Did DESI DR2 truly reveal dynamical dark energy?

Deng Wang[*]

Instituto de Física Corpuscular (CSIC-Universitat de València), E-46980 Paterna, Spain

David Mota

Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway

A fundamental question in cosmology is whether dark energy evolves over time, a topic that has gained prominence since the discovery of cosmic acceleration. Recently, the DESI collaboration has reported increasing evidence for evolving dark energy using combinations of cosmic microwave background (CMB), type Ia supernova (SN), and their new measurements of baryon acoustic oscillations (BAO). However, our analysis reveals that these combinations are problematic due to clear tensions among the CMB, BAO and SN datasets. Consequently, DESI's claim of dynamical dark energy (DDE) is not robust. A more reliable approach involves constraining the evolution of dark energy using each dataset independently. Through a statistical comparison for each dataset, on average, we find that DDE is strongly preferred over the ΛCDM model. This suggests that DDE likely exists, although its real parameter space remains elusive due to weak constraints on the dark energy equation of state and inconsistencies among the datasets. Interestingly, when considering DDE, none of the individual datasets—including CMB, DESI DR2, Pantheon+, Union3, and DESY5—can independently detect cosmic acceleration at a significant level. Our findings not only clarify the current understanding of the nature of dark energy but also challenge the established discovery of cosmic acceleration and the long-held notion that dark energy exerts negative pressure. Both individual and combined datasets suggest that the ultimate fate of the universe is likely to be dominated by matter rather than dark energy.

Introduction. The standard cosmological model, Λ cold dark matter (ΛCDM), which has been confirmed by the CMB [1–5], BAO [6–12], and SN observations [13, 14], can successfully characterize various kinds of physical phenomena such as the cosmic acceleration on large scales and the clustering of matter on small scales [15]. However, it confronts two intractable challenges, namely the cosmological constant conundrum [16, 17] and the coincidence problem, while suffering from the emergent cosmic tensions such as the so-called Hubble constant (H_0) tension and the matter fluctuation amplitude (S_8) discrepancy [18–22]. It is very logically reasonable to query the validity of ΛCDM in verifying the fundamental theory and depicting the background dynamics and structure formation of the universe. So far, to solve these discrepancies, there are a great deal of alternative scenarios proposed by different authors (see [21, 22] for reviews). It is worth noting that, besides the theoretical developments, more importantly, we require new independent and powerful probes with higher precision to give definite answers on some core puzzles. To achieve this goal, a very promising probe is BAO.

BAO are regular and periodic matter density fluctuations of the universe [15], which originate from sound waves induced by hot baryon-photon plasma before the epoch of recombination. The characteristic scale of BAO, approximately 150 Mpc, which is the maximum distance that the acoustic waves could travel in the primordial plasma before the plasma cooled to the point where it became neutral atoms at the recombination epoch, serves as a standard ruler in cosmology. Many BAO experiments such as 2dF [7], 6dF [8], SDSS [6] and eBOSS [11, 12]

map the late-time expansion history of the universe by measuring the apparent size of this ruler at different redshifts. BAO are very clean probes to explore the evolution of the universe over time, which is unaffected by the nonlinear physics on small scales and relatively robust to systematic uncertainties compared to other cosmological probes.

Recently, the DESI collaboration give the substantial evidence of DDE [23], based on their measurements of BAO in galaxy, quasar and Lyman-α forest tracers from the first data release (DR1) of the Dark Energy Spectroscopic Instrument (DESI) [24, 25]. Interestingly, this DDE evidence is enhanced [26, 27] by the DESI's second data release (DR2) including more than 14 million galaxies and quasars, based on three years of operation [28].

In theory, DDE predicts: (i) the equation of state (EoS) and energy densities of dark energy (DE) evolves over time; (ii) different expansion history of the universe from ΛCDM; (iii) the rate at which cosmic structures like galaxies and clusters form can be changed; (iv) the fate of the universe can be significantly affected. If DDE is finally demonstrated to be true, it will indicate that the vacuum is not empty and it does have matter. Therefore, the DESI's finding of DDE evidence is crucial for theory. Up to date, the addition of CMB and SN data to DESI DR2 leads to $2.8 - 4.2\,\sigma$ evidence of DDE [26], depending on which SN sample is used. Although the unprecedented precision and number of data points lead to the evidence of DDE, we should be very cautious about these results. The key reason is that the DDE evidence is derived by the data combination of CMB, DESI DR2

and SN, not from each probe independently. If each of CMB, DESI DR2 and SN gives consistent constraints on the cosmological parameters including the matter fraction and DE EoS, one can safely claim that DDE do exist in the late-time universe. Based on this concern, one has to seriously question: whether does DESI truly see DDE? Our results show that it is too early to claim the existence of DDE using the combinations of CMB, DESI DR2 and SN data, but independent datasets still give strong statistical preferences of DDE over ΛCDM. Future high precision observations can help clarify the status of DE.

Basics. In the theory of general relativity [29], considering a homogeneous and isotropic universe, the Friedmann equations read as $H^2 = (8\pi G\rho)/3$ and $\ddot{a}/a = -4\pi G(\rho + 3p)/3$, where a is the scale factor, H is the cosmic expansion rate and ρ and p are the mean energy density and pressure of different species including radiation, baryons, dark matter and DE. Combining two Friedmann equations, one can express the dimensionless Hubble parameter $E(z) \equiv H(z)/H_0$ for a flat Chevallier-Polarski-Linder (CPL) universe [30, 31] as

$$E(a) = \left[\Omega_m a^{-3} + (1 - \Omega_m)a^{-3(1+\omega_0+\omega_a)}\mathrm{e}^{3\omega_a(a-1)}\right]^{\frac{1}{2}},$$
(1)

where Ω_m is the matter fraction. It reduces to ΛCDM when $\omega_0 = -1$ and $\omega_a = 0$.

Data and methodology. We use the Planck 2018 high-ℓ `plik` temperature (TT) likelihood at multipoles $30 \leqslant \ell \leqslant 2508$, polarization (EE) and their cross-correlation (TE) data at $30 \leqslant \ell \leqslant 1996$, and the low-$\ell$ TT `Commander` and `SimAll` EE likelihoods at $2 \leqslant \ell \leqslant 29$ [32]. We adopt conservatively the Planck lensing likelihood [33] from `SMICA` maps at $8 \leqslant \ell \leqslant 400$. We use the most recent 13 BAO measurements from DESI DR2 including the BGS, LRG1, LRG2, LRG3+ELG1, ELG2, QSO and Lyα samples at effective redshifts $z_{\mathrm{eff}} = 0.295$, 0.51, 0.706, 0.934, 1.321, 1.484 and 2.33, respectively [26–28]. To completely explore the DE EoS at late times, we adopt three well-calibrated SN compilations: (i) Pantheon+ consisting of 1701 data points from 18 different surveys in $z \in [0.00122, 2.26137]$ [34]; (ii) Union3 with 22 spline-interpolated data points derived by 2087 SN from 24 different surveys in $z \in [0.05, 2.26]$ [35]; (iii) DESY5 including 1735 effective data points in $z \in [0.025, 1.130]$ [36].

To calculate the background dynamics of the universe and theoretical power spectra, we use the Boltzmann solver `CAMB` [37]. To implement the Bayesian analysis, we employ the Monte Carlo Markov Chain (MCMC) method to infer the posterior distributions of model parameters using the publicly available package `Cobaya` [38]. We assess the convergence of MCMC chains via the Gelman-Rubin criterion $R - 1 \lesssim 0.01$ [39] and analyze them using `Getdist` [40].
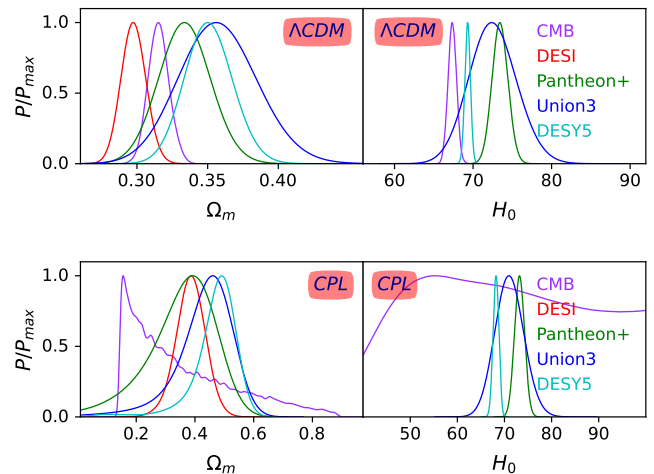

FIG. 1: One-dimensional posterior distributions of the parameters Ω_m and H_0 from CMB, DESI DR2 and SN observations in the ΛCDM (*upper*) and CPL (*lower*) models, respectively.

We use the following uniform priors for free parameters: the baryon fraction $\Omega_b h^2 \in [0.005, 0.1]$, cold dark matter fraction $\Omega_c h^2 \in [0.001, 0.99]$, acoustic angular scale at the recombination epoch $100\theta_{MC} \in [0.5, 10]$, scalar spectral index $n_s \in [0.8, 1.2]$, amplitude of the primordial scalar power spectrum $\ln(10^{10}A_s) \in [2, 4]$, optical depth $\tau \in [0.01, 0.8]$, present-day DE EoS $\omega_0 \in [-15, 20]$ and the amplitude of DE evolution $\omega_a \in [-30, 10]$. To produce a matter-dominated era at high redshifts, we impose the condition $\omega_0 + \omega_a < 0$ in the Bayesian analysis. The reason why we take such wide priors for the parameter pair (ω_0, ω_a) is that a large enough parameter space can completely present the constraining power of the DESI DR2 BAO measurements [41].

Ω_m *and* H_0 *tensions from independent probes.* The DESI collaboration have noticed that there is a Ω_m tension among CMB, DESI DR2 and three SN samples under ΛCDM [26]. SN datasets clearly prefer a larger matter fraction than CMB and DESI DR2. However, the accompanying H_0 tension is not reported. In Fig.1, we find that Pantheon+, Union3 and DESY5 exhibit H_0 tensions with CMB [1] at $5.31\,\sigma$, $1.69\,\sigma$ and $3.03\,\sigma$ levels, respectively. Although three SN samples are well calibrated, they suffer from internal inconsistencies in their preferred H_0 values. For instance, Pantheon+ is in a $3.86\,\sigma$ tension with DESY5. The main goal of DESI is exploring the nature of DE including its possible dynamics. Based on the new motivation that DDE could help resolve the Ω_m tension in ΛCDM, we implement constraints on the CPL DDE and find that CMB prefers a smaller Ω_m, while DESI DR2 and SN prefer larger matter fractions. Interestingly, Ω_m tensions between DESI DR2 and CMB, Pantheon+, Union3, and DESY5 are well alleviated from
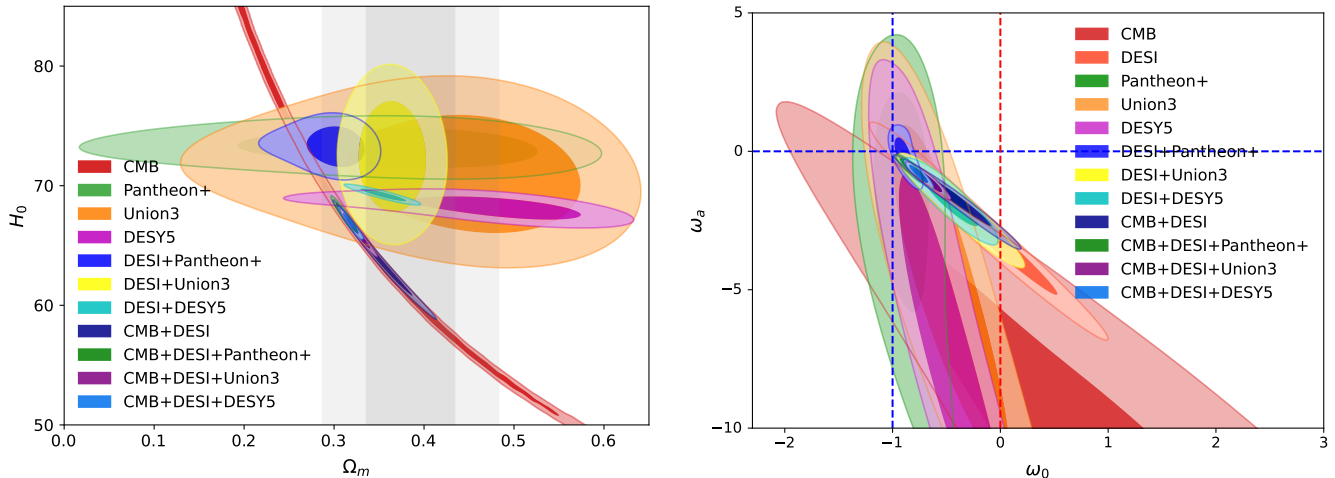
FIG. 2: Two-dimensional posterior distributions of the parameter pairs (Ω_m, H_0) and (ω_0, ω_a) from different datasets in the CPL model. The vertical shaded grey regions are the constrained 1σ and 2σ Ω_m values from DESI DR2. The cross point of blue dashed lines represents ΛCDM. The red dashed line denotes $\omega_0 = 0$.

$1.57\,\sigma$, $1.83\,\sigma$, $2.10\,\sigma$ and $2.81\,\sigma$ to $0.14\,\sigma$, $0.21\,\sigma$, $0.49\,\sigma$ and $0.94\,\sigma$, respectively. It seems that DDE solves the Ω_m discrepancies, however, the price is DESI DR2 and SN give larger Ω_m (e.g. ~ 0.5) in CPL than in ΛCDM, while the H_0 tension between Pantheon+ and DESY5 increases from $3.86\,\sigma$ to $4.29\,\sigma$ (see Tab.I). Therefore, the well-known fact that the late universe is dominated by DE is largely challenged in CPL. Note that CMB cannot constrain H_0 in CPL, due to the weak constraint on the DE EoS.

Inconsistencies from data combinations. The strong evidence for DDE primarily comes from the combination of CMB, BAO, and SN data. However, this result accommodates the inconsistencies among them. Hence, it is reasonable to question the validity of the combination. In Fig.2, the insensitivity of CMB to (ω_0, ω_a) leads to a much weaker constraint on H_0 and Ω_m in CPL than that in ΛCDM. Fortunately, the strong anti-correlation between H_0 and Ω_m remains. Combining CMB with BAO and SN, this anti-correlation will largely help compress the parameter space and consequently tighten constraints on (ω_0, ω_a). Unfortunately, there are beyond $1\,\sigma$ tensions between CMB and SN. Especially, DESY5 gives a $\sim 2\,\sigma$ tension with CMB. Even worse, the addition of DESI DR2 to SN leads to beyond $2\,\sigma$ tensions with CMB, particularly, DESY5 plus DESI DR2 gives a beyond $3\,\sigma$ tension with CMB. These tensions can also be captured in r_d values. Adding DESI DR2 to Pantheon+, Union3 and DESY5 leads to a $5.30\,\sigma$, $2.86\,\sigma$ and $4.26\,\sigma$ tension with CMB when estimating r_d, respectively. Notice that there is a beyond $2\,\sigma$ tension between Pantheon+ plus DESI DR2 and DESY5 plus DESI DR2. This suggests a clear discrepancy among SN samples. Interestingly, CMB plus DESI DR2 is in beyond $3\,\sigma$, beyond $2\,\sigma$ and $\sim 1.5\,\sigma$ ten-

sions with Pantheon+, DESY5 and Union3, respectively. All these discrepancies demonstrate that the DDE evidences from combined constraints are problematic.

Furthermore, we give more complete constraints on (ω_0, ω_a) using a wider prior than that the Planck and DESI collaborations used [1, 26, 27]. We find that CMB is in a $\sim 2\,\sigma$ tension with DESI DR2 and three SN samples are basically inconsistent with CMB at $\sim 1\,\sigma$ level. Since DESI DR2 with a clear different degeneracy direction of (ω_0, ω_a) from SN has a $\sim 1\,\sigma$ tension with SN, the DDE evidences from DESI DR2 plus CMB or SN are problematic. Additionally, even for the SN-only case, there is also an inconsistency among SN samples, i.e., Pantheon+ is consistent with ΛCDM within $1\,\sigma$ level, while Union3 and DESY5 exhibit beyond $1\,\sigma$ tensions with ΛCDM. Therefore, we should not place too much trust in the constraints derived from any pairwise combination of the datasets. Starting from this viewpoint, the reason why Ω_m values from the combination of CMB, DESI DR2 and SN are so close to $\Omega_m = 0.3153 \pm 0.0073$ [1] from the CMB-only constraint on ΛCDM should be a coincidence.

Solution. Due to the unprecedented precision and increasing number of data points, we should be cautious when studying possible new physics using the data combinations, which may bias the results away from the truth. Although there are discrepancies among CMB, BAO and SN data, an undeniable fact is that they all prefer the region of $\omega_0 > -1$ and $\omega_a < 0$. Especially, DESI DR2, giving a strong enough anti-correlation of (ω_0, ω_a), shows a $\sim 2\,\sigma$ preference with a relatively high precision. Concerning this, we implement a statistical comparison between CPL and ΛCDM. For CMB, we find that the Bayesian factor $\ln B_{ij} = 6.34 > 5$ [45], indicating a

TABLE I: Mean values and 1σ (68%) uncertainties of free parameters from different datasets in the CPL model. We quote the 2σ (95%) upper limit of ω_0 in the CMB-only case. The symbols "★" and ♦ denote unconstrained parameters by data and parameters with poor constraints, respectively. Here $h \equiv H_0/100$ in units of km s^{-1} Mpc^{-1}.

Parameter	ω_0	ω_a	Ω_m	H_0	r_d	hr_d
CMB	2.4 ± 1.9	< -3.62	$0.344^{+0.054}_{-0.200}$	♦	147.32 ± 0.27	103^{+20}_{-30}
DESI	-0.17 ± 0.44	-2.8 ± 1.6	0.385 ± 0.049	★	★	$91.5^{+4.4}_{-4.9}$
Pantheon+	-0.89 ± 0.17	$-2.1^{+3.2}_{-1.8}$	$0.360^{+0.130}_{-0.086}$	73.2 ± 1.0	★	★
Union3	$-0.45^{+0.28}_{-0.40}$	$-5.4^{+4.7}_{-3.1}$	$0.437^{+0.100}_{-0.066}$	71.1 ± 3.0	★	★
DESY5	$-0.35^{+0.30}_{-0.41}$	$-9.0^{+5.4}_{-4.5}$	$0.471^{+0.075}_{-0.043}$	68.20 ± 0.60	★	★
DESI+Pantheon+	-0.885 ± 0.061	-0.19 ± 0.46	$0.299^{+0.025}_{-0.016}$	73.3 ± 1.0	136.1 ± 2.1	99.72 ± 0.93
DESI+Union3	-0.37 ± 0.23	-2.07 ± 0.82	0.365 ± 0.024	72.4 ± 3.0	129.3 ± 6.3	93.5 ± 2.6
DESI+DESY5	-0.47 ± 0.17	-1.75 ± 0.61	0.354 ± 0.016	69.24 ± 0.34	136.6 ± 2.5	94.6 ± 2.1
CMB+Pantheon+	-0.868 ± 0.092	$-0.56^{+0.48}_{-0.42}$	$0.311^{+0.011}_{-0.013}$	67.8 ± 1.2	147.13 ± 0.25	99.7 ± 1.8
CMB+Union3	-0.63 ± 0.14	$-1.39^{+0.68}_{-0.60}$	$0.319^{+0.012}_{-0.014}$	66.9 ± 1.3	147.17 ± 0.25	98.5 ± 2.0
CMB+DESY5	-0.73 ± 0.10	-1.04 ± 0.51	$0.3151^{+0.0094}_{-0.0110}$	$67.3^{+1.10}_{-0.95}$	147.15 ± 0.25	$99.1^{+1.6}_{-1.4}$
CMB+DESI	$-0.41^{+0.21}_{-0.25}$	$-1.74^{+0.75}_{-0.59}$	$0.353^{+0.022}_{-0.025}$	63.7 ± 2.0	147.16 ± 0.23	93.7 ± 3.1
CMB+DESI+Pantheon+	-0.843 ± 0.054	$-0.58^{+0.23}_{-0.19}$	0.3108 ± 0.0058	67.62 ± 0.60	147.28 ± 0.22	99.59 ± 0.89
CMB+DESI+Union3	-0.673 ± 0.087	$-1.04^{+0.30}_{-0.27}$	0.3268 ± 0.0086	66.02 ± 0.84	147.22 ± 0.21	97.2 ± 1.2
CMB+DESI+DESY5	-0.757 ± 0.057	-0.82 ± 0.22	0.3184 ± 0.0057	66.86 ± 0.57	147.24 ± 0.22	98.44 ± 0.84

strong evidence of CPL from CMB. For DESI DR2, Pantheon+, Union3 and DESY5, we obtain ΔBIC = 2.25, 25.63, 3.92 and 11.49 [46], respectively, indicating positive evidences from DESI DR2 and Union3 and strong evidences from Pantheon+ and DESY5 for DDE. Hence, DDE likely exists, however, we cannot determine the real parameter space of DDE according to such independent probes, due to their weak constraints on (ω_0, ω_a) and inconsistencies. If future observations (CMB, BAO or SN) with increasing precision can provide inconsistent constraints on DDE, we can safely claim its existence.

The fate of the universe. The existence of DDE will affect the composition, fate, expansion history and structure formation of the universe. The fact that three SN datasets allow $\Omega_m > 0.5$ in CPL means that the late universe could be matter dominated not DE dominated. At least, CMB, DESI DR2 and SN all independently allow a large $\Omega_m \sim 0.5$. Interestingly, CMB, DESI DR2, Union3 and DESY5 do not rule out $\omega_0 > 0$ and $\omega_0 > 1/[3(\Omega_m - 1)]$ [47]. Only Pantheon+ finds a beyond 1σ hint of late-time cosmic acceleration. One has to question whether the universe is accelerating now. CMB, DESI DR2, Union3 and DESY5 give, respectively, $\omega_0 = 2.4 \pm 1.9$, -0.17 ± 0.44, $-0.45^{+0.28}_{-0.40}$ and $-0.35^{+0.30}_{-0.41}$, allowing that current universe could be slowing down or moving at a constant speed. Particularly, CMB gives a 1.3σ hint of $\omega_0 > 0$, allowing that DE has a positive pres-

sure. Our findings not only profoundly challenge the understanding of cosmic acceleration, but also challenge the long-held notion that the pressure of DE is negative. Interestingly, we find that both independent and combined datasets prefer that the ultimate destiny of the universe is completely filled with matter not DE, i.e., $\Omega_m = 1$. At some point in the distant future, matter will dominate the evolution of the universe. Finally, the universe will miraculously stop moving [48]. More details about the fate of the universe will be shown in [49].

In summary, the DESI DR2 data, when combined with CMB and SN data, appears to provide increasing evidence for Dynamical Dark Energy (DDE). However, our analysis demonstrates that this conclusion is not robust. By constraining the CPL model with independent observations and various data combinations, we identify significant tensions between different datasets. These tensions lead to problematic constraints when incompatible datasets are combined.

Although the combined constraints yield Ω_m and H_0 values close to those from the CMB-only constraint on ΛCDM, we believe this to be coincidental. In the CPL model, the effect of the cosmological constant in ΛCDM is partially replaced by a larger matter fraction and DDE.

The combination of CMB, DESI DR2, and SN data results in a lower H_0 value because DESI DR2 indicates a high $\Omega_m = 0.385 \pm 0.049$. This high matter density

directly leads to a low $H_0 = 63.7 \pm 2.0$ km s^{-1} Mpc^{-1} when combined with CMB data, due to the strong anti-correlation between H_0 and Ω_m in CMB observations. Given the crucial role of H_0 in the universe's background evolution, we explore the effects of H_0 and $H_0 r_d$ on the parameters ω_0 and ω_a for DESI DR2 in the supplementary material (SM). Additionally, we find that allowing for a free lensing amplitude A_L can reduce the significance of DDE by approximately 1σ, as A_L and DDE are degenerate in the CMB lensing potential (see SM).

It is important to note that as the precision and volume of cosmological data increase, so do the tensions between different probes. This growing statistical complexity challenges our understanding of the data, underlying physics, and potential systematics. We are currently at a critical juncture in addressing these challenges.

---

* Electronic address: dengwang@ific.uv.es

[1] N. Aghanim *et al.* [Planck], "Planck 2018 results. VI. Cosmological parameters," Astron. Astrophys. **641**, A6 (2020) [erratum: Astron. Astrophys. **652**, C4 (2021)].

[2] T. Louis *et al.* [ACT], "The Atacama Cosmology Telescope: DR6 Power Spectra, Likelihoods and ΛCDM Parameters," [arXiv:2503.14452 [astro-ph.CO]].

[3] L. Balkenhol *et al.* [SPT-3G], "Measurement of the CMB temperature power spectrum and constraints on cosmology from the SPT-3G 2018 TT, TE, and EE dataset," Phys. Rev. D **108**, no.2, 023510 (2023).

[4] D. N. Spergel *et al.* [WMAP], "First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters," Astrophys. J. Suppl. **148**, 175-194 (2003).

[5] P. A. R. Ade *et al.* [Planck], "Planck 2013 results. XVI. Cosmological parameters," Astron. Astrophys. **571**, A16 (2014).

[6] D. J. Eisenstein *et al.* [SDSS], "Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies," Astrophys. J. **633**, 560-574 (2005).

[7] S. Cole *et al.* [2dFGRS], "The 2dF Galaxy Redshift Survey: Power-spectrum analysis of the final dataset and cosmological implications," Mon. Not. Roy. Astron. Soc. **362**, 505-534 (2005).

[8] F. Beutler *et al.* [6dF], "The 6dF Galaxy Survey: Baryon Acoustic Oscillations and the Local Hubble Constant," Mon. Not. Roy. Astron. Soc. **416**, 3017-3032 (2011)

[9] S. Alam *et al.* [eBOSS], "Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory," Phys. Rev. D **103**, no.8, 083533 (2021).

[10] E. de Carvalho, A. Bernui, G. C. Carvalho, C. P. Novaes and H. S. Xavier, "Angular Baryon Acoustic Oscillation measure at $z = 2.225$ from the SDSS quasar survey," JCAP **04**, 064 (2018).

[11] M. Ata *et al.* [eBOSS], "The clustering of the SDSS-IV extended Baryon Oscillation Spectroscopic Survey DR14 quasar sample: first measurement of baryon acoustic oscillations between redshift 0.8 and 2.2," Mon. Not. Roy. Astron. Soc. **473**, no.4, 4773-4794 (2018).

[12] J. Hou *et al.* [eBOSS], "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: BAO and RSD measurements from anisotropic clustering analysis of the Quasar Sample in configuration space between redshift 0.8 and 2.2," Mon. Not. Roy. Astron. Soc. **500**, no.1, 1201-1221 (2020).

[13] A. G. Riess *et al.* [Supernova Search Team], "Observational evidence from supernovae for an accelerating universe and a cosmological constant," Astron. J. **116**, 1009-1038 (1998).

[14] S. Perlmutter *et al.* [Supernova Cosmology Project], "Measurements of Ω and Λ from 42 high redshift supernovae," Astrophys. J. **517**, 565-586 (1999).

[15] D. H. Weinberg, M. J. Mortonson, D. J. Eisenstein, C. Hirata, A. G. Riess and E. Rozo, "Observational Probes of Cosmic Acceleration," Phys. Rept. **530**, 87-255 (2013).

[16] S. Weinberg, "The Cosmological Constant Problem," Rev. Mod. Phys. **61**, 1 (1989).

[17] S. M. Carroll, "The Cosmological constant," Living Rev. Rel. **4**, 1 (2001).

[18] E. Di Valentino *et al.*, "Snowmass2021 - Letter of interest cosmology intertwined I: Perspectives for the next decade," Astropart. Phys. **131**, 102606 (2021).

[19] E. Di Valentino *et al.*, "Snowmass2021 - Letter of interest cosmology intertwined II: The hubble constant tension," Astropart. Phys. **131**, 102605 (2021).

[20] E. Di Valentino, L. A. Anchordoqui, Ö. Akarsu, Y. Ali-Haimoud, L. Amendola, N. Arendse, M. Asgari, M. Ballardini, S. Basilakos and E. Battistelli, *et al.* "Cosmology Intertwined III: $f\sigma_8$ and S_8," Astropart. Phys. **131**, 102604 (2021).

[21] E. Abdalla *et al.*, "Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies," JHEAp **34**, 49-211 (2022).

[22] E. Di Valentino *et al.*, "The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics," [arXiv:2504.01669 [astro-ph.CO]].

[23] A. G. Adame *et al.* [DESI], "DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations," [arXiv:2404.03002 [astro-ph.CO]].

[24] A. G. Adame *et al.* [DESI], "DESI 2024 III: Baryon Acoustic Oscillations from Galaxies and Quasars," [arXiv:2404.03000 [astro-ph.CO]].

[25] A. G. Adame *et al.* [DESI], "DESI 2024 IV: Baryon Acoustic Oscillations from the Lyman Alpha Forest," [arXiv:2404.03001 [astro-ph.CO]].

[26] M. Abdul Karim *et al.* [DESI], "DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints," [arXiv:2503.14738 [astro-ph.CO]].

[27] K. Lodha *et al.* [DESI], "Extended Dark Energy analysis using DESI DR2 BAO measurements," [arXiv:2503.14743

[astro-ph.CO]].

[28] M. Abdul Karim *et al.* [DESI], "DESI DR2 Results I: Baryon Acoustic Oscillations from the Lyman Alpha Forest," [arXiv:2503.14739 [astro-ph.CO]].

[29] A. Einstein, "The foundation of the general theory of relativity.," Annalen Phys. **49**, no.7, 769-822 (1916).

[30] M. Chevallier and D. Polarski, "Accelerating universes with scaling dark matter," Int. J. Mod. Phys. D **10**, 213-224 (2001).

[31] E. V. Linder, "Exploring the expansion history of the universe," Phys. Rev. Lett. **90**, 091301 (2003).

[32] N. Aghanim *et al.* [Planck], "Planck 2018 results. V. CMB power spectra and likelihoods," Astron. Astrophys. **641**, A5 (2020).

[33] N. Aghanim *et al.* [Planck], "Planck 2018 results. VIII. Gravitational lensing," Astron. Astrophys. **641**, A8 (2020).

[34] D. Brout *et al.*, "The Pantheon+ Analysis: Cosmological Constraints," Astrophys. J. **938**, no.2, 110 (2022).

[35] D. Rubin *et al.*, "Union Through UNITY: Cosmology with 2,000 SNe Using a Unified Bayesian Framework," [arXiv:2311.12098 [astro-ph.CO]].

[36] T. M. C. Abbott *et al.* [DES], "The Dark Energy Survey: Cosmology Results with ∼1500 New High-redshift Type Ia Supernovae Using the Full 5 yr Data Set," Astrophys. J. Lett. **973**, no.1, L14 (2024).

[37] A. Lewis, A. Challinor and A. Lasenby, "Efficient computation of CMB anisotropies in closed FRW models," Astrophys. J. **538**, 473-476 (2000).

[38] J. Torrado and A. Lewis, "Cobaya: Code for Bayesian Analysis of hierarchical physical models," JCAP **05**, 057 (2021).

[39] A. Gelman and D. B. Rubin, "Inference from Iterative Simulation Using Multiple Sequences," Statist. Sci. **7**, 457-472 (1992).

[40] A. Lewis, "GetDist: a Python package for analysing Monte Carlo samples," [arXiv:1910.13970 [astro-ph.IM]].

[41] D. Wang, "The Self-Consistency of DESI Analysis and Comment on 'Does DESI 2024 Confirm ΛCDM?'," [arXiv:2404.13833 [astro-ph.CO]].

[42] R. Trotta, "Applications of Bayesian model selection to cosmological parameters," Mon. Not. Roy. Astron. Soc. **378**, 72-82 (2007).

[43] G. Schwarz, "Estimating the Dimension of a Model," Annals Statist. **6**, 461-464 (1978).

[44] A. Heavens *et al.*, "No evidence for extensions to the standard cosmological model," Phys. Rev. Lett. **119**, no.10, 101301 (2017).

[45] For CMB, choosing ΛCDM as the reference model, we use the `MCEvidence` package [44] to calculate the Bayesian evidences of CPL and ΛCDM, ε_i, and the Bayes factor, $B_{ij} = \varepsilon_i/\varepsilon_j$, where ε_j is the statistical evidence of the reference model. We use a revised and more conservative version of the so-called Jeffreys' scale [42], i.e., $\ln B_{ij} = 0-1$, $\ln B_{ij} = 1-2.5$, $\ln B_{ij} = 2.5-5$ and $\ln B_{ij} > 5$ implying an *inconclusive*, *weak*, *moderate* and *strong* preference of the model i over the reference model j, respectively. Note that data prefers the reference model if $\ln B_{ij} < 0$ for an experiment. Here the reference model is ΛCDM.

[46] For DESI DR2 and SN, we implement the statistical comparison using the Bayesian information criterion (BIC) [43], which is defined as BIC $= \chi^2_{\min} + n \ln N$, where n and N denotes the numbers of model parameters and data points. It is noteworthy that the relative values of this criterion between different models are more useful than the absolute values to distinguish which model is preferred by observations. Hence, we define the relative variation ΔBIC between models as follows ΔBIC $=$ BIC$^{\mathrm{model}} -$ BIC$^{\mathrm{\Lambda CDM}}$, where we have chosen the ΛCDM model as the reference model. Generally, the differences $\Delta\mathrm{BIC} \sim 2$ and $\Delta\mathrm{BIC} \sim 6$ indicate a positive and strong evidence against the reference model, respectively.

[47] In CPL DDE, cosmic acceleration requires $\omega_0 < 1/[3(\Omega_m - 1)]$ easily derived from the violation of the strong energy condition $\rho + 3p \geqslant 0$.

[48] J. D. Barrow and F. J. Tipler, "The Anthropic Cosmological Principle." Oxford University Press (1986).

[49] In preparation.

Supplementary Material for "Did DESI DR2 truly reveal dynamical dark energy?"

In this supplementary material, first of all, we study the effect of CMB lensing amplitude A_L on the DDE constraints using the combinations of CMB, DESI DR2 and SN observations. Since the DE EoS is closely related to the present-day cosmic expansion rate, we then investigate the effect of H_0 and $H_0 r_d$ on the DDE constraints using only DESI DR2 BAO measurements. Finally, we compare the CMB-only constraints on the CPL DDE and ΛCDM.
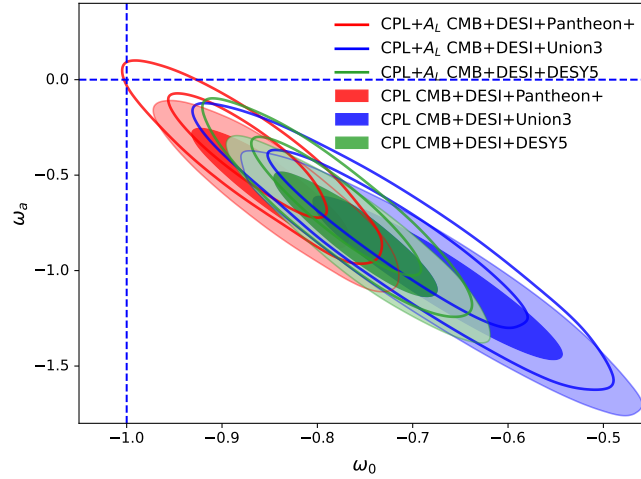

FIG. 1: Two-dimensional posterior distributions of the parameter pairs (ω_0, ω_a) from CMB, DESI DR2 and SN observations in the CPL model with and without the lensing amplitude A_L. The cross point of blue dashed lines corresponds to ΛCDM.
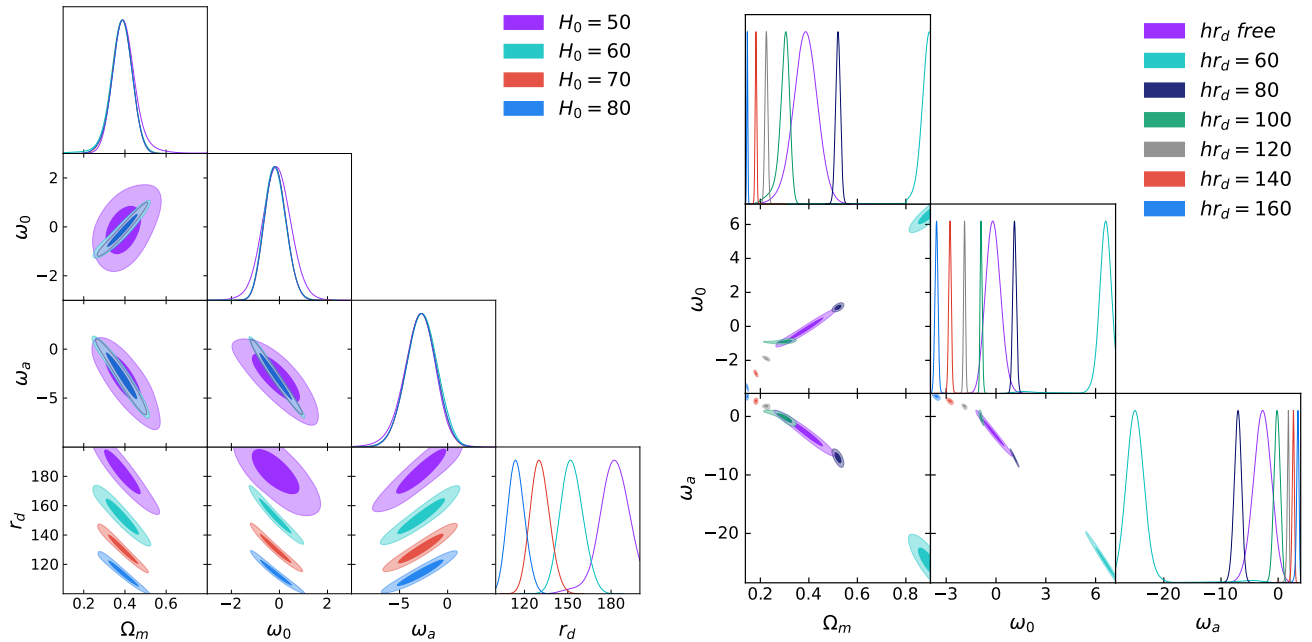

FIG. 2: One-dimensional and two-dimensional posterior distributions of model parameters in the CPL model from the DESI DR2 data when considering different values of H_0 and hr_d, respectively. For the case of hr_d, we use a free hr_d as a comparison.
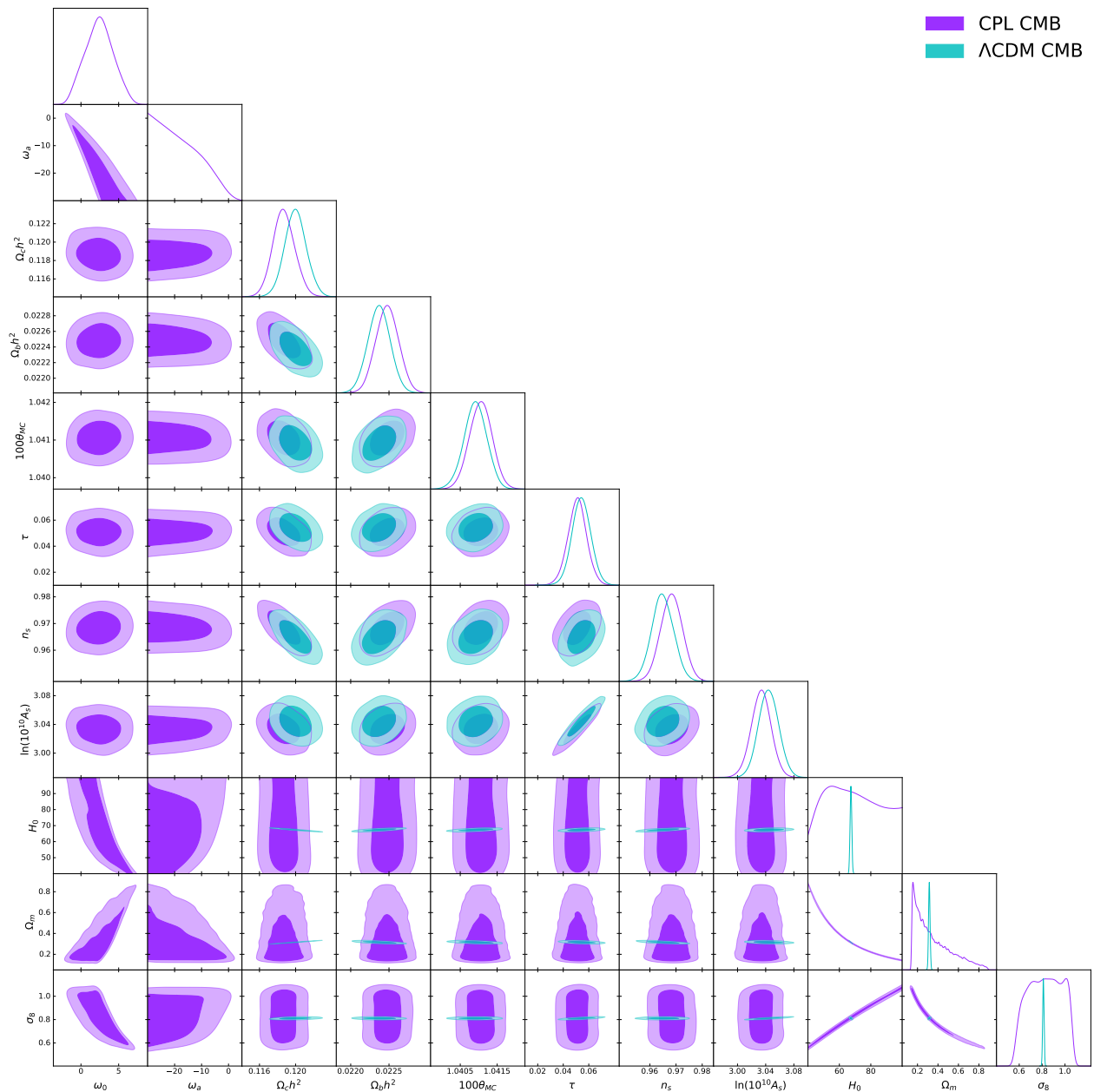
FIG. 3: One-dimensional and two-dimensional posterior distributions of model parameters in the CPL and ΛCDM models from the CMB observations.

A. The effect of lensing amplitude on DDE

As we know, the CMB lensing anomaly is strongly degenerated with many new physics on cosmic scales, e.g., modified gravity [1, 2], cosmic curvature [3] and effective field theory of DE [1]. Since both DDE and A_L have impacts on the gravitational potential, considering A_L could change the constraints on (ω_0, ω_a). Employing the data combination of CMB, DESI DR2 and SN, we find that a free A_L can reduce a $\sim 1\,\sigma$ significance of DDE (see Fig.1). This result holds for all three SN samples considered here.

B. The effects of H_0 and hr_d on DDE

In theory, BAO require the information of the comoving sound horizon r_d at the drag epoch from CMB [] to help determine H_0, since BAO cannot independently constrain H_0. However, it is interesting to see how the correlations between r_d and the DE EoS (or matter density ratio) vary over different H_0 values. In Fig.2, as expected, varying H_0 hardly changes the constraints on the matter fraction. Larger H_0 leads to smaller r_d. r_d inherits the anti-correlations between H_0 and Ω_m (or ω_0) and the positive correlation between H_0 and ω_a. It is worth noting that the whole parameter space will be enlarged when taking small H_0 values. Furthermore, we study how the compound parameter $H_0 r_d$ impacts the DDE constraints. Similar to the case of H_0, larger $H_0 r_d$ gives smaller Ω_m and ω_0 as well as larger ω_a. The constraints from the case of free $H_0 r_d$ fall well in between those from $H_0 r_d = 80$ and 100, because it gives $H_0 r_d = 91.5^{+4.4}_{-4.9}$ (see the table in the main text).

C. CPL vs ΛCDM in light of CMB

In Fig.3, we make a comparison between the CPL DDE and ΛCDM models. Overall, DDE gives similar constraints on six basic parameters, although there are small shifts in some parameters. It is noteworthy that CMB is phenomenologically insensitive to the late-time DE EoS. This insensitivity leads to a poor constraint on (ω_0, ω_a). Therefore, one cannot well constrain the background quantities such as H_0 and Ω_m in the CPL DDE model.

––––––––

* Electronic address: dengwang@ific.uv.es

[1] N. Aghanim *et al.* [Planck], "Planck 2018 results. VI. Cosmological parameters," Astron. Astrophys. **641**, A6 (2020) [erratum: Astron. Astrophys. **652**, C4 (2021)].

[2] D. Wang and O. Mena, "Robust analysis of the growth of structure," Phys. Rev. D **109**, no.8, 083539 (2024).

[3] E. Di Valentino, A. Melchiorri and J. Silk, "Planck evidence for a closed Universe and a possible crisis for cosmology," Nature Astron. **4**, no.2, 196-203 (2019).