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New insights on a sign-switching Λ

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ABSTRACT

The proposal for a sudden sign-switching cosmological constant Λ in the local universe, emulating a phase transition from anti-de Sitter (AdS) to de Sitter (dS) space, has markedly revamped the fit to observational data and lays out a propitious framework for ameliorating major cosmological tensions, such as the H_0 and S_8 tensions. This proposal is widely known as Λ_sCDM. We investigate the possibility that Λ does not only flip sign at the transition but has also different curvature radii in the AdS and dS phases. We show that the critical redshift of the transition z_c is strongly correlated with the vacuum energy in the AdS phase Ω_{Λ_-}, and that these two variables do not correlate strongly with the other cosmological parameters. We also show that the cost of adding an additional parameter to the Λ_sCDM cosmological model does not improve the goodness of fit. Armed with our findings, we demonstrate that for a proper choice of z_c, the vacuum energy in the dS phase may not necessarily be $-\Omega_{\Lambda_-}$, for comparable degree of conformity between the model prediction and experimental data.

1. Introduction

Λ cold dark matter (ΛCDM) has proven incredibly successful at describing many features of cosmology that we observe in our experiments [7]. The most famous example, arguably, is the agreement with data from the cosmic microwave background (CMB) [8]. Yet, with the increase in precision of cosmological observations over the past decade, this success has been challenged. Two of the most compelling shortcomings of ΛCDM are its predictions of the present-day expansion rate H_0 and the amplitude of the matter clustering in the late Universe (parameterized by S_8) [9]. Strictly speaking, the values $H_0 = 67.4 \pm 0.5$ km/s/Mpc and $S_8 = 0.834 \pm 0.016$ inferred from *Planck*'s CMB data assuming ΛCDM [8] are in $\sim 5\sigma$ tension with $H_0 = 73.04 \pm 1.04$ km/s/Mpc from the SH0ES distance ladder measurement (using Cepheid-calibrated type-Ia supernovae) [10,11] and in $\sim 3\sigma$ tension with $S_8 = 0.766^{+0.020}_{-0.014}$ from the cosmic shear data of the Kilo-Degree Survey (KiDS-1000) [12], respectively. Systematic effects do not seem to be responsible for these discrepancies (see e.g. [13]), which have become a new cornerstone of theoretical physics. Naturally, many new physics setups are rising to the challenge [14–17].

Λ_sCDM [18–21] is one of the many new physics setups that have been proposed to simultaneously accommodate the H_0 and S_8 tensions.[1] The setup relies on an empirical conjecture which postulates that Λ may have switched sign (from negative to positive) at critical redshift $z_c \sim 2$;

$$\Lambda \quad \to \quad \Lambda_s \equiv \Lambda_0 \, \mathrm{sgn}(z_c - z), \tag{1.1}$$

with $\Lambda_0 > 0$, and where $\mathrm{sgn}(x) = -1, 0, 1$ for $x < 0$, $x = 0$ and $x > 0$, respectively. Apart from resolving the three major cosmological tensions, Λ_sCDM achieves quite a good fit to Lyman-α data provided $z_c \lesssim 2.3$ [18], and it is in agreement with the otherwise puzzling JWST observations [22,23].

The colossal success of Λ_sCDM in accommodating observations of baryon acoustic oscillations (BAO) is in effect contingent on the (angular) transversal two dimensional (2D) BAO data on the shell, which are less model dependent than the 3D BAO data. This is because the 3D BAO data sample relies on ΛCDM to determine the distance to the spherical shell, and hence could potentially introduce a bias when analyzing cosmological scenarios beyond ΛCDM [24,25]. Indeed, by using 2D BAO data the actual SH0ES H_0 measurement and the angular diameter distance to the last scattering surface can be simultaneously accommodated, but at the expense of having an effective negative energy density for $z \gtrsim 2$.

Another caveat associated to Λ_sCDM is that the instantaneous transition of the vacuum energy density, which is governed by the signum

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[1] For related works, see [1–4]. An alternative model that simultaneously addresses H_0 and S_8 is discussed in [5,6].

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function, gives rise to a hidden sudden singularity at z_c [26]. Note that the scale factor a of Λ_sCDM is continuous and non-zero at the critical time $t = t_c$, but its first derivative $\dot{a}$ is discontinuous, and its second derivative $\ddot{a}$ diverges. However, the sudden singularity yields a minimal impact on the formation and evolution of cosmic bound structures, thereby preserving the viability of Λ_sCDM [27].

The changeover of Λ at z_c can be interpreted as a phase transition between anti-de Sitter (AdS) and (dS) spaces, because n-dimensional dS and AdS spaces can be regarded as solutions of Einstein's field equations of empty spaces with cosmological constant

$$\Lambda = (n-2)R_i/(2n)\,, \tag{1.2}$$

where $i = \{\mathrm{dS}_n, \mathrm{AdS}_n\}$, $R_{\mathrm{dS}_n} = n(n-1)/\ell^2_{\mathrm{dS}_n}$ and $R_{\mathrm{AdS}_n} = -n(n-1)/\ell^2_{\mathrm{AdS}_n}$ are respectively the dS and AdS Ricci scalars, and ℓ_i is the radius of curvature [28].

The essence of the instantaneous sign-switching cosmological constant posits a challenging puzzle in identifying a concrete theoretical model able to accommodate the AdS → dS transition. The puzzle is actually exacerbated by the AdS distance conjecture, which states that there is an arbitrarily large distance between AdS and dS vacua in metric space [29]. Having said that, the phenomenological success of Λ_sCDM, despite its simplistic structure, provides robust motivation to search for possible underlying physical mechanisms to describe the conjectured AdS → dS transition. Many theoretical realizations have been proposed [30–39]. Motivated by the phenomenological success of Λ_sCDM, in this paper we investigate the possibility that Λ does not only flip sign at the transition but has also different curvature radii in the AdS and dS phases. In plain English, the AdS radius ℓ_{AdS_4} characterized by Λ_- and the dS radius ℓ_{dS_4} characterized by Λ_+ satisfy $|\Lambda_-| \neq |\Lambda_+|$.

The layout of the paper is as follows. In Section 2 we introduce the cosmological parameters explored in this work. In Section 3 we describe the analysis method and the observational datasets/likelihoods used to constrain the cosmological parameters. After that we implement the numerical computations, present our results, and discuss their implications. The paper wraps up in Section 4 with some conclusions.

2. Cosmological parameters

There are two basic hypotheses in modern cosmology: *(i)* the assumption of the validity of General Relativity and *(ii)* the cosmological principle, which is the assumption that the universe on cosmological scales is homogeneous an isotropic. Together, these two hypotheses set constraints on the four-dimensional spacetime metric, which reduces to the maximally-symmetric Friedmann–Lamaître–Robertson–Walker line element

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\phi\, d\phi^2)\right], \tag{2.1}$$

where (t, r, θ, ϕ) are co-moving coordinates, $k(= -1, 0, 1)$ parametrizes the curvature of the homogeneous and isotropic spatial sections, and $a(t)$ is the cosmic scale factor, which is related to the redshift z by $a = 1/(1+z)$ [40]. Observations favor a spatially flat ($k = 0$) universe [7]. The expansion rate of the Universe is measured by the Hubble parameter,

$$H = \frac{\dot{a}}{a}\,, \tag{2.2}$$

and its present-day value is known as the Hubble constant $H_0 = 100\,h$ km/Mpc/s, with $0 < h < 1$ [41].

The widely accepted spatially-flat ΛCDM model requires only 6 independent parameters

$$\mathcal{P}_{\Lambda\mathrm{CDM}} = \{\omega_b,\, \omega_{cdm},\, \theta_s,\, \tau_{\mathrm{reio}},\, n_s,\, A_s\}\,, \tag{2.3}$$

to completely specify the cosmological evolution, where $\omega_b \equiv \Omega_b h^2$ is the baryon density, $\omega_{cdm} \equiv \Omega_c h^2$ is the CDM density, θ_s is the angular size of the sound horizon at recombination, τ_{reio} is the Thomson scattering optical depth due to reionization, n_s is the scalar spectral index, and A_s is the power spectrum amplitude of adiabatic scalar perturbations. The Ω_i parameters are defined as the ratio of the present day mean density of each component i to the critical density; by definition $\sum_i \Omega_i = 1$. Neglecting smaller order terms, $\Omega_c + \Omega_b + \Omega_\Lambda \sim 1$.

The specific set of six parameters used to define the cosmological model is somewhat open to choice. Within the context of fitting a ΛCDM model to a CMB power spectrum, the six selected key parameters are primarily chosen to avoid degeneracies and thus speed convergence of the model fit to the data [42–44]. Other interesting parameters providing additional physical insight may be derived from the model once the defining six parameters have been set. These include:

- The present-day expansion rate H_0.
- The amplitude of the matter clustering in the late universe, parameterized by

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}, \tag{2.4}$$

  where σ_8 is the root mean square of the amplitude of matter perturbations smoothed over 8 h^{-1}Mpc and $\Omega_m = \Omega_c + \Omega_b$ is the non-relativistic matter density.
- The effective number of relativistic neutrino-like species N_{eff} is a convenient parametrization of the relativistic energy density of the universe beyond that of photons, in units of the density of a single Weyl neutrino species [45]. Using conservation of entropy, fully thermalized relics with g_* degrees of freedom contribute

$$N_{\mathrm{eff}} = 3.043 + g_* \left(\frac{43}{4g_s}\right)^{4/3} \begin{cases} 4/7 & \text{for bosons} \\ 1/2 & \text{for fermions} \end{cases}, \tag{2.5}$$

  where 3.043 is the standard-model benchmark [46] and g_s denotes the effective degrees of freedom for the entropy of the other thermalized relativistic species that are present when they decouple [47].[2]

Herein, we aim to explore possible deviations from ΛCDM. To quantitatively assess these deviations we study the Λ_sCDM 7-parameter model,

$$\mathcal{P}_{\Lambda_s\mathrm{CDM}} = \{\omega_b,\, \omega_{cdm},\, \theta_s,\, \tau_{\mathrm{reio}},\, n_s,\, A_s,\, z_c\}\,, \tag{2.6}$$

and the $\Lambda_\mp$CDM 8-parameter model

$$\mathcal{P}_{\Lambda_\mp\mathrm{CDM}} = \{\omega_b,\, \omega_{cdm},\, \theta_s,\, \tau_{\mathrm{reio}},\, n_s,\, A_s,\, z_c,\, \Omega_{\Lambda_-}\}\,. \tag{2.7}$$

As might be expected, for both these models the first six parameters are common ones with ΛCDM.

Before proceeding, we pause to mention additional, non-cosmological parameters that are included in the model. First, there are 53 nuisance parameters needed to characterize the Planck and KiDS-1000 likelihoods, described in the next section. More importantly, the absolute magnitude of type Ia supernovae M_B (needed for the Pantheon+ likelihood; see next section), must be considered too. It has been suggested that the H_0 tension is actually a tension on M_B [54,55], because the base ΛCDM cosmology inferred from *Planck* leads to $M_B = -19.401 \pm 0.027$ mag [56], whereas the SH0ES Cepheid photometry and Pantheon supernova peak magnitudes yield $M_B = -19.244 \pm 0.037$ mag [55]. It has been shown that Λ_sCDM cosmology provides a robust solution to the M_B tension [21].

We consider two scenarios with $N_{\mathrm{eff}} = 3.043$ and $N_{\mathrm{eff}} = 3.294$. The latter characterizes a model that explains the AdS → dS transition using the contribution to the Casimir energy of fields (the graviton, a real scalar, and three right-handed neutrinos) propagating in the bulk of a five-dimensional spacetime [30]. The scalar field has a potential holding two local minima with very small difference in vacuum energy and bigger curvature (mass) of the lower one, and thus when the false

[2] We adopt the most recent NLO calculation of N_{eff} in the standard model [46], which yields a reduction from previous estimates [48–53].

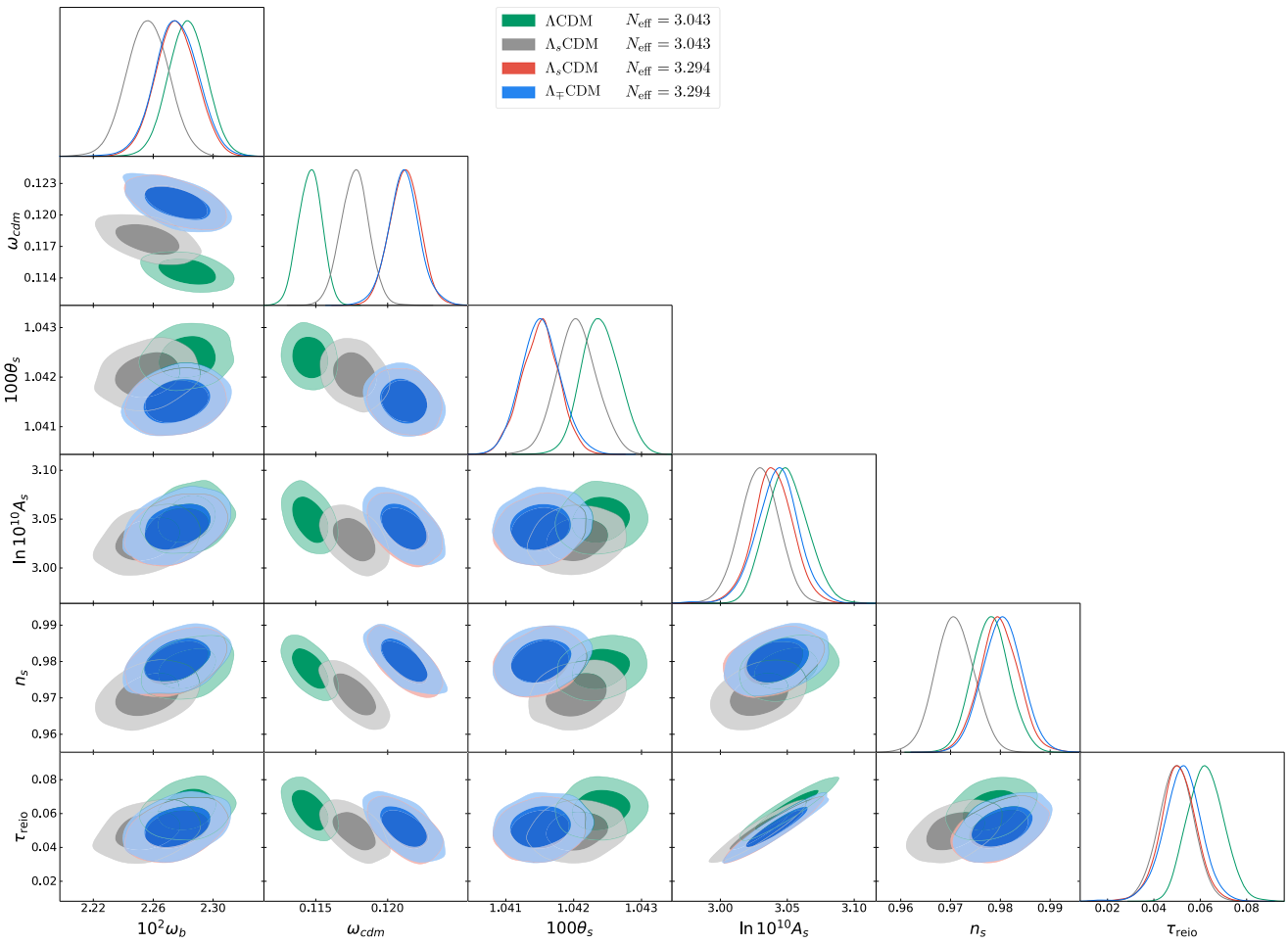

Fig. 1. Triangle plot showing two-dimensional contours at 68% and 95% CL and one-dimensional posterior probability distribution functions of the six parameters which are common to ΛCDM, Λ_sCDM, and $\Lambda_\mp$CDM.

vacuum tunnels to its true vacuum state, the field becomes more massive and its contribution to the Casimir energy becomes exponentially suppressed [37]. The tunneling process then changes the difference between the total number of fermionic and bosonic degrees of freedom contributing to the quantum corrections of the vacuum energy in a way that leads to a sign-switching cosmological constant at $z_c \sim 2$.

3. Statistical methodology, observational data, and numerical analysis

We adopt the Markov Chain Monte Carlo (MCMC) technique. A (discrete-time) Markov chain with (finite or countable) state space $\mathscr{X}$ consists of a sequence $X_0, X_1, \ldots$ of $\mathscr{X}$-valued random variables such that for all states $i, j, k_0, k_1 \cdots$ and all times $n = 0, 1, 2, \ldots$,

$$P(X_{n+1} = j \parallel X_n = i, X_{n-1} = k_{n-1}, \ldots) = p(i, j) \tag{3.1}$$

where $p(i, j)$ depends only on the states i, j, and not on the time n or the previous states $k_{n-1}, k_{n-2}, \ldots$. The numbers $p(i, j)$ are called the transition probabilities of the chain. Note that each number is stochastically obtained from the previous number without explicitly being dependent on it. In our analysis the states of a chain consist on specific values of the free parameters in a given cosmological model.

To run the MCMC we adopt the `MontePython` code, which interfaces with the Cosmic Linear Anisotropy Solving System `CLASS` [57–59]. To explore the full parameter space of the models characterized by (2.6) and (2.7) we have modified `CLASS` to introduce the possibility of an AdS → dS transition. We derive constraints on the cosmological parameters of these two models and ΛCDM from data-sets and likelihoods given below using the Metropolis–Hastings algorithm [60], while enforcing the so-called Gelman–Rubin convergence criterion of $R-1 < 10^{-2}$ in all the runs [61]. We make use of a series of astrophysical and cosmological probes to construct our reference dataset:

- **2018 Planck CMB data**: The CMB temperature, polarization, and lensing angular power spectra from the *Planck* 2018 legacy release [8,62].
- **Transversal BAO**: Measurements of 2D baryon acoustic oscillations (BAO), $\theta_{\rm BAO}(z)$, obtained in a weakly model-dependent approach, and compiled in Table I of [63].
- **Pantheon+**: The 1701 light curves of 1550 distinct supernovae type Ia, which are distributed in the redshift interval $0.001 \leq z \leq 2.26$ [64]. We incorporate the most recent SH0ES Cepheid host distance anchors [10] into the likelihood function by integrating distance modulus measurements of the Pantheon+ supernovae.
- **Cosmic Shear**: KiDS-1000 data [65,66], including the weak lensing two-point statistics data for both the auto and cross-correlations across five tomographic redshift bins [67]. We follow the KiDS team analysis and adopt the COSEBIs (Complete Orthogonal Sets of E/B-Integrals) likelihood [68]. Non-linearities are implemented into the analysis using `HALOFIT` [69,70].[3]

[3] This implementation comes up with a difference to the data analysis carried out in [21] (which was executed using the `HMcode` [71]), but such a difference leads to (almost) negligible effects in the results.

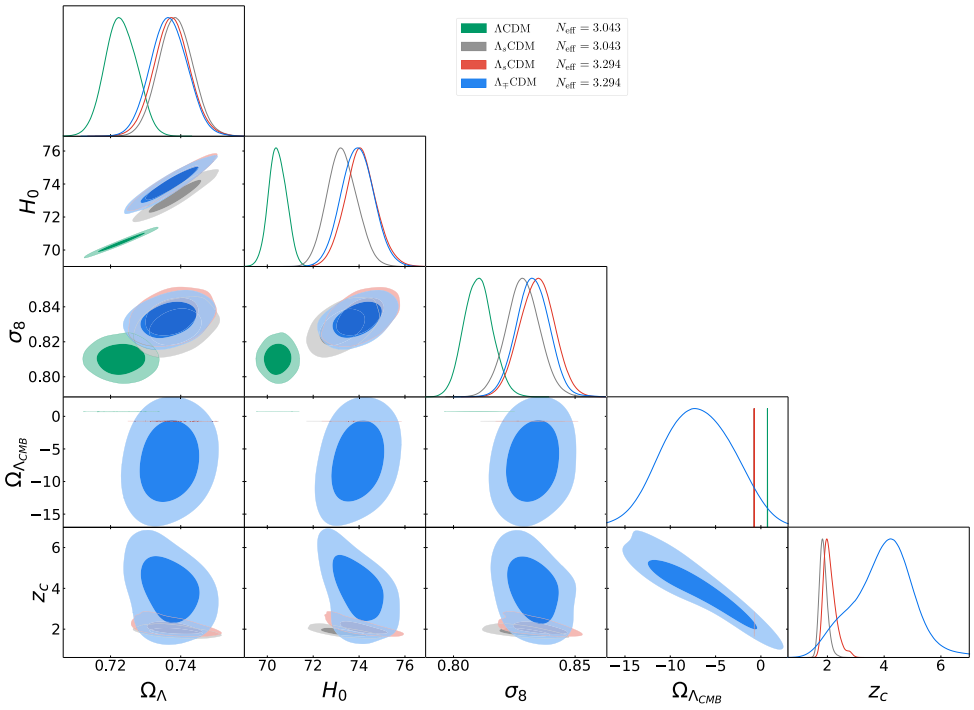

Fig. 2. Triangle plot showing two-dimensional contours at 68% and 95% CL and one-dimensional posterior probability distribution functions of H_0, σ_8, Ω_Λ, and $\Omega_{\Lambda_{\rm CMB}}$ for ΛCDM, Λ_sCDM, and $\Lambda_\mp$CDM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Marginalized constraints, mean values with 68% CL (95% CL), on the free and some derived parameters of the ΛCDM, Λ_sCDM and $\Lambda_\mp$CDM models for different values of ($N_{\rm eff}$).

Model	ΛCDM(3.043)	Λ_sCDM(3.043)	Λ_sCDM(3.294)	$\Lambda_\mp$CDM(3.294)
$10^2\omega_{\rm b}$	$2.283\ ^{0.013}_{0.013}\ (^{0.024}_{0.025})$	$2.256\ ^{0.014}_{0.014}\ (^{0.028}_{0.028})$	$2.275\ ^{0.014}_{0.014}\ (^{0.027}_{0.027})$	$2.276\ ^{0.014}_{0.014}\ (^{0.028}_{0.029})$
$\omega_{\rm cdm}$	$0.1146\ ^{0.0008}_{0.00083}\ (^{0.00151}_{0.00154})$	$0.11771\ ^{0.00093}_{0.00099}\ (^{0.0019}_{0.00197})$	$0.1212\ ^{0.001}_{0.0011}\ (^{0.002}_{0.002})$	$0.1211\ ^{0.001}_{0.0011}\ (^{0.0023}_{0.0022})$
$100\theta_s$	$1.0424\ ^{0.00026}_{0.0003}\ (^{0.00055}_{0.00052})$	$1.04204\ ^{0.0003}_{0.00029}\ (^{0.0006}_{0.00056})$	$1.04151\ ^{0.00027}_{0.00029}\ (^{0.00054}_{0.00056})$	$1.04152\ ^{0.00029}_{0.00029}\ (^{0.0006}_{0.00056})$
$\ln 10^{10} A_s$	$3.05\ ^{0.015}_{0.016}\ (^{0.03}_{0.029})$	$3.029\ ^{0.015}_{0.014}\ (^{0.028}_{0.03})$	$3.039\ ^{0.015}_{0.014}\ (^{0.029}_{0.03})$	$3.042\ ^{0.016}_{0.015}\ (^{0.032}_{0.033})$
n_s	$0.9781\ ^{0.0035}_{0.0037}\ (^{0.0074}_{0.007})$	$0.9708\ ^{0.0039}_{0.0039}\ (^{0.0076}_{0.0076})$	$0.9798\ ^{0.004}_{0.0037}\ (^{0.0078}_{0.0076})$	$0.9804\ ^{0.0039}_{0.004}\ (^{0.0077}_{0.0077})$
$\tau_{\rm reio}$	$0.0624\ ^{0.0077}_{0.0082}\ (^{0.0151}_{0.0149})$	$0.0496\ ^{0.0074}_{0.0073}\ (^{0.0144}_{0.0155})$	$0.0505\ ^{0.0075}_{0.007}\ (^{0.0152}_{0.0158})$	$0.0521\ ^{0.0083}_{0.0075}\ (^{0.0159}_{0.0177})$
Ω_Λ	$0.723\ ^{0.0047}_{0.0045}\ (^{0.0085}_{0.0085})$	$0.7386\ ^{0.0048}_{0.0048}\ (^{0.0096}_{0.0095})$	$0.7375\ ^{0.0051}_{0.0049}\ (^{0.0103}_{0.01})$	$0.7367\ ^{0.0053}_{0.0051}\ (^{0.0102}_{0.0101})$
$\Omega_{\Lambda_{\rm CMB}}$	$0.723\ ^{0.0047}_{0.0045}\ (^{0.0085}_{0.0085})$	$-0.7386\ ^{0.0048}_{0.0049}\ (^{0.0095}_{0.0096})$	$-0.7375\ ^{0.0049}_{0.0051}\ (^{0.01}_{0.0103})$	$-6.9\ ^{3.9}_{4.}\ (^{6.5}_{6.3})$
z_c	–	$1.86\ ^{0.11}_{0.16}\ (^{0.3}_{0.27})$	$2.09\ ^{0.14}_{0.26}\ (^{0.49}_{0.39})$	$4.\ ^{1.12}_{0.96}\ (^{1.97}_{2.35})$
M_B [mag]	$-19.356\ ^{0.01}_{0.011}\ (^{0.021}_{0.021})$	$-19.279\ ^{0.017}_{0.018}\ (^{0.034}_{0.033})$	$-19.256\ ^{0.018}_{0.018}\ (^{0.037}_{0.035})$	$-19.26\ ^{0.018}_{0.019}\ (^{0.037}_{0.037})$
H_0 [km/s/Mpc]	$70.45\ ^{0.38}_{0.4}\ (^{0.77}_{0.76})$	$73.26\ ^{0.62}_{0.68}\ (^{1.31}_{1.24})$	$74.07\ ^{0.68}_{0.68}\ (^{1.43}_{1.31})$	$73.93\ ^{0.69}_{0.69}\ (^{1.42}_{1.39})$
σ_8	$0.8102\ ^{0.0055}_{0.0062}\ (^{0.0119}_{0.0111})$	$0.8286\ ^{0.0069}_{0.0068}\ (^{0.0139}_{0.0138})$	$0.8344\ ^{0.0069}_{0.0072}\ (^{0.0137}_{0.014})$	$0.8326\ ^{0.0066}_{0.0065}\ (^{0.0131}_{0.0133})$

Our results are encapsulated in Figs. 1 and 2, and Table 1. There, for the sake of compactness, Ω_Λ has its standard meaning for ΛCDM and Λ_sCDM, and it is Ω_{Λ_+} for $\Lambda_\mp$CDM. Similarly, $\Omega_{\Lambda_{\rm CMB}}$ stands for Ω_Λ in ΛCDM, for $-\Omega_\Lambda$ in Λ_sCDM, and for Ω_{Λ_-} in $\Lambda_\mp$CDM. For this reason,some of these parameters are not independent from each other (that is, they are 100% correlated), making some of the numbers in Table 1 redundant.

It is straightforward to see that the fitted parameters of Λ_sCDM and $\Lambda_\mp$CDM are all consistent with each other at 95%CL, independent of the value of $N_{\rm eff}$. Moreover, for $N_{\rm eff} = 3.294$, they are effectively indistinguishable in regards to the six base parameters, as well as the derived H_0 and σ_8. This implies that scenarios with $N_{\rm eff} = 3.294$ can simultaneously resolved the H_0 and S_8 tensions. For ΛCDM, we find $\chi^2_{\rm min} = 4224.7$. For Λ_sCDM, the goodness of fit always improves with respect to ΛCDM; namely, if $N_{\rm eff} = 3.043$ we find $\chi^2_{\rm min} = 4192.08$, whereas if $N_{\rm eff} = 3.294$ we find $\chi^2_{\rm min} = 4195.94$.[4] On the other hand, while there is an improvement in the chi-squared fit of $\Lambda_\mp$CDM when compared to ΛCDM, there is no improvement in the $\chi^2_{\rm min}$ when $\Lambda_\mp$CDM with $N_{\rm eff} = 3.294$ is compared to Λ_sCDM.[5] We conclude that by adding the curvature radius in the AdS phase as a free model parameter we do not make better the fit to the data.

In Fig. 2, due to the large plot range needed to show the $\Omega_{\Lambda_{\rm CMB}}$ distribution for $\Lambda_\mp$CDM, the corresponding distributions for ΛCDM and Λ_sCDM apparently collapse into a line. Specifically, the ΛCDM (green) and Λ_sCDM (overlapping red and gray, not always distinguishable) *lines*

[4] There is a difference of decimal digits with respect to the $\chi_{\rm min}$ reported in [32], where a LO $N_{\rm eff} = 3.044$ was used.

[5] We note in passing that for $\Lambda_\mp$CDM cosmology with $N_{\rm eff} = 3.043$ we obtain very similar results, but with $\chi^2_{\rm min} = 4191.92$.

are approximately at 0.72 and −0.74. It is easily seen that Ω_{Λ_-} and z_c are highly correlated with each other, and show almost no correlation with the rest of the parameters. This means that changes in Ω_{Λ_-} can be made compatible with observational data by a judicious choice of z_c: an earlier AdS to dS transition allows for larger (in magnitude) Ω_{Λ_-} values. One can roughly quantify this relation by choosing a sample of the MCMC points with largest likelihood and modeling the relation between these parameters. For instance, choosing the top 1% points by likelihood, this relation is captured by

$$\Omega_{\Lambda_-} \approx -\frac{1}{2}\, z_c^2 + 1.33\,. \tag{3.2}$$

We end with two observations:

- From Table 1 it is straightforward to see that both Λ_sCDM and $\Lambda_{\mp}$CDM provide a solution of the M_B tension, for the two fiducial values of $N_{\rm eff}$.
- Our results are consistent with and complement those recently reported in [72].

4. Conclusions

Λ_sCDM extends the ΛCDM concordance model of cosmology by promoting the assumption of a positive cosmological constant Λ to a rapidly sign-switching cosmological constant Λ_s, at critical redshift z_c. The innovative Λ_sCDM cosmology provides a profitable arena to simultaneously accommodate the H_0 and S_8 tensions. In this paper we explored the possibility of a similar transition, but between AdS and dS phases with different curvature radii. We have shown that z_c is strongly correlated with the vacuum energy Ω_{Λ_-} in the AdS phase, and that there is no linear association between these variables and the other cosmological parameters. We have also shown that the cost of adding an additional parameter to the Λ_sCDM cosmological model does not improve the goodness of fit. Armed with our findings, we have demonstrated that for a proper choice of z_c, the vacuum energy in the dS phase may not necessarily be $-\Omega_{\Lambda_-}$, for comparable degree of conformity between the model prediction and experimental data.

CRediT authorship contribution statement

Jorge F. Soriano: Conceptualization, Investigation, Writing – review & editing. **Shimon Wohlberg:** Conceptualization, Investigation, Writing – review & editing. **Luis A. Anchordoqui:** Conceptualization, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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