla-Padmanabhan parametrization

The third parameterization studied in this work is the model proposed by Jassal-Bagla-Padmanabhan in ref. [178] (JBP hereafter). In this case the DE EoS is

$$w(a) = w_0 + w_a \times a(1 - a). \quad (2.7)$$

It is characterized by the sum of a linear and a quadratic term in the scale factor. When a^2 is close to 1, the term $-w_a a^2$ becomes comparable to $w_a a$, thereby leading to expected differences at low redshift compared to CPL.

2.4 Logarithmic parametrization

We consider the following logarithmic form for the EoS:

$$w(a) = w_0 - w_a \times \ln a. \quad (2.8)$$

To the best of our knowledge, this parameterization was originally introduced by G. Efstathiou in ref. [169] to capture the behaviour of a wide class of potential scalar field models of DE at low redshift $z \lesssim 4$. Here, with a fair amount of courage and following thorough stability tests, we extend this parameterization all the way up to $z \rightarrow \infty$. In principle, for some combinations of parameters, the logarithmic term can actually grow in absolute value and cause instabilities.⁹ However, given the current data constraints and the slow logarithmic growth, this is not the case. We find that the parameterization can be safely extended to high redshift because the DE contribution remains largely negligible compared to other components in the Universe’s energy budget.

2.5 Barboza-Alcaniz parametrization

The last (but as we shall see, not least) model involved in our analysis is the one proposed by Barboza and Alcaniz in ref. [181] (referred to as BA hereafter). In this case, the DE EoS is characterized by the following functional form:

$$w(a) = w_0 + w_a \times \frac{1 - a}{a^2 + (1 - a)^2}. \quad (2.9)$$

This parameterization shows a linear behavior at low redshifts and remains well-behaved as $z \rightarrow \infty$, while allowing for deviations from the baseline CPL scenario.

3 Methods

In this section, we describe the statistical methodologies and observational datasets employed in our analysis.

3.1 Statistical analyses

The cosmology resulting from all the five DDE models listed in section 2 can be characterized by 8 free parameters: the physical baryon energy density $\Omega_b h^2$, the physical cold dark matter energy density $\Omega_c h^2$, the amplitude of the primordial scalar spectrum A_s , its spectral index n_s , the optical depth to reionization τ , the angular size of the sound horizon θ_{MC} , and the two free parameters describing the DE sector — i.e., the present-day value of the DE EoS w_0 and the parameter describing its dynamical evolution w_a . To compare the theoretical predictions against observations, we implement these models in five different modified versions of the publicly available cosmological code CAMB [388, 389] and explore the posterior distributions of the 8-dimensional parameter space by performing Markov Chain Monte Carlo (MCMC)

⁹To address this problem, in ref. [313], some of us adopted flat priors $w_a \in [-3, 0]$, thus removing positive values of w_a *a priori*. In this work, we have performed additional stability tests, which revealed that numerical instabilities arise only when CMB data are considered on their own (we do not report these results for any of the models under study, as they are not informative). Without late-time data, DE parameters remain essentially unconstrained, and w_a can acquire large positive values. Despite the logarithmic nature of the equation of state, for these values, the DE energy density does not remain negligible in the early Universe, triggering warnings and errors in the Boltzmann solver code CAMB [388, 389]. In contrast, when late-time data are included, the DE parameters are significantly constrained in the region $w_a < 0$, and no large positive values are allowed. As a result, in the allowed region of parameter space, the DE energy density remains negligible at early times and does not affect early Universe cosmology.

Parameter	Prior
$\Omega_b h^2$	[0.005, 0.1]
$\Omega_c h^2$	[0.01, 0.99]
$\log(10^{10} A_s)$	[1.61, 3.91]
n_s	[0.8, 1.2]
τ	[0.01, 0.8]
$100\theta_{\text{MC}}$	[0.5, 10]
w_0	[-3, 1]
w_a	[-3, 2]

Table 1. Ranges for the flat prior distributions imposed on the free cosmological parameters in the analysis.

analyses via the publicly available sampler `Cobaya` [390, 391] that employs the fast dragging speed hierarchy implementation [392]. The convergence of the generated MCMC chains is assessed via the Gelman-Rubin parameter $R - 1$ [393]. For *all* models and datasets, we require $R - 1 < 0.01$ for the chains to be considered converged. In table 1, we present the flat prior ranges on which the parameters are left to freely vary.

3.2 Datasets

The datasets involved in our analyses are:

- *Planck*: Measurements of the Planck CMB temperature anisotropy and polarization power spectra, their cross-spectra, and the combination of the ACT and Planck lensing power spectrum. All CMB likelihoods employed in this work are listed below:
 - (i) Measurements of the power spectra of temperature and polarization anisotropies, C_ℓ^{TT} , C_ℓ^{TE} , and C_ℓ^{EE} , at small scales ($\ell > 30$), obtained by the Planck `plik` likelihood [40, 394];
 - (ii) Measurements of the spectrum of temperature anisotropies, C_ℓ^{TT} , at large scales ($2 \leq \ell \leq 30$), obtained by the Planck `Commander` likelihood [40, 394];
 - (iii) Measurements of the spectrum of E-mode polarization, C_ℓ^{EE} , at large scales ($2 \leq \ell \leq 30$), obtained by the Planck `SimAll` likelihood [40, 394];
 - (iv) Reconstruction of the spectrum of the lensing potential, obtained by the Planck PR4 NPIPE data release [395] used in combination with ACT-DR6 lensing likelihood [56, 269].¹⁰

¹⁰The NPIPE lensing map [395] covers CMB angular scales in the range $100 \leq \ell \leq 2048$ using the quadratic estimator and re-processing Planck time-ordered data with several improvements, including around 8% more data compared to the `plik-lensing` likelihood. Notice also that NPIPE and ACT-DR6 measurements explore distinct angular scales, as ACT uses only CMB multipoles $600 < \ell < 3000$ and has only partial overlap with the 67% sky fraction used in the Planck analysis [269]. Additionally they have different noise levels and instrument-related systematics. Therefore they can be regarded as nearly independent lensing measurements.

- *DESI*: Baryon acoustic oscillations (BAO) measurements extracted by observations of galaxies & quasars [58], and Lyman- α [396] tracers from the first year of observations using the Dark Energy Spectroscopic Instrument (DESI). These include measurements of the transverse comoving distance, the Hubble horizon, and the angle-averaged distance as summarized in table I of ref. [336].
- *PantheonPlus*: Distance moduli measurements of 1701 light curves of 1550 spectroscopically confirmed type Ia SN sourced from eighteen different surveys, gathered from the Pantheon-plus sample [55, 358].
- *DESY5*: Distance moduli measurements of 1635 Type Ia SN covering the redshift range of $0.10 < z < 1.13$ that have been collected during the full five years of the Dark Energy Survey (DES) Supernova Program [60–62], along with 194 low-redshift SN in the redshift range of $0.025 < z < 0.1$ which are in common with the Pantheon-plus sample [55, 358].

We conclude this subsection with a final remark. Our analysis focuses on two samples of Type-Ia SN: PantheonPlus and DESY5, excluding the Union3 sample. As highlighted in the DESI paper [336], among these three SN samples, PantheonPlus (which uses spectroscopically confirmed SN) produces the smallest, yet significant, preference for DDE, deviating by about 2.5σ from the cosmological constant scenario. In contrast, DESY5 (which uses photometry) shows the largest shift towards DDE, at $\sim 3.9\sigma$. The Union3 sample (which also uses spectroscopically confirmed SN) shows a preference for DDE around 3.5σ , falling between PantheonPlus and DESY5. Although Union3 provides valuable confirmation of these results, here we focus on the two samples that represent the smallest and largest deviations from the cosmological constant.

4 Results

In this section, we present the observational constraints on the five DDE models considered in this article. We discuss the results model by model, testing each case against three different data combinations: Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5. We make no secret that due to the large number of analyzed models and the similarity of the results obtained, the following discussion may appear somewhat repetitive (though necessary). Therefore, readers interested in the results of specific models can find the numerical constraints, two-dimensional correlations, and one-dimensional posterior distribution functions of key parameters as follows:

- Table 2 and figure 1 summarize the numerical constraints and parameter correlations for the baseline CPL case (2.5). The results for this case are detailed in section 4.1.
- Table 3 and figure 2 present the results for the exponential parameterization (2.6), discussed in section 4.2.
- Table 4 and figure 3 provide the results for the JBP EoS (2.7), discussed in section 4.3.
- Table 5 and figure 4 summarize the results for the logarithmic parameterization (2.8), detailed in section 4.4.
- Table 6 and figure 5 present the results for the BA parameterization (2.9), discussed in section 4.5.

Parameter	Planck+DESI	Planck+DESI+PantheonPlus	Planck+DESI+DESY5
$\Omega_c h^2$	0.11993 ± 0.00098	0.11962 ± 0.00099	0.11978 ± 0.00098
$\Omega_b h^2$	0.02238 ± 0.00014	0.02241 ± 0.00014	0.02239 ± 0.00014
$100\theta_{\text{MC}}$	1.04092 ± 0.00029	1.04098 ± 0.00030	1.04094 ± 0.00030
τ	0.0530 ± 0.0073	0.0547 ± 0.0073	0.0538 ± 0.0074
n_s	0.9655 ± 0.0038	0.9663 ± 0.0038	0.9659 ± 0.0038
$\log(10^{10} A_s)$	3.040 ± 0.013	3.044 ± 0.013	3.042 ± 0.013
w_0	$-0.44^{+0.34}_{-0.21}$	-0.820 ± 0.064	-0.726 ± 0.069
w_a	$-1.81^{+0.37}_{-1.1}$	-0.77 ± 0.28	$-1.05^{+0.34}_{-0.28}$
Ω_m	$0.344^{+0.033}_{-0.027}$	0.3088 ± 0.0070	0.3161 ± 0.0066
σ_8	$0.791^{+0.021}_{-0.028}$	0.8186 ± 0.0094	0.8130 ± 0.0091
S_8	$0.846^{+0.016}_{-0.013}$	0.8304 ± 0.0097	0.8345 ± 0.0097
H_0 [km/s/Mpc]	$64.6^{+2.2}_{-3.3}$	67.98 ± 0.72	67.22 ± 0.66
r_{drag} [Mpc]	147.11 ± 0.24	147.16 ± 0.23	147.14 ± 0.23
$\Delta\chi^2$	-6.8	-8.4	-15.2

Table 2. *CPL Parametrization (2.5)* — 68% CL constraints on the free and derived cosmological parameters for 3 different data combinations detailed in section 3. Negative values of $\Delta\chi^2 = \chi_{\text{CPL}}^2 - \chi_{\Lambda\text{CDM}}^2$ indicate an improvement in the fit to the data compared to ΛCDM .

Conversely, readers interested in a comprehensive overview of the results, their interpretation, and implications can refer directly to section 5. Instead, a comprehensive discussion of the behavior of the EoS inferred from the different datasets employed in the analysis across various models, as well as constraints on crucial quantities that aid in interpreting the results discussed in this section — such as the pivot redshift (i.e., the redshifts where the equation of state is better constrained by current data) and phantom crossing — is presented in appendix A and summarized in figure 7 and table 7. Interested readers can refer to this appendix for further details.

4.1 Results for the CPL parameterization

The numerical constraints obtained by adopting a baseline CPL parametrization are given in table 2. Figure 1 displays key parameters that characterize this model (i.e., the present-day value of the EoS w_0 and the parameter quantifying its redshift evolution w_a) as well as their correlations with other cosmological parameters of intrinsic interest for the late-time expansion history of the Universe such as the Hubble constant H_0 , the present-day matter fractional energy density Ω_m , and the matter clustering parameter S_8 .

We recover all the results discussed in the recent DESI release paper [336]. For Planck+DESI, the constraints favor a present-day quintessence EoS with $w_0 = -0.44^{+0.34}_{-0.21}$ at 68% CL,¹¹ showing a notable shift away from $w_0 = -1$. On the other hand, $w_a = -1.81^{+0.37}_{-1.1}$ provides hints of dynamical evolution towards the phantom regime.

The addition of PantheonPlus significantly refines the constraints on the parameter space, reducing the error bars on the DE parameters by up to a factor of 5. Although w_0 shifts

¹¹Hereafter, constraints will always be quoted at 68% CL unless otherwise specified.

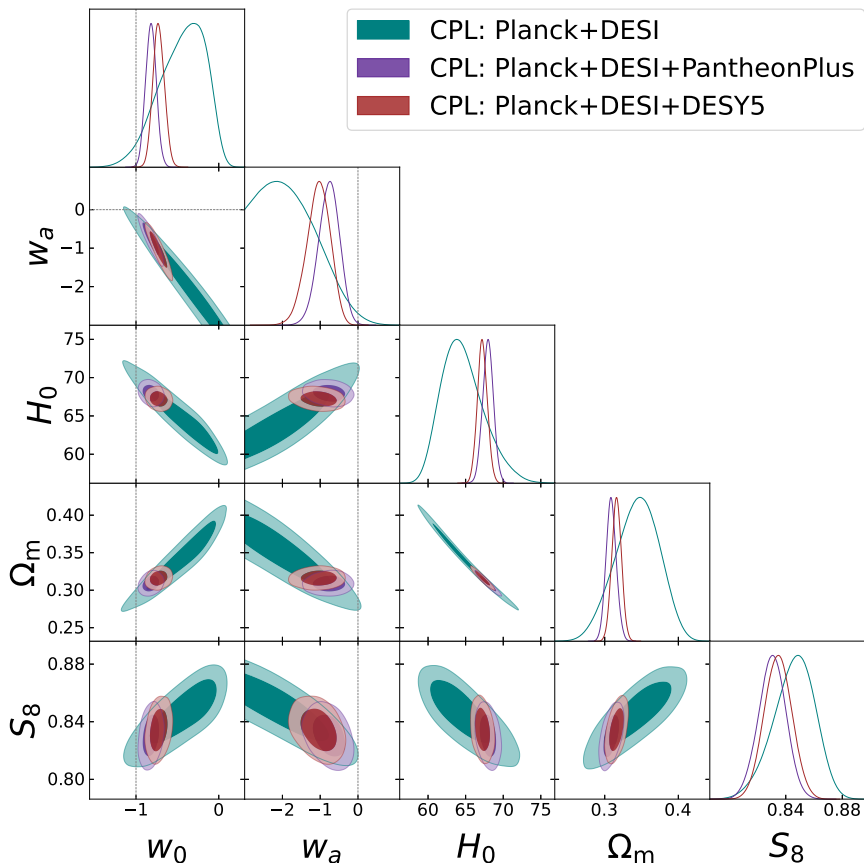


Figure 1. *CPL parametrization (2.5)* — one-dimensional posterior distributions and two-dimensional marginalized contours for the main key parameters as obtained from the Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5 dataset combinations.

towards -1 , it remains strictly in the quintessence regime: $w_0 = -0.820 \pm 0.064$. Consistent with DESI 2024 findings [59], the mean value of w_a increases compared to Planck+DESI, now reading $w_a = -0.77 \pm 0.28$. This boosts the evidence for a past phantom-like DDE component to approximately 2.5σ , see also figure 1.

When replacing PantheonPlus with DESY5 type Ia SN, we observe a shift of w_0 away from -1 , resulting in $w_0 = -0.726 \pm 0.069$. This places w_0 deep in the quintessence regime, see also figure 1. Similarly, $w_a = -1.05^{+0.34}_{-0.28}$ is found to be non-zero at high statistical significance. Thus, the evidence for DDE remains stronger in the Planck+DESI+DESY5 case compared to Planck+DESI+PantheonPlus, and the cosmological constant case falls well outside the joint probability contours in the w_0 - w_a plane, as seen in figure 1.

4.2 Results for the exponential parametrization

We present the constraints obtained by assuming an exponential parametrization for the DE EoS in table 3. In figure 2, we show the one-dimensional posterior distribution functions and the two-dimensional marginalized contours for the key cosmic parameters.

As usual, we test the model against three different combinations of data involving the DESI BAO measurements. Focusing on the minimal Planck+DESI combination, we find

Parameter	Planck+DESI	Planck+DESI+PantheonPlus	Planck+DESI+DESY5
$\Omega_c h^2$	0.1201 ± 0.0010	0.11962 ± 0.00098	0.1198 ± 0.0010
$\Omega_b h^2$	0.02237 ± 0.00014	0.02241 ± 0.00014	0.02239 ± 0.00014
$100\theta_{\text{MC}}$	1.04089 ± 0.00030	1.04097 ± 0.00030	1.04094 ± 0.00030
τ	0.0525 ± 0.0073	0.0545 ± 0.0071	0.0539 ± 0.0074
n_s	0.9650 ± 0.0038	0.9662 ± 0.0038	0.9657 ± 0.0039
$\log(10^{10} A_s)$	3.040 ± 0.013	3.044 ± 0.013	3.042 ± 0.013
w_0	-0.50 ± 0.27	-0.876 ± 0.045	$-0.804^{+0.045}_{-0.051}$
w_a	$-1.40^{+0.75}_{-0.62}$	$-0.51^{+0.20}_{-0.17}$	$-0.71^{+0.23}_{-0.19}$
Ω_m	0.352 ± 0.035	0.3088 ± 0.0067	0.3157 ± 0.0066
σ_8	$0.788^{+0.026}_{-0.029}$	0.8192 ± 0.0098	0.8150 ± 0.0092
S_8	0.852 ± 0.017	0.8310 ± 0.0095	0.8360 ± 0.0098
H_0 [km/s/Mpc]	$64.0^{+2.9}_{-3.5}$	67.98 ± 0.72	67.28 ± 0.65
r_{drag} [Mpc]	147.08 ± 0.24	147.16 ± 0.23	147.12 ± 0.24
$\Delta\chi^2$	-6.9	-7.8	-15.2

Table 3. *Exponential Parametrization (2.6)* — 68% CL constraints on the free and derived cosmological parameters for 3 different data combinations detailed in section 3. Negative values of $\Delta\chi^2 = \chi^2_{\text{exp}} - \chi^2_{\Lambda\text{CDM}}$ indicate an improvement in the fit to the data compared to ΛCDM .

$w_0 = -0.50 \pm 0.27$ — significantly different from -1 and deep in the quintessence regime. Similarly, $w_a = -1.40^{+0.75}_{-0.62}$ is almost 2σ away from the non-dynamical $w_a = 0$ case, lending weight to the Planck+DESI preference for DDE.

The addition of PantheonPlus SN measurements reinforces this preference: the constraints on $w_0 = -0.876 \pm 0.045$ shrink in the quintessence regime, deviating from $w_0 = -1$ by more than 2.5σ . Additionally, $w_a = -0.51^{+0.20}_{-0.17}$ is found to be non-zero at more than 2σ . Overall, Planck+DESI+PantheonPlus provides evidence for DDE with the present-day EoS in the quintessence regime and a dynamical evolution that crosses into the phantom regime, as clearly shown in figure 2.

When we focus on the Planck+DESI+DESY5 data combination, the evidence for DDE becomes significantly more pronounced. $w_0 = -0.804^{+0.045}_{-0.051}$ remains strictly in the quintessence regime, while $w_a = -0.71^{+0.23}_{-0.19}$ is 3σ away from the non-dynamical $w_a = 0$ scenario; see again figure 2.

Overall, in terms of constraints on cosmic parameters, these results are in agreement with those derived for the CPL parametrization in the previous section, underscoring the resilience of the evidence for DDE and relieving concerns about dependence on the model for these particular results.

4.3 Results for the JBP parametrization

The numerical constraints for the JBP parametrization are given in table 4, while the marginalized probability contours for the usual parameters are shown in figure 3.

When considering Planck+DESI, unlike the other parametrizations described so far (e.g., CPL and exponential form), w_a remains unbounded and an upper limit $w_a < 0.648$ can be

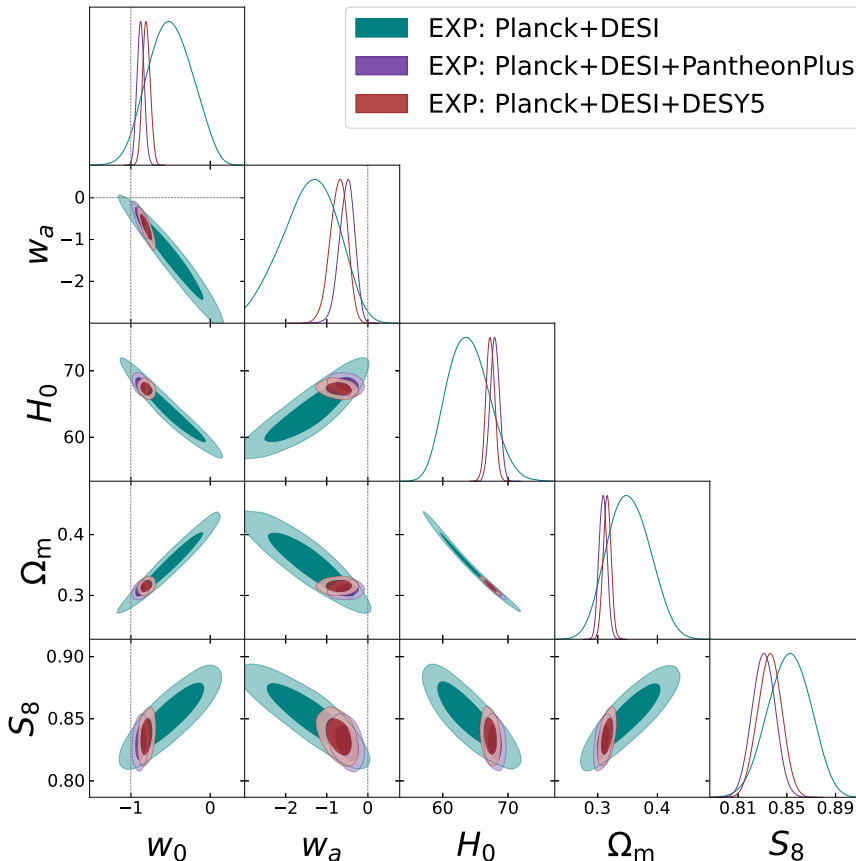


Figure 2. *Exponential parameterization (2.6)* — one-dimensional posterior distributions and two-dimensional marginalized contours for the main key parameters as obtained from the Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5 dataset combinations.

derived at 95% CL. Conversely, w_0 remains in the quintessence regime ($w_0 = -0.79^{+0.31}_{-0.14}$), confirming the overall tendency for a present-day quintessence EoS.

When considering PantheonPlus in combination with Planck and DESI, we get $w_a = -1.50 \pm 0.57$ — non-null at more than 2.6σ . Additionally, the constraints on $w_0 = -0.767 \pm 0.086$ are narrowed down within the quintessence portion of the parameter space as seen in figure 3. Thus, effectively, evidence of DDE is confirmed for this parametrization as well.

Finally, we replace PantheonPlus with DESY5 SN measurements. In this case, we obtain $w_0 = -0.641^{+0.095}_{-0.067}$ and $w_a = -2.12^{+0.38}_{-0.68}$, confirming that the evidence of DDE becomes much more pronounced with DESY5. This evidence reaches a statistical significance $\gtrsim 3\sigma$. Having said that, comparing figure 3 with the respective triangular plots of the other parameterizations, we notice that for this model, the uncertainties remain much broader, especially for the parameters describing DE EoS. This can be explained in terms of the peculiar evolution of the DE EoS obtained in this model. As discussed in detail in appendix A, among the five models analyzed, the JBP parameterization presents a more articulated phenomenology regarding the evolution of the DE EoS. Due to its quadratic nature in the scale factor, the evolution of the EoS within the JBP parameterization crosses $w = -1$ twice. At low redshift, it behaves similarly to the other parameterizations; however, after the first quintessence-to-phantom

Parameter	Planck+DESI	Planck+DESI+PantheonPlus	Planck+DESI+DESY5
$\Omega_c h^2$	0.11940 ± 0.00098	0.11934 ± 0.00096	0.11947 ± 0.00094
$\Omega_b h^2$	0.02242 ± 0.00013	0.02243 ± 0.00014	0.02242 ± 0.00014
$100\theta_{\text{MC}}$	1.04099 ± 0.00029	1.04102 ± 0.00029	1.04100 ± 0.00029
τ	0.0558 ± 0.0075	0.0564 ± 0.0073	0.0557 ± 0.0072
n_s	0.9668 ± 0.0038	0.9670 ± 0.0038	0.9667 ± 0.0038
$\log(10^{10} A_s)$	3.046 ± 0.014	3.048 ± 0.013	3.047 ± 0.013
w_0	$-0.79^{+0.31}_{-0.14}$	-0.767 ± 0.086	$-0.641^{+0.095}_{-0.067}$
w_a	< 0.648	-1.50 ± 0.57	$-2.12^{+0.38}_{-0.68}$
Ω_m	$0.304^{+0.023}_{-0.019}$	0.3096 ± 0.0068	0.3180 ± 0.0065
σ_8	$0.822^{+0.019}_{-0.025}$	0.8151 ± 0.0093	0.8083 ± 0.0086
S_8	$0.826^{+0.012}_{-0.011}$	0.8279 ± 0.0093	0.8321 ± 0.0093
H_0 [km/s/Mpc]	$68.6^{+1.9}_{-2.8}$	67.83 ± 0.71	66.96 ± 0.64
r_{drag} [Mpc]	147.20 ± 0.23	147.21 ± 0.23	147.19 ± 0.22
$\Delta\chi^2$	-5.6	-6.4	-16.0

Table 4. *JBP* parametrization (2.7) — 68% CL constraints and 95% CL upper limits on the free and derived cosmological parameters for 3 different data combinations detailed in section 3. Negative values of $\Delta\chi^2 = \chi^2_{\text{JBP}} - \chi^2_{\Lambda\text{CDM}}$ indicate an improvement in the fit to the data compared to ΛCDM .

transition, $w(z)$ approaches a minimum value around $z \sim 1$ before rising again, leading to a second phantom-to-quintessence crossing at $z \sim 4$. This behavior contrasts with other models, where the EoS remains within the phantom regime. As detailed in appendix A, the interplay between low and high redshift behaviors results in two different pivot redshifts at low and high z . This interplay may contribute to tilting the 2-D probability contours in the w_0 and w_a plane, as shown in figure 3 (see also figure 6 for comparisons with other models). Additionally, the increased uncertainties at low redshift might suggest that this phenomenology is not ideal for consistently fitting all the data across low and high redshift. This concern is confirmed when comparing the differences between the best-fit χ^2 obtained within each DDE model and the best-fit χ^2 obtained within ΛCDM . Indeed, this model consistently leads to the smallest improvement over ΛCDM across all datasets and DDE models. For more details, we refer to appendix A.

4.4 Results for the logarithmic parametrization

Table 5 summarizes the constraints on the model where the DE EoS is described by the logarithmic parametrization. Figure 4 displays the usual marginalized contours on relevant parameters.

Starting with Planck+DESI, $w_0 = -0.48^{+0.28}_{-0.33}$ is confined to the quintessence regime at more than 68% CL, while $w_a = 1.33^{+0.79}_{-0.56}$ is constrained to be different from zero at more than 2.3σ — confirming once more the preference for DDE in Planck+DESI.

When PantheonPlus is added to Planck+DESI, we find $w_0 = -0.843 \pm 0.055$; i.e., shifted towards $w_0 = -1$ although with error bars smaller by a factor of 5. However, also in this parameterization, w_0 is preferred to be in the quintessence regime, excluding $w_0 = -1$ at more than 2.8σ . Similarly, the result on $w_a = -0.53^{+0.22}_{-0.18}$ confirms the overall preference for DDE, see figure 4.

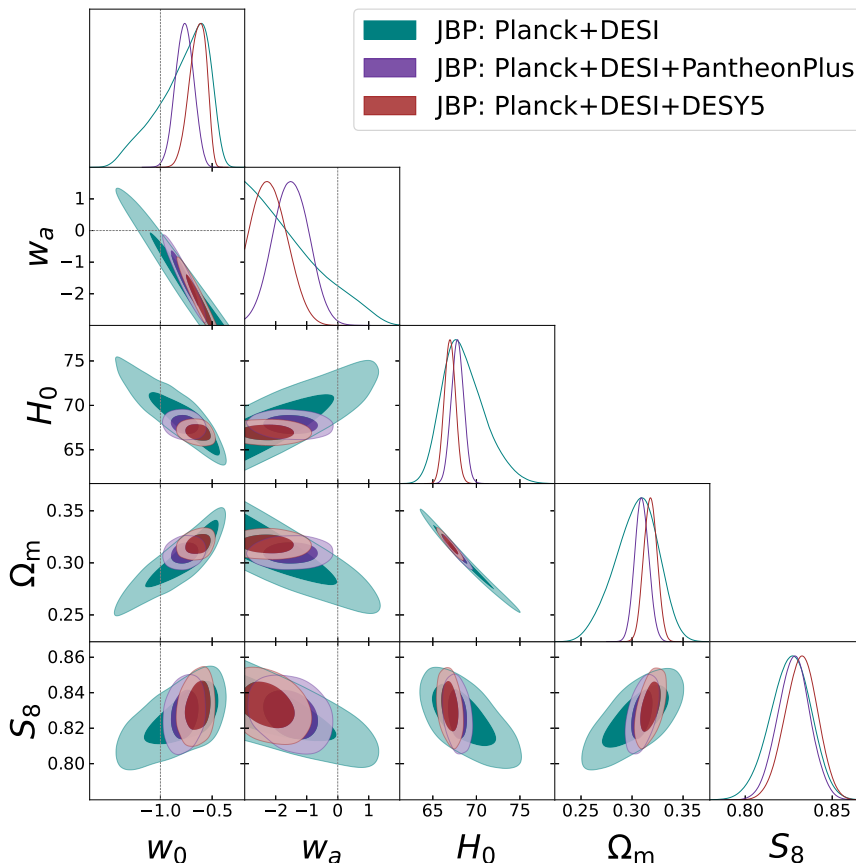


Figure 3. *JBP parametrization* (2.7) — one-dimensional posterior distributions and two-dimensional marginalized contours for the main key parameters as obtained from the Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5 dataset combinations.

Considering DESY5 in place of PantheonPlus, the constraints on w_0 and w_a change to $w_0 = -0.763^{+0.054}_{-0.062}$ and $w_a = -0.72^{+0.25}_{-0.19}$, respectively. As a result, w_0 remains in the quintessence regime at more than 95% CL, while w_a is found to be non-zero at almost 3σ . It is noteworthy that the evidence of DDE is consistently more pronounced in the presence of DESY5 compared to PantheonPlus, see figure 4.

4.5 Results for the BA parametrization

The observational constraints for the last model analyzed in this work — the BA parametrization — are given in table 6. As usual, we illustrate the correlations among the key cosmic parameters in figure 5.

Combining Planck with DESI, we get $w_0 = -0.39^{+0.30}_{-0.34}$, approaching $-1/3$ and approximately 2σ away from $w_0 = -1$. Additionally, $w_a = -1.07^{+0.55}_{-0.43}$ is significantly different from $w_a = 0$, confirming the preference for DDE in a similar fashion to other parameterizations discussed throughout the manuscript.

The inclusion of PantheonPlus gives $w_0 = -0.848 \pm 0.054$ (deep in the quintessence regime) and $w_a = -0.38^{+0.15}_{-0.13}$ (non-zero at more than 2σ). Thus, for Planck+DESI+PantheonPlus,

Parameter	Planck+DESI	Planck+DESI+PantheonPlus	Planck+DESI+DESY5
$\Omega_c h^2$	0.1201 ± 0.0010	0.11964 ± 0.00099	0.11986 ± 0.00099
$\Omega_b h^2$	0.02237 ± 0.00014	0.02240 ± 0.00014	0.02239 ± 0.00014
$100\theta_{\text{MC}}$	1.04090 ± 0.00030	1.04095 ± 0.00029	1.04094 ± 0.00029
τ	0.0520 ± 0.0073	0.0542 ± 0.0073	0.0535 ± 0.0073
n_s	0.9648 ± 0.0039	0.9661 ± 0.0038	0.9657 ± 0.0038
$\log(10^{10} A_s)$	3.039 ± 0.013	3.043 ± 0.013	3.042 ± 0.013
w_0	$-0.48_{-0.33}^{+0.28}$	-0.843 ± 0.055	$-0.763_{-0.062}^{+0.054}$
w_a	$-1.33_{-0.56}^{+0.79}$	$-0.53_{-0.18}^{+0.22}$	$-0.72_{-0.19}^{+0.25}$
Ω_m	$0.346_{-0.035}^{+0.030}$	0.3086 ± 0.0067	0.3156 ± 0.0066
σ_8	0.792 ± 0.025	0.8189 ± 0.0097	0.8142 ± 0.0092
S_8	0.848 ± 0.016	0.8305 ± 0.0095	0.8350 ± 0.0094
H_0 [km/s/Mpc]	$64.6_{-3.1}^{+2.8}$	68.01 ± 0.71	67.29 ± 0.66
r_{drag} [Mpc]	147.07 ± 0.23	147.17 ± 0.24	147.12 ± 0.23
$\Delta\chi^2$	-6.5	-9.3	-14.8

Table 5. *Logarithmic parametrization (2.8)* — 68% CL constraints on the free and derived cosmological parameters for 3 different data combinations detailed in section 3. Negative values of $\Delta\chi^2 = \chi_{\log}^2 - \chi_{\Lambda\text{CDM}}^2$ indicate an improvement in the fit to the data compared to ΛCDM .

Parameter	Planck+DESI	Planck+DESI+PantheonPlus	Planck+DESI+DESY5
$\Omega_c h^2$	0.1201 ± 0.0010	0.11963 ± 0.00099	0.1198 ± 0.0010
$\Omega_b h^2$	0.02237 ± 0.00014	0.02240 ± 0.00014	0.02239 ± 0.00014
$100\theta_{\text{MC}}$	1.04090 ± 0.00029	1.04097 ± 0.00030	1.04095 ± 0.00029
τ	0.0523 ± 0.0073	0.0544 ± 0.0074	0.0539 ± 0.0074
n_s	0.9649 ± 0.0039	0.9663 ± 0.0039	0.9658 ± 0.0038
$\log(10^{10} A_s)$	3.039 ± 0.013	3.044 ± 0.014	3.043 ± 0.013
w_0	$-0.39_{-0.34}^{+0.30}$	-0.848 ± 0.054	-0.770 ± 0.057
w_a	$-1.07_{-0.43}^{+0.55}$	$-0.38_{-0.13}^{+0.15}$	$-0.51_{-0.14}^{+0.16}$
Ω_m	$0.357_{-0.040}^{+0.033}$	0.3084 ± 0.0069	0.3155 ± 0.0066
σ_8	0.783 ± 0.028	0.8189 ± 0.0097	0.8138 ± 0.0093
S_8	0.852 ± 0.017	0.8302 ± 0.0095	0.8344 ± 0.0098
H_0 [km/s/Mpc]	63.6 ± 3.3	68.03 ± 0.73	67.30 ± 0.67
r_{drag} [Mpc]	147.07 ± 0.24	147.17 ± 0.23	147.13 ± 0.24
$\Delta\chi^2$	-8.7	-9.4	-16.2

Table 6. *BA parametrization (2.9)* — 68% CL constraints on the free and derived cosmological parameters for 3 different data combinations detailed in section 3. Negative values of $\Delta\chi^2 = \chi_{\text{BA}}^2 - \chi_{\Lambda\text{CDM}}^2$ indicate an improvement in the fit to the data compared to ΛCDM .

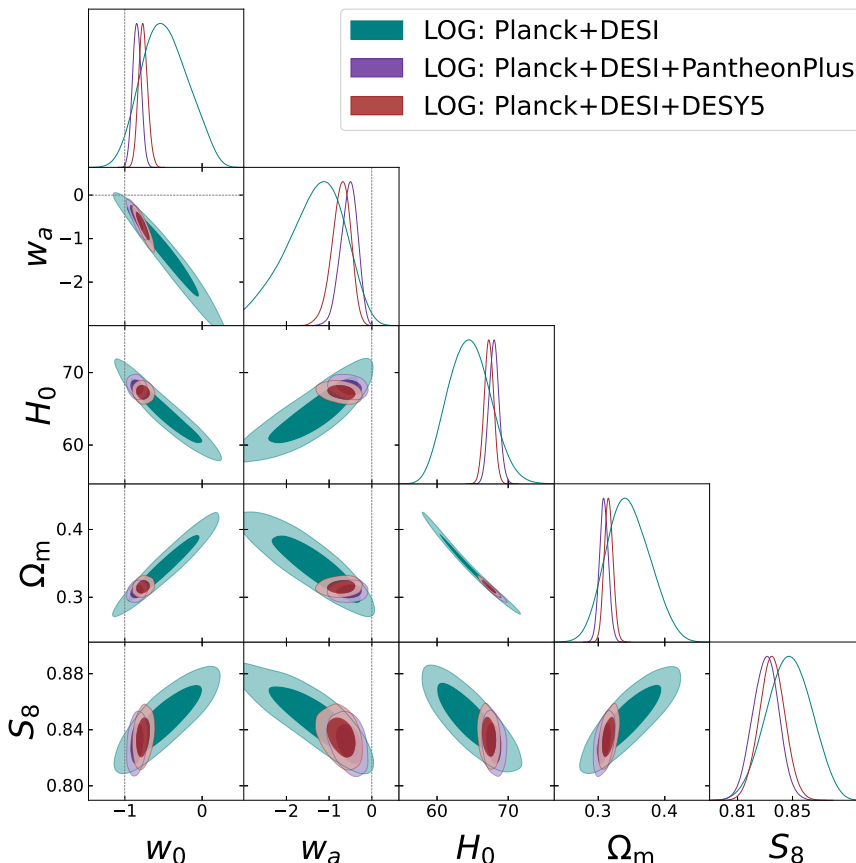


Figure 4. *Logarithmic parametrization* (2.8) — one-dimensional posterior distributions and two-dimensional marginalized contours for the main key parameters as obtained from the Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5 dataset combinations.

evidence of dynamical dark energy is clearly indicated, consistent with all the other parameterizations described so far.

In the case of Planck+DESI+DESY5, $w_0 = -0.770 \pm 0.057$ shifts further away from -1 , strengthening the preference for a quintessence EoS. Meanwhile, $w_a = -0.51^{+0.16}_{-0.14}$ is found to be non-zero at more than 3σ , as visualized in figure 5.

Interestingly, when comparing the difference between the best-fit χ^2 obtained within each DDE model and the best-fit χ^2 obtained within Λ CDM, this model consistently leads to the most significant improvement over Λ CDM across all three data combinations analyzed. It performs better than the CPL parameterization, as seen by comparing the last line in table 2 and the last line in table 6. As discussed in appendix A, when comparing the evolution of the EoS inferred in this model with the other cases analyzed so far, we find that at low redshift it behaves similarly to the CPL parameterization. The most notable differences emerge at $z \gtrsim 1$. In all models, the EoS moves deeply into phantom values (except for the JBP model, where it is compelled to rise back towards quintessence-like values). In contrast, within the BA model, $w(z)$ does not trend towards very negative values at $z \gtrsim 1$. While it remains phantom, it stabilizes on a distinctive, nearly flat plateau.

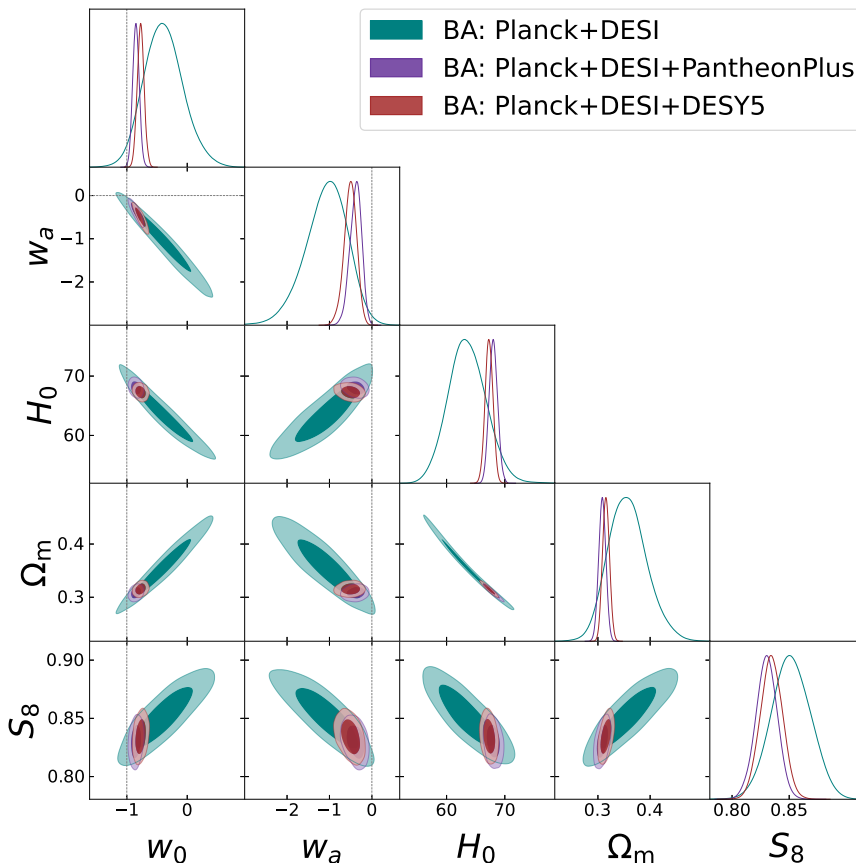


Figure 5. *BA parametrization* (2.9) — one-dimensional posterior distributions and two-dimensional marginalized contours for the main key parameters as obtained from the Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5 dataset combinations.

5 Discussions and conclusions

The recent DESI BAO measurements, when combined with CMB data from Planck and two samples of Type Ia supernovae (Pantheon-Plus and DESY5), reveal a preference for a present-day quintessence-like equation of state that crossed into the phantom regime in the past. The statistical significance of this preference for dynamic dark energy ranges between 2.5σ and 3.9σ , depending on the specific data combinations analyzed. A core *ansatz* for this result is the use of the Chevallier-Polarski-Linder (CPL) parameterization to describe the redshift evolution of the equation of state. Despite its several advantages — such as capturing the effective behavior of a wide range of models with up to 0.1% accuracy — the CPL parameterization forces the evolution of the equation of state to be linear in the scale factor.

In this paper, we tested whether and to what extent the preference for a present-day quintessence equation of state that evolves towards the phantom regime depends on the parameterization adopted to describe its dynamical behavior. To avoid broadening uncertainties in cosmological parameters and facilitate direct comparison with the baseline CPL case, we focused on some well-known alternative models: the exponential, Jassal-Bagla-Padmanabhan, logarithmic, and Barboza-Alcaniz parameterizations for the equation of state. Like the

CPL model, all these parameterizations consist of only two free parameters: the present-day value of the equation of state (w_0) and a parameter quantifying its dynamical evolution (w_a). However, they allow for deviations from linear behavior at both high and low redshifts. Therefore, given the same pair of values (w_0, w_a), different late-time expansion histories are obtained within the four models, thereby affecting cosmological observables differently.

To assess whether the preference for a dynamical dark energy component characterized by $w_0 > -1$ and $w_a < 0$ remains a robust prediction of the data, we tested these models against the most recent high and low redshift observations: the Planck 2018 CMB measurements, DESI BAO, as well as PantheonPlus and DESY5 SN measurements. For all the dataset combinations explored — i.e., Planck+DESI, Planck+DESI+PantheonPlus, and Planck+DESI+DESY5 — we find that w_0 consistently remains in the quintessence regime. Additionally, the constraints on w_a consistently indicate a preference for a dynamical evolution that crossed into the phantom regime ($w_a < 0$). Therefore, our findings confirm the DESI results, regardless of the parameterization adopted to describe the dynamics of the dark energy sector.

Notably, convincing hints of a dynamical evolution of the equation of state are found even with just Planck+DESI. As clearly seen in figure 6 — which summarizes the results for the different models — the pair $w_0 = -1$ and $w_a = 0$ (corresponding to the standard cosmological constant model of structure formation, Λ CDM) always falls outside the 95% confidence level contour.

However, the real step forward in terms of preference for dynamical dark energy comes when we consider Type Ia supernovae. Including distance moduli measurements gathered from the PantheonPlus catalog, the error bars on w_0 and w_a tighten by a factor of 5 compared to Planck+DESI alone. The contours on w_0 significantly shrink within the quintessence portion of the parameter space $w_0 > -1$, while the contours on w_a significantly reduce within the $w_a < 0$ region. Replacing PantheonPlus data with DESY5 SN measurements, the preference for dynamical dark energy becomes substantially more significant, to the point where it is not an exaggeration to refer to it as *evidence* rather than mere preference. This is again clearly illustrated in figure 6: for all models, the constraints shift further away from a cosmological constant, which always falls well outside the 95% marginalized probability contours.

At first glance, figure 6 also reveals that the contours in the w_0 - w_a plane show similar trends for all four parameterizations (including the baseline CPL case), especially when SN measurements are included in the analysis. This simultaneously underscores the intrinsic robustness of the preference for dynamical dark energy as reported by the DESI BAO and SN measurements and its resilience against different parameterizations. Given these results, there is solid ground to conclude that the choice of parameterization has a minimal impact.

Last but not least, we examined statistical metrics to quantify the extent to which the different parameterizations analyzed in this study are successful in explaining observations. Specifically, for each model and data combination, we report the difference between the best-fit χ^2 obtained within each dynamical dark energy model and the best-fit χ^2 obtained within Λ CDM.

Once more, all models exhibit similar trends: for Planck+DESI, we consistently observe an improvement in the fit over Λ CDM, with $\Delta\chi^2$ ranging from -5.6 to -8.7 , depending on the specific model. This improvement in the fit is further enhanced when PantheonPlus SN

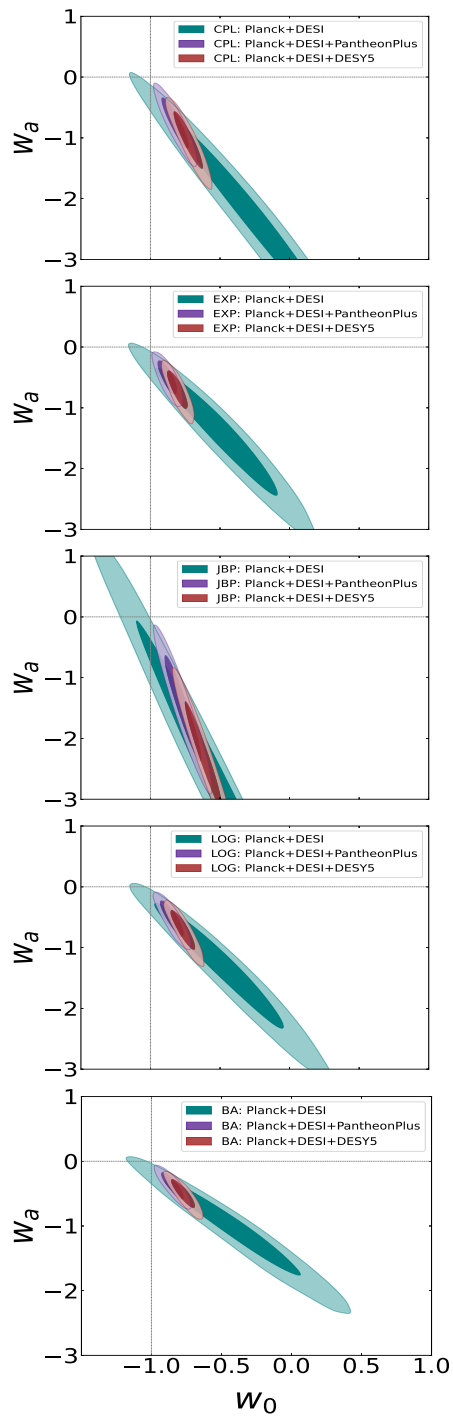


Figure 6. *Summary plot* — two-dimensional marginalized contours in the (w_0, w_a) plane for all models and datasets analyzed in this study.

measurements are included ($\Delta\chi^2$ ranges from -6.4 to -9.4) and is substantially increased — by up to a factor of ~ 2 — when adopting DESY5 SN data (in this case, $\Delta\chi^2$ ranges from -14.8 to -16.2). This trend follows the overall preference for dynamical dark energy discussed thus far. Interestingly, the linear CPL parameterization is never the best-fitting model. The equation of state proposed by Barboza-Alcaniz, given by eq. (2.9), consistently leads to the most significant improvement in $\Delta\chi^2$ over Λ CDM across all three data combinations analyzed. Conversely, the Jassal-Bagla-Padmanabhan parameterization, given by eq. (2.7), shows the smallest improvement in fit compared to Λ CDM among the models considered. The only exception is for Planck+DESI+DESY5, where $\Delta\chi^2 = -16$ indicates a better fit to this dataset compared to the CPL, logarithmic, and exponential parameterizations, although it is still smaller compared to the Barboza-Alcaniz model. For further discussion and physical interpretation of the different phenomenological behaviors of the models analyzed so far, we refer to appendix A. Specifically, figure 7 presents constraints on the evolution of the equation of state with respect to redshift, as inferred from various datasets across all models. Table 7 provides constraints on other important properties, such as the pivot redshift, the corresponding values (and uncertainties) of the equation of state, and the epoch of the quintessence-to-phantom transition. Overall, these results support the main conclusions regarding the resilience of the DESI and SN preference for evolving dark energy, while suggesting that current data are approaching a precision that could enhance our understanding of its physical nature, should future surveys and data releases confirm these findings.

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A Equation of State, pivot redshift, and phantom crossing across the different models

In this article, we have emphasized the resilience of the results recently delivered by the DESI collaboration, showing that DESI BAO data, in combination with Planck CMB observations and two different catalogs of SN distance moduli measurements (i.e., PantheonPlus and DESY5), consistently indicate a preference for DDE across various parameterizations of the EoS. While the primary goal was to confirm that this preference remains stable regardless of the specific DDE model, minor differences have emerged across the five cases analyzed, warranting further investigation. In this appendix, we explore these differences in more

Model	Dataset	z_p	$w(z_p)$	z_c
CPL	Planck+DESI+PantheonPlus	0.27	-0.982 ± 0.028	$0.31^{+0.08}_{-0.06}$
	Planck+DESI+DESY5	0.25	-0.937 ± 0.026	$0.35^{+0.07}_{-0.05}$
Exponential	Planck+DESI+PantheonPlus	0.21	-0.974 ± 0.028	$0.27^{+0.10}_{-0.07}$
	Planck+DESI+DESY5	0.22	-0.942 ± 0.026	$0.32^{+0.08}_{-0.05}$
JBP	Planck+DESI+PantheonPlus	0.21	-0.985 ± 0.027	$0.24^{+0.06}_{-0.04}$
		4.6	-0.988 ± 0.027	4.2 ± 0.9
	Planck+DESI+DESY5	0.21	-0.945 ± 0.026	$0.27^{+0.05}_{-0.03}$
		4.7	-0.946 ± 0.026	3.6 ± 0.5
Logarithmic	Planck+DESI+PantheonPlus	0.29	-0.979 ± 0.028	$0.34^{+0.10}_{-0.07}$
	Planck+DESI+DESY5	0.26	$-0.930^{+0.027}_{-0.026}$	$0.39^{+0.08}_{-0.05}$
BA	Planck+DESI+PantheonPlus	0.28	$-0.974^{+0.027}_{-0.028}$	$0.33^{+0.08}_{-0.06}$
	Planck+DESI+DESY5	0.28	$-0.937^{+0.026}_{-0.027}$	$0.37^{+0.06}_{-0.04}$

Table 7. Constraints at 68% CL on the pivot redshift z_p , the corresponding value of the EoS $w(z_p)$, and the redshift z_c where the EoS crosses the phantom divide, for Planck+DESI+PantheonPlus and Planck+DESI+DESY5.

detail, aiming to provide a stronger physical interpretation of the results presented in the manuscript. For all five models, we reconstruct the evolution of the EoS with redshift, $w(z)$, based on the constraints on w_0 and w_a inferred from the Planck+DESI+PantheonPlus and Planck+DESI+DESY5 datasets. In figure 7, we present the mean value of $w(z)$ (dashed lines), along with its uncertainties at the 68% (dark regions) and 95% (light regions) CL, across the redshift range $0 \lesssim z \lesssim 6$ for all models and both data combinations. From the reconstructed shape of $w(z)$, we extract crucial information that helps compare the different models and clarify the results presented in the manuscript. Specifically, in table 7, we present the results for:

- (i) the pivot redshift z_p and the corresponding value of the EoS, $w(z_p)$, which indicate the redshift and the EoS value at which $w(z)$ is best constrained by the two datasets across the five models;¹²
- (ii) the redshift z_c when the EoS crosses the phantom divide (i.e., $w(z_c) = -1$), informing us of when the phantom crossing occurs, along with their respective uncertainties.

Starting from the baseline CPL model as the reference case,¹³ we summarize the main features and differences across the various models.

- *Exponential:* As seen when comparing the top panels with those in the second row from the top in figure 7, from a phenomenological perspective, the exponential parameterization

¹²See, e.g., refs. [397, 398] for discussions on the importance of the pivot redshift.

¹³Note that the features presented in this appendix for the CPL model have been discussed in detail by the DESI collaboration — see, e.g., section 5.2 of ref. [336]. As we essentially recover all of the DESI results, we omit further discussion of the CPL model here.

closely resembles the CPL model. This similarity was already highlighted in the main text when comparing the improvement in $\Delta\chi^2$ over Λ CDM (which is quite similar for both scenarios). The agreement in predictions is further supported by table 7. The only noticeable difference between the models is a slightly smaller pivot redshift z_p in the exponential parameterization. However, the EoS at this pivot is constrained with comparable precision. Additionally, the predictions regarding the redshift of the phantom crossing z_c agree within one standard deviation for both Planck+DESI+PantheonPlus and Planck+DESI+DESY5.

- JBP*: Among the five models analyzed, the JBP parameterization presents a more nuanced phenomenology regarding the evolution of the DE EoS. As shown in the third panels from the top in figure 7, due to its quadratic nature in the scale factor, the evolution of the EoS within the JBP parameterization crosses $w = -1$ twice. At very low redshift, it behaves similarly to the other parameterizations, remaining within the quintessence region $w(z) > -1$, albeit with larger uncertainties compared to the other models. The first quintessence-to-phantom transition is estimated to occur at $z = 0.24^{+0.06}_{-0.04}$ ($z = 0.27^{+0.05}_{-0.03}$) for Planck+DESI+PantheonPlus (Planck+DESI+DESY5) at 68% CL. After this transition, $w(z)$ approaches a minimum value around $z = 1$ before rising towards less negative values. Eventually, a second phantom-to-quintessence crossing occurs at $z = 4.2 \pm 0.9$ ($z = 3.6 \pm 0.5$) for Planck+DESI+PantheonPlus (Planck+DESI+DESY5), both at 95% CL. This behavior contrasts with other models, where the EoS remains within the phantom regime, often trending towards more negative $w(z)$ values at high redshift. In contrast, within the JBP model, the EoS cannot move towards (more) phantom values but is compelled to transition back towards less negative values at $z > 1$. The double crossing of regimes achieved within this parameterization is also reflected in the pivot scale z_p , at which the EoS is well constrained by data. In table 7, we distinguish between two different regimes: the redshift range $0 < z < 1$ (capturing the first quintessence-to-phantom crossing) and the range $z > 1$ (covering the second phantom-to-quintessence crossing). In these two regions, we identify two distinct pivot redshifts: the first at $z_p \sim 0.21$ and the second at $z_p \sim 4.6$. In both cases (and for both datasets), the EoS is constrained within the same minimal error. This confirms that, within this model, due to the functional form of the EoS, constraints at low redshift (i.e., around $z \sim 0.21$) also dictate the behavior of the parameterization at higher redshifts. The interplay between low and high redshift behaviors, as highlighted by the two pivot redshifts, could contribute to the increased uncertainties at low redshift and the tilting of the probability contours seen in figure 6. As discussed in the main manuscript, this model offers relatively modest improvements in the fit compared to Λ CDM, particularly in datasets covering $z \gtrsim 1$, where the model's deviations from the others become more pronounced.
- Logarithmic*: When it comes to the logarithmic parameterization, the behavior of $w(z)$ for $z \lesssim 1$, shown in the fourth panel of figure 7, is similar to that of the CPL and exponential models. This is also reflected in the values we inferred for z_p , $w(z_p)$, and z_c , all summarized in table 7 and consistent with those models. However, we observe that at $z \gtrsim 1$, the EoS is forced down into deep phantom values, and the descent towards these very negative

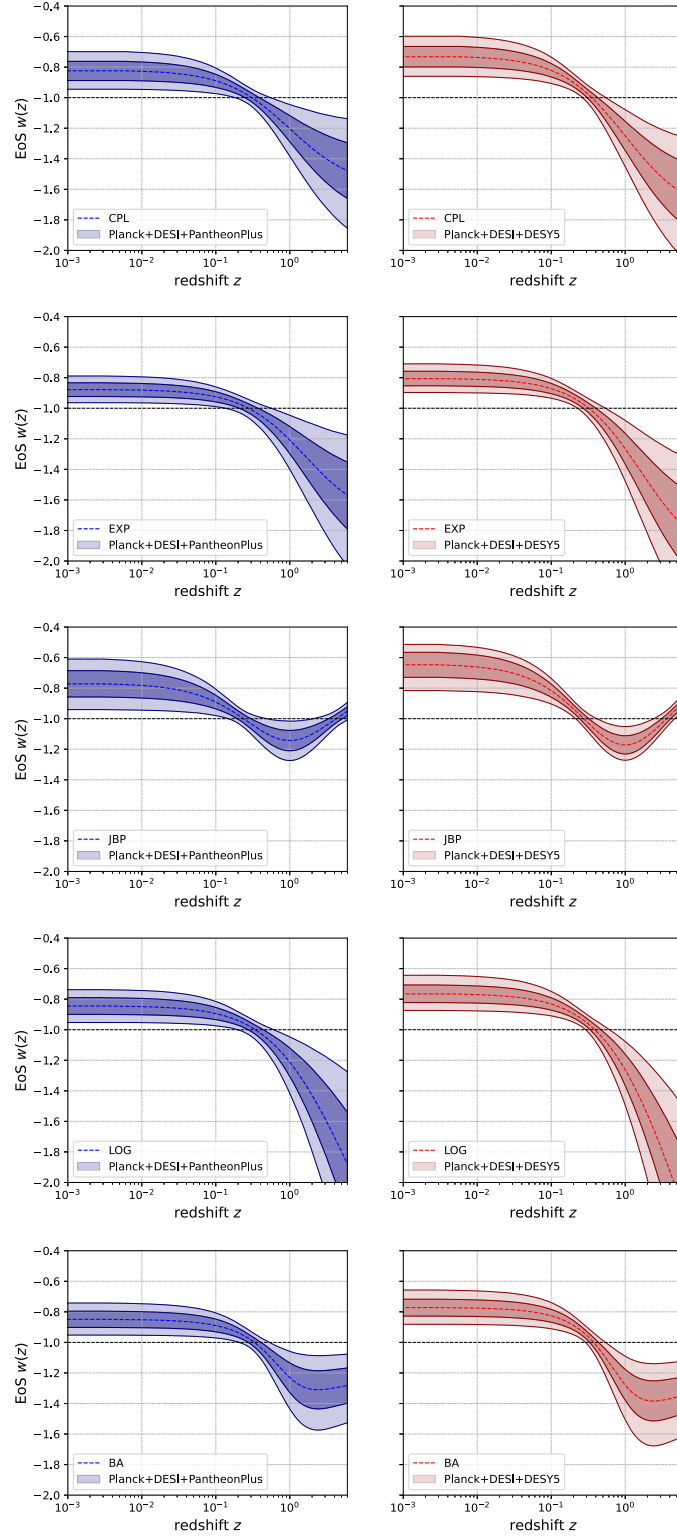


Figure 7. Evolution of $w(z)$ for $0 < z < 6$ across all DDE models, inferred from CMB+DESI+PantheonPlus (left panels) and CMB+DESI+DESY5 (right panels). The dashed lines represent the mean values, while the dark and light shaded regions indicate the 1σ and 2σ uncertainties, respectively.

values is steeper than in the CPL and exponential cases. This is due to the fact that at $z \gtrsim 1$, the scale factor a approaches small values (moving towards $a \rightarrow 0$), causing $\log(a)$ to decrease to negative values quite rapidly. This sudden decline in $w(z)$ for $z \gtrsim 1$ can lead to changes in the fit to data spanning $1 \lesssim z \lesssim 3$, which is covered by BAO and SN observations, resulting in the differences in the χ^2 of the fit discussed in the manuscript.

- *BA*: Last but not least, the evolution of $w(z)$ obtained for the BA model is presented in the bottom panel of figure 7. As we argued in the manuscript, this model provides the most significant improvement in the fit over Λ CDM across all datasets analyzed in this study. Therefore, it is interesting to examine what is different in the evolution of the EoS compared to the other models. Looking at the low-redshift part of the EoS, we see that the model behaves very similarly to CPL (and its relatives). However, for the pivot redshift, we obtain $z_p = 0.28$, slightly larger than in any other model, while $w(z_p)$ takes values consistent with the other cases. We estimate the quintessence-to-phantom transition to occur at $z_c = 0.33_{-0.06}^{+0.08}$ ($z_c = 0.37_{-0.04}^{+0.06}$) for Planck+DESI+PantheonPlus (Planck+DESI+DESY5) at 68% CL. The most noticeable difference in the EoS occurs at $z \gtrsim 1$. In all other models studied so far, the EoS either moved deeply into phantom values (characterized by more or less steep functional forms of $w(z)$) or was compelled to increase back towards quintessence-like values in the JBP model. Referring to the bottom panel of figure 7, we observe that for $z \gtrsim 1$, the evolution of $w(z)$ in the BA model remains phantom but does not trend towards very negative values. Instead, $w(z)$ stabilizes on a sort of second plateau that is distinctive of the BA model.

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