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Do cosmological observations allow a negative Λ?

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ABSTRACT

In view of the recent measurement of H_0 from the *Hubble Space Telescope* and Supernova H0 for the Equation of State (SH0ES) team, we explore the possibility of existence of a negative cosmological constant [anti-de Sitter (AdS) vacua in the dark energy sector] in the Universe. In this regard, we consider quintessence fields on top of a negative cosmological constant and compare such construction with Λ cold dark matter (ΛCDM) model using a different combination of cosmic microwave background, Type Ia supernova, baryon acoustic oscillation, and H_0 data. Various model comparison estimators show that quintessence models with a negative Λ are either preferred over ΛCDM or perform equally as the ΛCDM model. This suggests that the presence of a negative Λ (AdS ground state) in our Universe, which can naturally arise in string theory, is consistent with cosmological observations.

Key words: cosmological parameters – cosmology: theory – dark energy.

1 INTRODUCTION

Our Universe is full of surprises and each surprise updates our understanding of the Universe in a remarkable way. Around two decades ago, one such surprising observation involving Type Ia supernova (SNIa) confirmed the accelerated cosmological expansion of our Universe (Riess et al. 1998; Perlmutter et al. 1999). This observational result completely changed the way we believe gravity works. It established that gravity is repulsive on large cosmological scales unlike its attractive nature as Newton and Einstein taught us. To account for this repulsive behaviour of gravity, we need to either include an exotic unseen component called 'dark energy' (DE) having negative pressure, in the energy budget of the Universe, or need to modify the gravity behaviour on large distance scales (Sahni & Starobinsky 2000; Padmanabhan 2003; Peebles & Ratra 2003; Copeland, Sami & Tsujikawa 2006; Clifton et al. 2012; Tsujikawa 2013). Both these approaches to model repulsive gravity, which in turn explain the observed accelerated expansion of the Universe, demand new insights into our field theoretic understanding of particle physics as well as gravity.

If DE is the answer to this puzzle, we should know what is the origin of this DE that has negative pressure and is also dark, i.e. it does not emit any light. Quantum field theory (QFT) provides a simple candidate for this: the ground state energy or 'vacuum energy' of the fields. Its energy momentum tensor has the structure $\rho_{\rm de} = -p_{\rm de} = \Lambda$ (Zel'Dovich 1967), which naturally results in negative pressure. Do note that for accelerated expansion, $\Lambda > 0$. This is termed as 'cosmological constant'. Unfortunately, such a Λ cannot be the DE that we observe today as QFT gives a value for Λ that is inconsistent with what we need, to explain the observed accelerated expansion (Sahni & Starobinsky 2000). Nevertheless, due to its simple structure, Λ has always been preferred by cosmologists as a candidate for DE. Together with cold dark matter (CDM), they construct the ΛCDM model in the Friedmann–Robertson–Walker (FRW) framework to describe our Universe on large cosmological scales, which can account for the accelerated expansion of the Universe. Although theoretically problematic, interestingly the ΛCDM model matches with almost all the observational data including very precise measurement of cosmic microwave background (CMB) radiation by *Planck*'s team (Planck Collaboration et al. 2020b), high-redshift SNIa observations (Scolnic et al. 2018), and baryon acoustic oscillation (BAO; Eisenstein et al. 2005) measurements by large galaxy surveys.

The observational evidence for a positive Λ confirms the presence of a scalar field at the non-zero positive minimum of its potential. This in turn results in the presence of a stable or metastable de Sitter (dS) vacuum depending on the nature of the minimum of the potential. It can also be possible that the scalar field is away from the minimum of the potential and is slowly rolling at the positive part of the potential. This scenario gives rise to a DE component that, unlike Λ, is not a constant but evolves with time, giving rise to a varying equation of state $w_{\rm de} = p_{\rm de}/\rho_{\rm de}$ for the DE (for Λ, $w_{\rm de} = -1$). Such evolving DE component is termed as 'quintessence' (Copeland et al. 2006; Tsujikawa 2013). Most of the quintessence scalar fields, studied in the context of DE, have a dS ground state. Hence, whether DE is Λ or an evolving quintessence field, asymptotically the Universe always settles in a dS phase in future.

To construct such a scenario for quintessence field with dS vacuum is extremely challenging from a string theory perspective (Silverstein 2008; Danielsson, Koerber & van Riet 2010; Danielsson et al. 2013; Cicoli et al. 2019). In fact, it has been argued that string theory might not contain any dS vacuum at all (Vafa 2005; Obied et al.

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2018; Ooguri et al. 2019). This can have far-reaching cosmological implications, in particular for both early (Garg & Krishnan 2019) and late time accelerating Universe. On the other hand, a slow-rolling quintessence field with anti-de Sitter (AdS) vacuum is theoretically consistent with the current late time acceleration and at the same time can be naturally obtained in string theory context using symmetry consideration like AdS/CFT (Conformal Field Theory) correspondence (Maldacena 1999). Unlike the case for a dS vacuum, there are a large number of consistent solutions in AdS background in string theory. So a quintessence field with AdS vacuum is theoretically quite natural. Yet, cosmological studies, in particular the late time cosmology, have mainly focused on the existence of an asymptotically dS phase where an evolving DE is always modelled with a slow-rolling scalar field having either a zero minimum or a dS vacuum.

Just recently, we have another very interesting cosmological result. This time, it is not the slope of the expansion rate of the Universe as measured in late nineties, but the expansion rate itself at present (at $z = 0$). We denote it by H_0, the Hubble parameter at present. The recent local measurement of H_0 by the SH0ES team using the Cepheid variables in the host SNIa is $H_0 = (73.30 \pm 1.04)$ km s^{-1} Mpc^{-1} (Riess et al. 2022, hereafter R22). This is, till date, the most accurate direct model-independent measurement of H_0 using low-redshift observations. There are other low-redshift observations that also give similar higher values for H_0 (Freedman et al. 2019; Pesce et al. 2020; Wong et al. 2020). The problem arises when we compare the R21 result with the indirect high-redshift measurement of H_0 by *Planck* using CMBR observation with the assumption that the Universe is governed by the ΛCDM model (Planck Collaboration et al. 2020b), which gives $H_0 = (67.36 \pm 0.54)$ km s^{-1} Mpc^{-1}. For the first time, these two measurements for H_0 are in tension at a statistical level of $\sim 5\sigma$ This is also called 'Hubble tension' in the literature (Verde, Treu & Riess 2019). Although ΛCDM is already theoretically problematic as discussed above, observationally for the first time, the ΛCDM model faces serious challenges due to this huge tension between low- and high-redshift measurements of the H_0 parameter and has opened up renewed interests for models beyond ΛCDM.

Recently, a large number models have been proposed to address the 'Hubble tension' (Di Valentino, Melchiorri & Silk 2016; Di Valentino et al. 2019, 2020b; Alestas, Kazantzidis & Perivolaropoulos 2020; Anchordoqui et al. 2020; Vagnozzi 2020; Banerjee et al. 2021). Both early Universe (Karwal & Kamionkowski 2016; Poulin et al. 2019; Cai et al. 2021; Freese & Winkler 2022; Gómez-Valent et al. 2021; Jiang & Piao 2021; Karwal et al. 2022; Niedermann & Sloth 2021; Vagnozzi 2021) and late Universe solutions (Di Valentino, Melchiorri & Mena 2017; Di Valentino et al. 2018, 2020a; Benevento, Hu & Raveri 2020; Gómez-Valent, Pettorino & Amendola 2020; Alestas et al. 2022; Alestas, Kazantzidis & Perivolaropoulos 2021; Di Valentino, Mukherjee & Sen 2021a; Efstathiou 2021; Yang et al. 2021) have been put forward in different studies (for a detail review, please see Di Valentino et al. 2021b; Perivolaropoulos & Skara 2022; Schöneberg et al. 2022). Interestingly, the quintessence models with AdS vacuum got certain momentum under such efforts (Dutta et al. 2020; Visinelli, Vagnozzi & Danielsson 2019; Akarsu et al. 2020; Ye & Piao 2020; Calderón et al. 2021; Yin 2022). None of these studies ruled out the presence of a negative Λ, although in statistical term, there is no positive evidence for it in comparison to the ΛCDM model. Also the full CMB likelihood was not considered in any of these studies related to models with AdS vacuum.

In this work, we consider the full CMB likelihood including the lensing likelihood as given by the *Planck*-2018 data release together with the Pantheon data, BAO measurements as well as the H_0 measurement by R21. We also consider a varying DE equation of state in addition to a constant equation of state for DE. Our aim is to have a definite answer to the issue of consistency of the presence of an AdS vacua (presence of a negative Λ) in the DE sector with the cosmological observations. We should stress that we do not aim to solve the problem of Hubble tension by adding a negative Λ in the DE sector.

2 DE MODELS WITH NON-ZERO VACUA

Quintessence models, which contain a non-zero vacuum, can be modelled as a rolling scalar field (ϕ) on top of a cosmological constant ($\Lambda \neq 0$). Both the field ϕ and Λ contribute to the total DE density of the Universe, $\rho_{\rm de} = \rho_\phi + \Lambda$ with the constraint that $\rho_{\rm de} > 0$ around present time to ensure late time accelerated expansion.

Instead of picking a particular scalar field with a potential for the quintessence field (Copeland et al. 2006; Tsujikawa 2013), we consider two most widely used parametrizations for the equation of state $w_\phi = p_\phi/\rho_\phi$ for the field ϕ. In one case, $w_\phi = w_0$ is a constant and it is usually referred to as the 'wCDM' model for ϕ. In another case, $w_\phi = w_0 + (1-a)w_a$, where w_0 and w_a are constants. This is referred to as the 'CPL' model (Chevallier & Polarski 2001; Linder 2003) for ϕ. The ρ_ϕ in these two cases scale as

$$\begin{aligned} \rho_\phi &\sim a^{-3(1+w_0)} \\ \rho_\phi &\sim a^{-3(1+w_0+w_a)} e^{3w_a a}. \end{aligned} \tag{1}$$

Here, a is the scale factor in the FRW metric and we normalize it at present day, $a_0 = 1$.

With this, for a spatially flat Universe, the FRW equation for the Hubble parameter $H(a)$ is given by

$$\begin{aligned} H^2 &= H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_{\rm de}(a)] \\ \Omega_{\rm de}(a) &= \Omega_\phi f(a) + \Omega_\Lambda, \end{aligned} \tag{2}$$

where Ω_m, Ω_r, Ω_ϕ, and Ω_Λ are the density parameters at present for matter (baryons + CDM), radiation, scalar field ϕ, and Λ. The form for $f(a)$ is given by equation (1) for wCDM or CPL models. As the Universe is spatially flat, we have the constraint $\Omega_m + \Omega_r + \Omega_\phi + \Omega_\Lambda = 1$. In our subsequent discussions, we term the DE model with constant w_0 plus a Λ as the 'wCDMCC' model and the DE model with CPL-type equation of state plus a Λ as 'cplCDMCC'. In addition to these two specific models with non-zero vacuum, we also consider the usual concordance ΛCDM model where $\rho_\phi = 0$ and $\rho_{\rm de} = \Lambda$.

Let us briefly study the effect of adding a non-zero Λ in the DE sector to achieve higher H_0 keeping the early universe physics unchanged. As we are not interested in modifying the early-time cosmology around the recombination period, the sound horizon at recombination ($r_{\rm s}$) is unchanged. Moreover, the angular scale of the sound horizon (θ) can be inferred from the peak spacing in the oscillations of CMB temperature anisotropy. It is a very precisely measured quantity, fixed by the latest *Planck* measurement. θ is related to $r_{\rm s}$ as $\theta = \frac{r_s}{D_{\rm A}}$, where $D_{\rm A}$ is the angular diameter distance to the last scattering surface:

$$D_{\rm A} \propto \frac{1}{H_0(1+z*)} \int_0^{z*} \frac{{\rm d}z}{E(z)}, \tag{3}$$

where $z* \sim 1100$ is the redshift at recombination and $E(z) = [\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_{\rm de}(z)]$. Given that both $r_{\rm s}$ and θ are fixed, $D_{\rm A}$ is also fixed. Hence, in order to incorporate a larger value of H_0, keeping $D_{\rm A}$ fixed, the term $A(z*) = \int_0^{z*} \frac{{\rm d}z}{E(z)}$ has to be increased.

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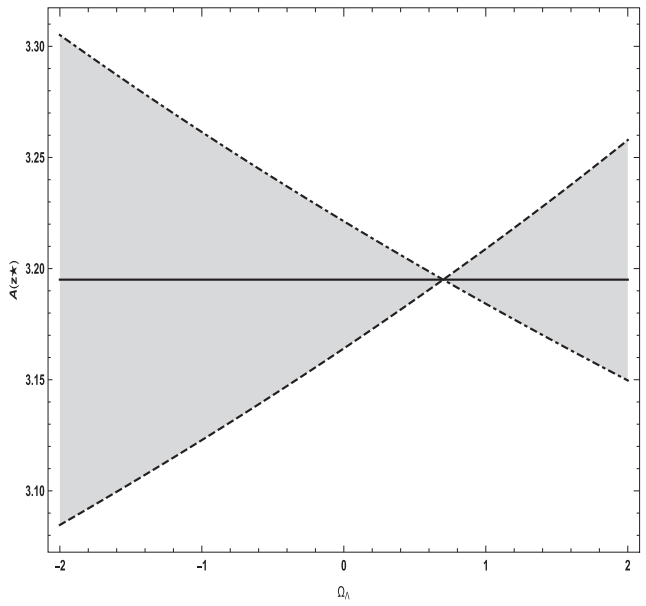


Figure 1. Variation $A(z*)$ versus Ω_Λ [see text for definition of $A(z*)$]. The solid line is for ΛCDM, the dashed line is for $w = -0.9$ (non-phantom), and the dot–dashed line is for $w = -1.1$ (phantom) models. We have fixed $\Omega_m = 0.3$.

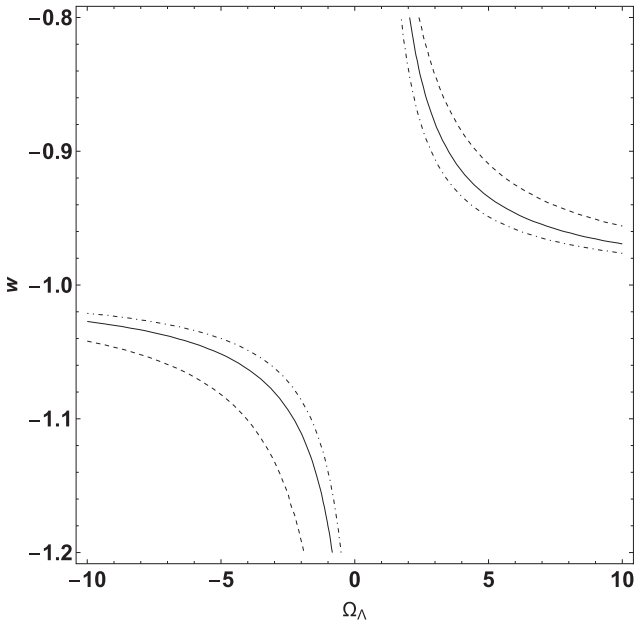


Figure 2. Ω_Λ versus w as described in the text. Solid line is for D_A at $z = 0.38$, dot–dashed line is for D_L at $z = 0.5$, and dotted line is for D_A at $z* = 1100$. Please see text for the explanation of these lines.

In Fig. 1, we show the variation of $A(z*)$ with Ω_Λ for the wCDMCC model assuming both non-phantom and phantom-type equation of state for the ρ_ϕ. For comparison, we also show the ΛCDM result. All the three model behaviours coincide at $\Omega_\Lambda = 0.7$ as expected (we ignore Ω_r and fix $\Omega_m = 0.3$ for these plots). It is also evident that with $\Omega_\Lambda = 0$, we always need phantom-type equation of state for the ρ_ϕ.

We assume $w = -1.1$ and -0.9 for phantom and non-phantom equations of state. For $-0.9 > w > -1.1$, all the lines will lie in the shaded region shown in Fig. 1, and for $-0.9 < w$ as well as $w < -1.2$, they will lie outside the shaded regions shown in Fig. 1.

As one can see in Fig. 1, the phantom model with both positive and negative Λ as well as non-phantom model with positive Λ give larger $A(z*)$ compared to ΛCDM. But the positive deviation from ΛCDM is larger for phantom models with negative Λ. In this regard, we want to mention that the same thing can happen for BAO measurements. Usually, BAO measurements are related as $\frac{r_d}{D_A}$, where r_d is the sound horizon at drag epoch and depends on the early Universe physics. D_A is the angular diameter distance to the redshift related to the BAO measurement. For a particular BAO measurement and for fixed r_d, D_A should be fixed and we again need a higher $A(z_{bao})$ for increased H_0, which can also be obtained in the similar way as mentioned above. So adding a negative Λ (in other words, a negative vacuum) in the DE component helps to achieve higher H_0 without changing the sound horizon at recombination (r_s) or at drag epoch (r_d).

In Fig. 2, we study the same thing in the w–Ω_Λ plane. We first consider three observables: D_A at last scattering ($z* = 1100$), D_A at one of the BAO measurements, e.g. at $z = 0.38$, and D_L, which is the luminosity distance related to SNIa observations at $z = 0.5$. We calculate these quantities using the ΛCDM model with $\Omega_m = 0.3$ and $H_0 = 67\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. Then in Fig. 2, we show the combinations of w–Ω_Λ that can reproduce the ΛCDM results but with $H_0 = 72\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. As one can see from the figure, there are two separate regions: one is phantom models with negative Λ and another is non-phantom models with positive Λ. For positive Ω_Λ, flatness condition plus the positivity of ρ_ϕ as well as ρ_m demand that $\Omega_\Lambda \leq 1$. And as one can see from Fig. 2, it is difficult to satisfy this constraint with the non-phantom equation of state. On the other hand, there is no such constraint for $\Omega_\Lambda < 0$. This confirms that adding a negative Λ or a AdS vacuum in the DE sector helps in achieving higher H_0 easily.

In the next sections, we study which region in the w–Ω_Λ parameter space, as shown in Fig. 2, is allowed by the combinations of CMB+BAO+SNIa+R21 data.

3 METHODOLOGY

In our analysis, we use the most recent and relevant observational results as follows:

(i) CMB data: We consider the recent CMB likelihood by the *Planck*-2018 Legacy release including the lensing likelihood. We use the *Planck*(2018)- TTTEEE+lowl-TT+lowl-EE+Lensing (Planck Collaboration et al. 2020a,b,c).

(ii) SNIa measurement: We consider the Pantheon sample of 1048 SNIa measurements of luminosity distance (Scolnic et al. 2018).

(iii) BAO observations: We also consider the BAO measurements by SDSS-MGS, BOSS-DR12 as well as 6dFGS collaborations (Beutler et al. 2011; Ross et al. 2015; Alam et al. 2017).

(iv) Finally, we consider the data $H_0 = 73.30 \pm 1.04\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ as measured by the SH0ES collaboration (R21).

We use publicly available CLASS code (Blas, Lesgourgues & Tram 2011) to compute the CMB temperature anisotropy spectra for the *Planck* likelihood. To constrain the cosmological models using the above set of observational data, we use the publicly available Markov Chain Monte Carlo (MCMC) sampling algorithm MONTEPYTHON (Audren et al. 2013; Brinckmann & Lesgourgues 2019) to generate the chains. We adopted the Gelman–Rubin convergence criteria $R - 1 < 0.02$ and subsequently use the GETDIST code (Lewis 2019) to analyse the chains.

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Table 1. Best-fitting, mean, and 1σ values of the parameters for the wCDMCC model.

Parameters	CMB	CMB+BAO	CMB+BAO+H_0
Ω_m	(0.215) $0.200^{+0.049}_{-0.068}$	(0.2956)0.304 ± 0.012	(0.2793)0.2791 ± 0.0065
H_0 (km s^{-1} Mpc^{-1})	(81.43)$87.2^{+9.6}_{-16}$	(69.6) $68.5^{+1.3}_{-1.5}$	(71.62)71.66 ± 0.85
$r_{\rm d}$	(147.2) 147.20 ± 0.38	(147)147.17 ± 0.22	(147)147.01 ± 0.22
σ_8	(0.936)$0.970^{+0.085}_{-0.11}$	(0.8335)0.818 ± 0.015	(0.8525)0.853 ± 0.011
$\tau_{\rm re}$	(0.05548)0.0550 ± 0.0025	(0.05494)0.0549 ± 0.0026	(0.05492)0.0541 ± 0.0026
Ω_ϕ	(6.63) $2.80^{+0.17}_{-2.3}$	(1.584)$1.86^{+0.46}_{-1.3}$	(1.539)$1.58^{+0.16}_{-0.87}$
w_0	$(-1.035) -1.47 \pm 0.51$	$(-1.034) - 1.017^{+0.030}_{-0.015}$	$(-1.061) - 1.072^{+0.037}_{-0.015}$
Ω_Λ	$(-5.845) - 2.00^{+2.5}_{-0.18}$	$(-0.8801) -1.17^{+1.3}_{-0.46}$	$(-0.8182) - 0.86^{+0.87}_{-0.16}$
$\Omega_{\rm de}$	(0.7849)$0.7999^{+0.068}_{-0.049}$	(0.7043) $0.6959^{+0.012}_{-0.012}$	(0.7206)$0.7208^{+0.0065}_{-0.0065}$

In our analysis, we only change the DE sector by incorporating non-zero vacua ($\Lambda \neq 0$) for the quintessence field and we do not vary the primordial power spectrum due to early inflationary era and hence keep the parameters n_s and A_s fixed at values as obtained by *Planck*-2018 (Planck Collaboration et al. 2020b). The main cosmological parameters are Ω_m, $r_{\rm d}$, H_0, σ_8, and $\tau_{\rm re}$, which are common for all three models. In addition to this, wCDMCC has two extra parameters w_0 and Ω_Λ and cplCDMCC has three extra parameters w_0, w_a, and Ω_Λ.

Regarding the priors for different parameters, we use the same priors already incorporated in the MONTEPYTHON code (Audren et al. 2013; Brinckmann & Lesgourgues 2019) while using the *Planck*-2018 likelihood for ΛCDM, wCDM, and CPL models. For the extra parameter due to the presence of Λ, we use the uniform prior for Ω_ϕ, [0.6, 4.5] and consider Ω_Λ as a derived parameter. Note that we have not assumed any prior for Λ to be negative as we need to study the Ω_Λ–w parameter space as shown in Fig. 2, which theoretically allows both positive and negative Ω_Λ. The lower limit for Ω_ϕ prior is chosen such that we always have sufficient scalar field energy density to accelerate the Universe. We want to stress that the acceleration of the Universe is due to slow rolling of the scalar field over its potential and it is sourced primarily by Ω_ϕ, which is always positive. The Ω_Λ contribution in $\Omega_{\rm de}$, as in equation (2), is due to non-zero minimum for the scalar field potential that can be positive or negative due to non-zero positive or negative minimum of the scalar field potential. Also, due to the assumption of spatial flatness, $\Omega_{\rm de} = 1 - \Omega_m - \Omega_r$ and hence is always positive.

4 RESULTS

To start with, we use the simplest wCDMCC model and study the effect of adding a non-zero vacuum in the scalar field DE through the addition of Ω_Λ and its effect on the measured value of the parameter H_0. First, we want to see whether for the wCDMCC model, the constraints on H_0 from CMB and CMB+BAO are consistent with the local H_0 measurement by R21. This is important for further adding the R21 H_0 data with CMB+BAO data.

As shown in Table 1, the CMB only constraint on H_0 is consistent with R21 measurement for H_0. Moreover, the best-fitting value for H_0 from CMB+BAO data combination is also consistent at around 2σ with the R21 constraint on H_0. This is already a substantial improvement from the ΛCDM model. Also for both CMB and CMB+BAO combinations, the best-fitting values for Ω_Λ are negative, confirming the consistency of the non-zero AdS vacuum for the DE. These allow us to add the R21 data for H_0 together with the CMB+BAO combination, which is shown in the last column of Table 1. It is evident that CMB+BAO+H_0 data are consistent with negative Ω_Λ, showing that DE with non-zero AdS vacuum is fully consistent with cosmological observations. Although we have a higher H_0, still the constraint on $r_{\rm d}$ is similar to the *Planck*-2018 constraint for the ΛCDM model showing that the early-time physics is unaffected.

Table 2. Evidence for the wCDMCC model for CMB+BAO+H_0 data.

Model	χ^2	AIC	ln($\mathcal{Z}$)	ΔAIC	**Δ ln($\mathcal{Z}$)**
ΛCDM	2803.04	2869.04	−1427.829	0	0
wCDMCC	2782.40	2852.40	−1420.259	−16.64	7.561

To compare the wCDMCC model with ΛCDM for CMB+BAO+H_0 data combination, we adopt the model comparison criteria based on the Akaike information criteria (AIC; Akaike 1974), which is defined as

$$\mathrm{AIC} = \chi^2_{\rm min} + 2k, \tag{4}$$

where $\chi^2_{\rm min}$ is the χ^2 value for the best-fitting parameters of the model and k is the number of model parameters. A model with lower AIC is preferred over a model with higher AIC. We also compute the 'Bayesian evidence' ($\mathcal{Z}$) or marginalized global likelihood for each model. We use the publicly available MCEVIDENCE package (Heavens et al. 2017) for this purpose. The quantity $\log \mathcal{Z}$ is an estimator to compare different models. The results are shown in Table 2. As shown in the table, for both the criteria, wCDMCC is decisively favoured over the ΛCDM model for CMB+BAO+H_0 data combination. This confirms that the local R21 measurement of H_0 when combined with CMB and BAO observations does signal the existence of a non-zero AdS vacuum (existence of a non-zero negative Λ) in the DE sector.

Next, we do similar analysis while adding the SNIa Pantheon data with CMB. The results are shown in Table 3. For CMB+SN, the best-fitting value for H_0 is consistent with the local R21 measurement at around 3σ, which is not as good as for CMB+BAO, but still there is substantial improvement from ΛCDM, which is at 5σ tension from the R21 result. We also show the constraints for CMB+BAO+SN data combination and the constraint on H_0 is similar to CMB+SN combination. For both combinations of data, the best-fitting value for Ω_Λ is negative, confirming that the CMB+BAO+SN also allow non-zero AdS vacuum for the DE (in other words, presence of a non-zero negative cosmological constant in the DE sector).

Going further, we finally consider all the data e.g. CMB+BAO+SN+H_0. It has been discussed in the literature that Pantheon SNIa data and local H_0 measurement may not be considered

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Table 3. Best-fitting, mean, and σ values of the parameters for the wCDMCC model.

Parameters	CMB+SN	CMB+SN+BAO
Ω_m	(0.3021)0.305 ± 0.010	(0.3045)0.3053 ± 0.0077
H_0 (km s^{-1} Mpc^{-1})	(68.77) 68.5 ± 1.1	(68.64)$68.39^{+0.79}_{-0.92}$
r_d	(147) 147.12 ± 0.22	(146.9)147.14 ± 0.21
σ_8	(0.8207)0.821 ± 0.011	(0.8252)$0.8185^{+0.0094}_{-0.011}$
τ_{re}	(0.05374)0.0543 ± 0.0026	(0.05455) 0.0547 ± 0.0025
Ω_ϕ	(0.8285)$1.91^{+0.22}_{-1.3}$	(2.703) $1.52^{+0.16}_{-0.91}$
w_0	(−1.031) − $1.016^{+0.020}_{-0.012}$	(−1.011) − $1.017^{+0.023}_{-0.012}$
Ω_Λ	(−0.1306) $-1.21^{+1.3}_{-0.22}$	(−2.008) − $0.83^{+0.92}_{-0.16}$
Ω_{de}	(0.6978)$0.6949^{+0.010}_{-0.010}$	(0.6954)$0.6946^{+0.0077}_{-0.0077}$
M_B	(−19.39) −19.402 ± 0.023	(−19.4) − 19.404 ± 0.018

together due to the dependence of the local H_0 measurement on the Pantheon measurements at redshifts within the Hubble flow (Camarena & Marra 2021). This is more important for models where the late time effects to increase H_0 are more prominent for $z < 0.02$ (Abdalla et al. 2022). An example of such models is hockey-stick DE model (Camarena & Marra 2021). In our case, we do not have such late transition in DE behaviour. Hence, we consider the full data combination to see how the constraints get affected. The results are shown in Table 4. In this case, we also consider the cplCDMCC model. For wCDMCC case, the results are similar to CMB+BAO+H_0 combination except that more negative values for Ω_Λ are allowed. The equation of state for the DE is slightly phantom. Moreover, the wCDMCC model allows larger contribution from negative Λ in the energy budget of the Universe compared to the cplCDMCC model. These results are similar to what obtained earlier by Visinelli et al (2019). Interestingly, with the inclusion of CMB+lensing data as well as the new R21 measurement for H_0, we get much stronger constraints on the lower limit of Ω_Λ compared to the results by Visinelli et al (2019). Moreover, the constraint on M_B for the ΛCDM model is 4.14σ away from the M_B prior corresponding to the SN measurements from SH0ES (Camarena & Marra 2021), whereas for wCDMCC, it is less than 3σ away from the SH0ES prior on M_B showing improvement over ΛCDM. [See Nunes & Valentino (2021) for similar results related to wCDM and interacting DE models.]

In Table 5, we show the χ^2_{min}, AIC, and ln(z) values for different models for 'ALL' data considered. As one can see, when compared with ΛCDM, both ΔAIC and Δln(z) decrease compared to CMB+BAO+H_0 combination. This is due to the addition of the SN data. But DE models with non-zero AdS vacuum still fare substantially better than the ΛCDM model.

For completeness, in Figs 3 and 4 we show the likelihood and contour plots for a few relevant parameters in different models. It is interesting to note from Fig. 4 that for wCDMCC, the shape of confidence contour in the w_0–Ω_Λ plane is consistent with what we show in Fig. 2 justifying our physical argument in Section 2.

Finally, we also use the absolute magnitude M_B prior instead of local H_0 prior in all data combination (Camarena & Marra 2021). The constraint on H_0 for wCDMCC case is $H_0 = 69.70^{+0.71}_{-0.80}$ km s^{-1} Mpc^{-1}. This is consistent with constraints on H_0 while using H_0 prior. In Fig. 5, we show the comparison between H_0 and M_B prior for constraints on model parameters e.g. Ω_Λ, w_0, and Ω_ϕ. It is evident that the results are almost identical, with M_B prior marginally favouring larger negative values for Ω_Λ.

The χ^2_{min}, AIC, and Bayesian evidence numbers for ΛCDM and wCDMCC models while using M_B prior are also shown in Table 6. The estimators like χ^2_{min} or AIC are similar to that for H_0 prior and hence the conclusions with H_0 prior still hold with M_B prior. In terms of the Bayesian evidence, ΛCDM and wCDMCC are equally consistent and none is preferred over the other. This also confirms that models with negative Λ (with AdS vacuum) are consistent with present cosmological observations with M_B prior as well.

5 FEW REMARKS ABOUT THE MODEL

As discussed in Section 2, we are considering DE models where the DE scalar field has non-zero vacuum. As shown in the results, the data prefer that this vacuum should be negative showing the existence of non-zero negative Λ in the DE sector. The total DE density $\Omega_{de} = \Omega_\phi + \Omega_\Lambda$ has the contribution from the scalar field DE density, which is Ω_ϕ, as well as from the negative Λ, which is Ω_Λ. This DE density Ω_{de} is positive at present as shown in Tables 1, 3, and 4. In Fig. 6, we also show the reconstructed evolution for ρ_{de} and $\rho_{de} + \rho_m$ for the CMB+BAO+H_0 combination for the wCDMCC model. As one sees, the ρ_{de} settles to a small negative value in the past and then increases to a positive value in late times to give the necessary contribution for the DE. This negative ρ_{de} behaviour in the past is consistent with earlier studies by Bonilla, Kumar & Nunes (2021). But the total contribution $\rho_m + \rho_{de}$ is always positive, ruling out any possible collapsing scenario in the past.

The behaviour for ρ_{de} can also lead to another interesting feature for models with AdS vacuum as considered here. Let us consider the conservation equation for ρ_{de}: $\rho'_{de} = 3(1 + w_{de})\rho_{de}/(1 + z)$, where 'prime' denotes the differentiation with respect to the redshift z. As shown in Fig. 6, ρ_{de} is a decreasing function with redshift z. Hence $\rho'_{de} < 0$. In the early time, $\rho_{de} < 0$, hence $(1 + w_{de}) > 0$ resulting in a non-phantom equation of state for DE sector, whereas at late times, $\rho_{de} > 0$, hence $(1 + w_{de}) < 0$ resulting in a phantom equation of state for the DE sector. This shows that the DE sector has a non-phantom-to-phantom transition as the Universe evolves. Hence, adding a negative cosmological constant in the DE sector can result in phantom crossing. This may be the simplest way to incorporate phantom crossing in the DE equation of state.

One should note that ours is a toy model for DE where we model ω_ϕ using simple equation of state parametrization. This results in a phantom equation of state for the ρ_{de} as constrained by the observational data. One can have a more realistic scenario constructed under string theory (Visinelli et al. 2019) where there may be multiple light bosonic degrees of freedom on top of a stable AdS vacua (Guo et al. 2005; Hu 2005; Saridakis & Weller 2010). An example of such scenario is string axiverse where we have multiple moduli fields related to the shapes and sizes of the extra dimensions (Svrcek & Witten 2006; Arvanitaki et al. 2010; Cicoli, Goodsell & Ringwald 2012; Visinelli 2017). The dynamics of these multiple scalar fields can give rise to an effective phantom equation of state for the DE sector that results in the ρ_{de} behaviour as shown in Fig. 6. But as the fields settle at the AdS ground state in future, the Universe will end up in an asymptotically AdS phase. The future Universe for such a scenario with negative energy density in future has recently been studied in an interesting paper by Andrei, Ijjas & Steinhardt (2022).

6 CONCLUSIONS

Although consistent with most of the cosmological observations, the ΛCDM model has always been a challenge for theoreticians because

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Table 4. Constraints (best fit, mean, and 1σ error bar) on cosmological and model parameters for the combined data CMB+BAO+Pantheon+R21.

Parameters	ΛCDM	wCDMCC	cplCDMCC
Ω_m	$(0.3033)0.3043^{+0.0039}_{-0.0042}$	$(0.287)0.288^{+0.0063}_{-0.0071}$	$(0.292)0.289^{+0.0055}_{-0.0061}$
H_0 (km s^{-1} Mpc^{-1})	$(68.32)68.2^{+0.31}_{-0.32}$	$(70.34)70.32^{+0.82}_{-0.77}$	$(69.89)70.25^{+0.67}_{-0.69}$
$r_{\rm d}$	$(147.2)147.3^{+0.2}_{-0.22}$	$(147.3)147.1^{+0.21}_{-0.22}$	$(147.2)147.1^{+0.2}_{-0.21}$
σ_8	$(0.804)0.805^{+0.0026}_{-0.0026}$	$(0.833)0.834^{+0.0096}_{-0.0097}$	$(0.835)0.835^{+0.0086}_{-0.0088}$
$\tau_{\rm re}$	$(0.0548)0.0556^{+0.0025}_{-0.0026}$	$(0.0554)0.0547^{+0.0028}_{-0.0025}$	$(0.0542)0.0547^{+0.0026}_{-0.0027}$
Ω_ϕ	–	$(3.191)\,2.504^{+0.28}_{-1.9}$	$(1.206)\,1.492^{+0.025}_{-0.84}$
Ω_Λ	–	$(-2.479)-1.792^{+1.90}_{-0.29}$	$(-0.498)-0.781^{+0.85}_{-0.03}$
$\Omega_{\rm de}$	$(0.6966)0.6956^{+0.0042}_{-0.0039}$	$(0.7129)0.7119^{+0.0071}_{-0.0063}$	$(0.7079)0.7109^{+0.0061}_{-0.0055}$
$\boldsymbol{w}_0$	–	$(-1.02)-1.04^{+0.035}_{-0.013}$	$(-1.02)-1.03^{+0.051}_{-0.039}$
$\boldsymbol{w}_a$	–	–	$(-0.12)-0.10^{+0.20}_{-0.14}$
M_B	$(-19.401)-19.404^{+0.00929}_{-0.00921}$	$(-19.362)-19.363^{+0.0150}_{-0.0151}$	$(-19.366)-19.360^{+0.0166}_{-0.0168}$

Table 5. Evidences of different models for all data.

Model	χ^2	AIC	$\ln(z)$	ΔAIC	$\Delta\ln(z)$
ΛCDM	3835.73	3901.73	−1944.75	0	0
wCDMCC	3823.58	3893.58	−1940.96	−8.15	+3.79
cplCDMCC	3824.29	3896.29	−1942.82	−5.44	+1.93

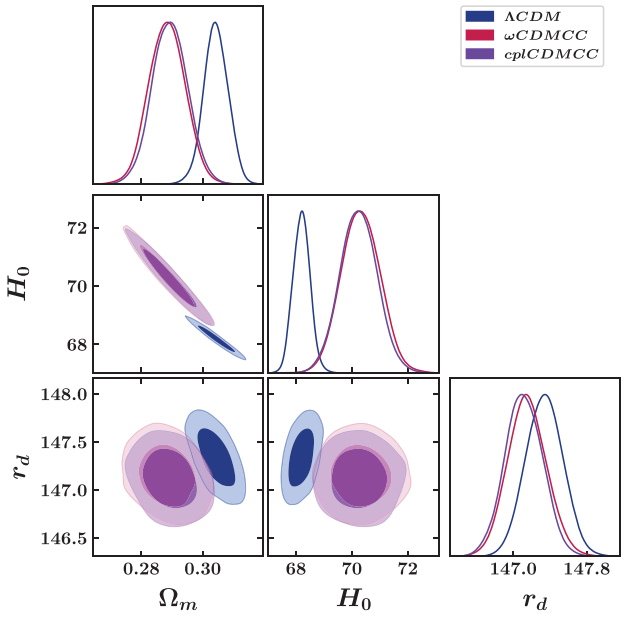


Figure 3. Combined likelihood and contour plots (68 per cent and 95 per cent) of different models for CMB+Pantheon+BAO+R21 data combination.

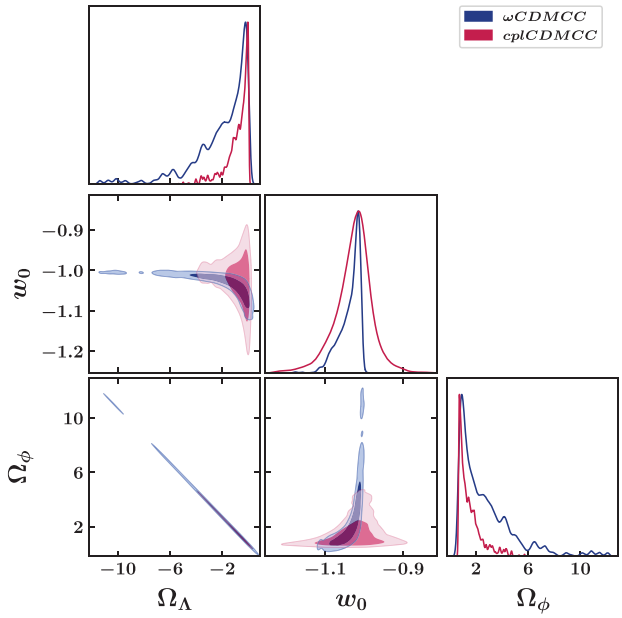


Figure 4. Combined likelihood and contour plots (68 per cent and 95 per cent) of different models for CMB+Pantheon+BAO+R21 data combination.

of the presence of a dS vacua. It is difficult to construct in string theory and the recent swampland conjecture put it in tight spot. But with current 5σ inconsistency between the local measurement of H_0 by SH0ES (R21) and that by *Planck* using CMB, the ΛCDM model seems to fall from its preferred position in terms of observational consistency and this has opened up the opportunity to revisit the quintessence models and to consider DE models with AdS vacua, which are more natural in string theory. As already mentioned in the introduction, the goal of this study is not to solve the H_0 tension with the introduction of AdS vacua in the DE sector, rather to see whether DE with AdS vacua is consistent with cosmological observation including the local R21 measurement of H_0.

In our study, we parametrize the quintessence models with two most widely used DE representations in the literature and add a non-zero vacua (in terms of a Λ that can be either positive or negative) and use the CMB likelihood, the latest H_0 measurement (R21) as well as the Pantheon and BAO data to constrain the parameter space as well as compare such models with ΛCDM.

For wCDMCC, both CMB and CMB+BAO data result in substantial increase in the constraints for H_0, decreasing the tension with the local R21 measurement to around 2σ. This allows us to add the local measurement of H_0 (R21) to CMB+BAO. The combined

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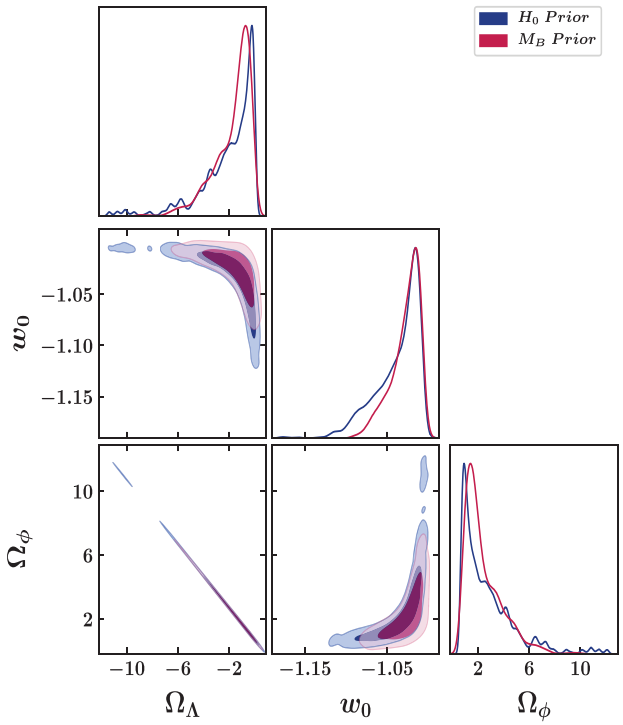


Figure 5. Same as Fig. 4 but with M_B prior.

Table 6. $\chi^2_{\rm min}$, ΔAIC, and Bayesian evidences for ΛCDM and wCDMCC for CMB+Lensing+Pantheon+BAO+M_B data combination.

Model	$\chi^2_{\rm min}$	ΔAIC	$\log(\mathcal{Z})$
ΛCDM	3833	–	−1941.97
wCDMCC	3824	−5.0	−1942.04

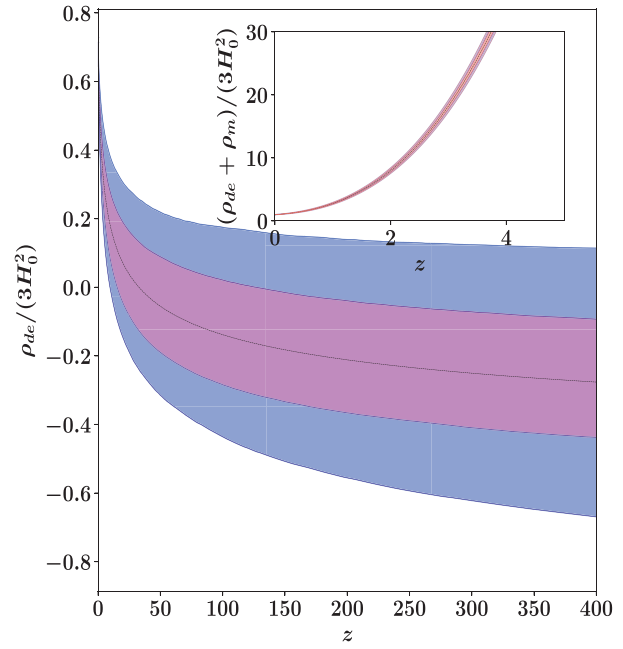


Figure 6. Reconstruction of $\rho_{\rm de}/3H_0^2$ and $(\rho_{\rm de}+\rho_m)/3H_0^2$.

CMB+BAO+H_0 data show that the wCDMCC model is decisively favoured over ΛCDM, confirming the consistency of the presence of AdS vacua (in terms of negative Λ) in the DE sector with the cosmological data. Interestingly, the constraint on $r_{\rm d}$ parameter is completely consistent with the *Planck*-2018 constraint for ΛCDM showing that the early Universe physics is unaffected.

Adding SN Pantheon data with CMB, we get a H_0 constraint that is within 3σ from the local R21 result. This is not as good as the result for the CMB+BAO combination but still much better than the 5σ tension in the ΛCDM model. With this, we consider the full data combination CMB+BAO+H_0+SN and show that models with AdS vacuum for the DE sector are consistent with the cosmological observations and are favoured over the ΛCDM model.

In 1998, the SNIa observations surprised us with the confirmation of an accelerating Universe and the presence of DE. Again, after two decades, low-redshift SNIa observations give us the H_0 measurement that is in 5σ conflict with *Planck* results assuming the ΛCDM model, the 'holy grail' for cosmologists. This has the potential to reveal another surprising aspect of our Universe. Can it be the presence of a negative Λ in our Universe? We show that this may indeed be true. This can have far-reaching implications in DE model building, especially while addressing the different cosmological tensions in the realm of string theory. Our results can be potentially the first cosmological signature of an aspect of string theory, namely the existence of a negative Λ. Moreover, as the Universe is asymptotically AdS, one can have interesting consequences related to the future light-cone structure of the Universe. This can open up many interesting directions for future research.

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DATA AVAILABILITY

The data that support the findings of this study are available upon reasonable request.

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