Testing AdS early dark energy with Planck, SPTpol and LSS data

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ABSTRACT: The Hubble tension might be resolved by injecting a new energy component, called Early Dark Energy (EDE), prior to recombination. An Anti-de Sitter (AdS) phase around recombination can make the injected energy decay faster, which thus allows a higher EDE fraction (so larger $H_0$) while prevents degrading the CMB fit. In this work, we test the AdS-EDE model with CMB and Large-Scale Structure (LSS) data. Our CMB dataset consists of low-$\ell$ part of Planck TT spectrum and SPTpol polarization and lensing measurements, since this dataset predicts the CMB lensing effect consistent with $\Lambda$CDM expectation. Combining it with BAO and Pantheon data, we find the bestfit values $H_0 = 71.92$ km/s/Mpc and $H_0 = 73.29$ km/s/Mpc without and with the SH0ES prior, respectively. Including cosmic shear and galaxy clusters data, we have $H_0 = 71.87$ km/s/Mpc and $S_8 = 0.785$, i.e. only $1.3\sigma$ discrepancy with direct $S_8$ measurement.
1 Introduction

Currently, the ΛCDM model is being confronted with unsolved tensions. One is the $H_0$ tension, i.e. the discrepancy between the direct and indirect measurements of Hubble constant $H_0$ [1, 2]. Based on standard ΛCDM model, the Planck collaboration found $H_0 = 67.27 \pm 0.60$ km/s/Mpc [3], see also recent SDSS-IV result [4]. In contrast, using Cepheid-calibrated supernovae, the SH0ES found $H_0 = 74.03 \pm 1.42$ km/s/Mpc [5], which is $4.4\sigma$ inconsistent with Planck’s result. Different local measurements (independent of cosmological model) have actually bring similar higher $H_0$, which make it unlikely to be blamed on single systematic error. Therefore, the physics beyond ΛCDM model might be required, see e.g.[6–8] for recent reviews.

Another is the $S_8$ tension, i.e. the discrepancy between CMB and Large-Scale Structure (LSS) observations, which is quantified using $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$, where $\sigma_8$ is the amplitude of matter density fluctuation at low redshift. Based on flat ΛCDM model, the Planck collaboration found $S_8 = 0.834 \pm 0.016$ [3]. However, the weak lensing measurements and redshift surveys prefer lower values, e.g. $S_8 = 0.766^{+0.020}_{-0.014}$ for KiDS-1000+BOSS DR12+2dfLenS [9] and $S_8 = 0.737^{+0.040}_{-0.036}$ for KiDS+VIKING-450 [10], see also [11].
Recently, the Early Dark Energy (EDE) scenario [12, 13] for resolving the $H_0$ tension has been proposed. In light of the requirement that EDE must be non-negligible only for a short period around matter-radiation equality and before recombination, this early dark component can be modelled as fields with certain phenomenological potentials, such as ultra-light axion-like potential [13, 14], power-law potential [15], also ADE [16], NEDE [17] and CEDE [18]. In particular, it is found in Ref.[19], see also [20], that the existence of an Anti-de Sitter (AdS) phase around recombination can lift $H_0$ more effectively while less spoil to CMB fit. In past years, the EDE models have been extensively studied [21–31], see also modified gravity models e.g.[32–36].

It has been noticed that the scenarios resolving the Hubble tension will inevitably exacerbate the $S_8$ tension between CMB and LSS. After adding LSS data, Ref.[37] showed that for ultra-light axion-like EDE, the fraction of EDE is downed to $f_{\text{EDE}} < 0.06$, which makes it impossible to resolve Hubble tension, see also similar results by using Effective Field Theory of Large-Scale Structure (EFTofLSS) [38, 39]. These seems suggest that the EDE is being faced with the significant challenge from LSS observations, see also [40], though it may due to our inappropriate Bayesian analysis method [41, 42].

There are also discords inside CMB datasets. It’s well-known that there seems to be inconsistency between the high-$\ell$ and low-$\ell$ part in Planck’s TT power spectrum [43], where the low-$\ell$ part favors higher $H_0$ and lower $S_8$. Planck blamed it to the combined effects of an oscillatory-like set of high-$\ell$ residuals and the deficit in low-$\ell$ ($\ell < 30$) power [44]. Gravitational lensing effect can smooth sound peaks (mainly affects high-$\ell$ part), which, however, is stronger than what is excepted in $\Lambda$CDM model [43, 45]. Generally, one quantifies this effect by $A_L$, which equals 1 in a self-consistent model, but actually $A_L = 1.180 \pm 0.065$ for Planck [3]. As a contrast, we have not found this over smoothing effect in ground-base CMB observations. Actually, we see $A_L = 1.01 \pm 0.11$ for ACT [46], while $A_L = 0.81 \pm 0.14$ SPTpol [47], which is even lower than excepted.

As the CMB observation covering the widest sky area, Planck measures the most precise TT spectrum in low-$\ell$ part. Ground based CMB observations, such as SPT, ACT and POLARBEAR, focus on the polarization power spectrum at small scale. They can cover higher $\ell$ than Planck. Therefore, Ref.[48, 49] discarded Planck’s high-$\ell$ part and chose to combine Planck low-$\ell$ TT power spectrum and SPTpol polarization spectrum to test the EDE model. In this way, the most debatable part of Planck data can be avoided, and interestingly, higher $H_0$ and lower $S_8$ are found. See also Ref.[50, 51] for results with ACT DR4 data.

In AdS-EDE model [19], $H_0 > 72 \text{ km/s/Mpc}$ is compatible with direct $H_0$ measurement at 1$\sigma$ level. However, it also suffers from the $S_8$ tension. Using datasets containing full Planck data, BAO, supernova, SH0ES data, we found $\sigma_8 = 0.8514$. This larger $\sigma_8$ seems inevitable due to the positive correlation between $\Omega_m h^2$ and $H_0$ [20]. Thus it is significant to revisit the constraining power of LSS on the AdS-EDE model using the different CMB dataset that predicts the consistent CMB lensing effect [48, 49]. Moreover, it is also interesting to estimate the effect of $H_0$ prior on AdS-EDE model. In this work, we will test AdS-EDE model with combined Planck low$\ell$+SPTpol dataset, as well as LSS data.

The paper is organized as follow. We give a brief review on AdS-EDE model in
section 2. The datasets and methodology are showed in section 3. Then we check the consistency of our CMB dataset in section 4 and present results in section 5. We discuss our result with power spectrum in section 6. And we conclude in section 7.

2 A brief review on AdS-EDE model

It is well-known that the CMB observations measures the angle $\theta^*_{s}$ projected on the last-scattering surface of sound horizon (when the photon decoupled),

$$\theta^*_{s} = \frac{r^*_{s}}{D^*_A},$$

(2.1)

where the sound horizon

$$r^*_{s} = \int_{0}^{t^*} \frac{dt}{a(t)} c_s(t) = \int_{z^*}^{\infty} \frac{dz}{H(z)} c_s(z)$$

(2.2)

with $c_s$ set by the densities of baryons and matter, and the angle distance $D^*_A$ to the last-scattering surface by

$$D^*_A = \int_{0}^{z^*} \frac{dz}{H(z)} \propto \frac{1}{H_0}.$$ 

(2.3)

Reducing $r_s$ will lift $H_0 \sim 1/r_s$, which can be achieved by injecting certain dark component prior to recombination [52]. The corresponding dark energy is usually called EDE, whose the parameter of state $w \approx -1$ at beginning and hereafter $w > 1/3$ around recombination to dilute faster than radiation.

In string theory, it is easy to construct AdS vacua e.g.[53, 54], which so are ubiquitous. And AdS vacua are also important due to AdS/CFT duality [55]. In contrast, a meta-stable dS vacuum is difficult to construct (i.e belongs to the swampland) [56–58]. See also e.g.[59–61] for the implications of AdS vacua on primordial Universe and e.g.[62–65] for the implications of AdS vacua on the late Universe. Our phenomenological potential modelling AdS-EDE is that in Ref.[19]:

$$V(\phi) = \begin{cases} 
V_0 \left( \frac{\phi}{M_{\text{Pl}}} \right)^4 - V_{\text{AdS}}, & \frac{\phi}{M_{\text{Pl}}} < \left( \frac{V_{\text{AdS}}}{V_0} \right)^{1/4} \\
0, & \frac{\phi}{M_{\text{Pl}}} > \left( \frac{V_{\text{AdS}}}{V_0} \right)^{1/4}
\end{cases}$$

(2.4)

where $M_{\text{Pl}}$ is the reduced Planck mass. $V_{\text{AdS}}$ is the depth of AdS phase. See Figure 1 for one of the best-fit potential in this work.

At beginning, the field is fixed in a high-energy region of its potential (left part in Figure 1) by Hubble fiction. Generally, we have $\rho_\phi = \dot{\phi}^2/2 + V(\phi)$, $P_\phi = \dot{\phi}^2/2 - V(\phi)$ for scalar field, so initially $w \equiv P/\rho \approx -1$, thus the field behaves like the dark energy. And the fraction of EDE raised with the redshift of matter and radiation. When $H$ is deceased to satisfy $\partial^2_\phi V(\phi) \approx 9H^2$, the field will roll down along its potential to AdS phase $V < 0$, where $w > 1$. Now $\rho_{\text{EDE}}$ will redshift as $\rho \propto a^{-3(1+w)}$. After recombination, the field will climb up the other side of the potential and maintains $V = \text{const.} \geq 0$, which might result in accelerated expansion of current Universe. Here we set it to 0.
Figure 1. The potential of AdS-EDE with best-fit values to Planck low $\ell$ + SPT + BAO + Pantheon + SH0ES. The field frozen at the initial point until $\partial^2_\phi V(\phi) \approx 9H^2$. Then it will roll through the AdS phase, and arrive at the flat region of potential with $V > 0$ finally.

By decaying in a faster way, AdS-EDE can avoid degrading the CMB fit, which makes higher EDE fraction (so a larger $H_0$) possible.

3 Methodology

As a phenomenological model [19], besides six parameters of $\Lambda$CDM model, we choose $\{\ln(1 + z_c), \omega_{\text{scf}}, \alpha_{\text{AdS}}\}$ rather than $\{V_0, V_{\text{AdS}}, \phi_I\}$ as EDE’s parameters. $z_c$ is the redshift that satisfy $\partial^2_\phi V(\phi_c) = 9H^2_c$, i.e. the redshift when EDE field starts to slow roll, $\omega_{\text{scf}}$ is the physical fraction of EDE, and $\alpha_{\text{AdS}}$ is defined by $V_{\text{AdS}} = \alpha_{\text{AdS}}(\rho_m(z_c) + \rho_r(z_c))$.

We modified CLASS v2.9.4 [66] and MontePython v3.4 [67, 68] to run Markov chain Monte Carlo (MCMC) analysis, and convert EDE parameters by shooting algorithm. Nonlinear matter power spectrum is calculated by using HALOFIT [69, 70], whose suitability for EDE model is checked in [37]. A large $\alpha_{\text{AdS}}$ will cause the field fails to climb up the potential while a small $\alpha_{\text{AdS}}$ is just a run-away potential without AdS phase. Thus we will fix it to a value that does not lead to a collapsing Universe while having a significant AdS phase. We follow [19] and set $\alpha_{\text{AdS}} = 3.79 \times 10^{-4}$. We also adopt the same neutrino assumption as Planck. In addition, since the field in AdS-EDE model does not oscillate and thus cannot be approximated using the fluid approximation, we choose to solve the Klein-Gordon equation directly (see [15] for EDE with power-law potential).

Here, all parameters are assumed with flat prior. The sampling range of $\ln(1 + z_c)$ is set as $[7.5, 9]$ to ensure the decaying of EDE before recombination. We also set a very small lower limit for $\omega_{\text{scf}}$ to avoid the sampling difficulty when $\omega_{\text{scf}}$ is too small and has too weak constraint power on other EDE parameters.\footnote{In fact, in light of the posterior distribution below, we need not to worry about it.} The Gelman-Rubin criterion for
all chains is converged to $R - 1 < 0.15$. The posterior distribution is analyzed and plotted using GetDist \cite{71}.

We consider the data sets as follows:

- **Planck\_low$\ell$:** The TT power spectrum of Planck 2018 \cite{3} at $\ell < 1000$, including $30 \leq \ell < 1000$ part of \texttt{Plik} likelihood and $\ell < 30$ part of \texttt{Commander} likelihood. All nuisance parameters are imposed with the same prior with Planck.

- **SPTpol:** The polarization power spectrum (TE and EE) measured by 500 deg$^2$ SPTpol survey \cite{47}. Their multipole range is $50 < \ell \leq 8000$. Due to very small sky area overlap between SPTpol and Planck, the correlation between them can be ignored. All nuisance parameters are imposed with the same prior with SPTpol.

- **SPTlen:** The CMB lensing potential measured by 500 deg$^2$ SPTpol survey \cite{72,73}. Their multipole range is $100 < \ell \leq 2000$. Here, for simplicity, we denote the dataset combination SPTpol + SPTlen as \textbf{SPT}.

- **BAO:** low redshift BAO measured by 6DF \cite{74} in $z = 0.106$ and SDSS DR7 MGS \cite{75} in $z = 0.15$, as well as the ‘consensus’ final result from BOSS DR12 combined analysis \cite{76}, their effective redshifts are $z = 0.38, 0.51, 0.61$.

- **Pantheon:** We take use of the magnitudes and luminosity distances data of supernovae from Pantheon. \cite{77}

- **SH0ES (R19):** The local $H_0$ measured with Cepheid-calibrated supernovae by SH0ES: $H_0 = 74.03 \pm 1.42$ km/s/Mpc \cite{5}, is regarded as a Gaussian prior.

- **RSD:** The ‘consensus’ final result from BOSS DR12 \cite{76}. RSD helps us constraint $f\sigma_8$. When we add RSD data, we also use the BAO data and the covariance of combined BAO+FS analysis.

- **WL:** We directly take use of the constraint to $S_8$ from the combined analysis of KiDS+VIKING-450 + DES-Y1 dataset, i.e. $S_8 = 0.755^{+0.019}_{-0.021}$ \cite{78} for $\Lambda$CDM. In principal, we should use the full likelihood, but as checked in \cite{37}, there is little difference in result between a Gaussian prior on $S_8$ and full likelihood for EDE.

In addition, we include Planck 2018 measurements of the low $\ell$ part of the EE spectrum ($\ell < 30$) \cite{3} by default in all datasets combinations. This part of data can constrain $\tau$, so as to break the degeneracy of $A_s e^{-2\tau}$.

### 4 Consistency check of CMB data sets

Our CMB dataset is Planck\_low$\ell$+SPT, i.e. Planck\_low$\ell$+SPTpol+SPTlen. Ref.\cite{48} has checked the consistency of this dataset by comparing its posterior distributions under $\Lambda$CDM model. However, as we have modified cosmological model, we will have different posterior distributions, some of which may be very different. Therefore, it is required to
recheck each part of CMB datasets under AdS-EDE model. We show the corresponding posterior distributions in Figure 2.

We see that they are still compatible under AdS-EDE due to large uncertainties in individual data sets. The differences between the cosmological parameters (including $S_8$) and AdS-EDE parameters are within $1\sigma$ between SPTpol and Planck$_{l\text{ow}}\ell$. The region of the posterior distribution is reduced by the inclusion of SPTlen, but does not change significantly. This indicates that there is no significant conflict within the CMB data combination Planck$_{l\text{ow}}\ell$+SPTpol+SPTlen.

Figure 2. Posterior distributions of CMB data sets (68% and 95% confidence range). We also plot the SH0ES constraint to $H_0$ [5] and the KiDS+VIKING-450+DES-Y1 constraint to $S_8$ [78] in light gray.
Table 1. Constraints on parameters under AdS-EDE for each data set, including mean values and ±1σ regions, with best-fit values in parentheses.

5 Results

5.1 Planck_lowℓ + SPT

The constraints of our combined Planck_lowℓ+SPT dataset on the parameters are shown in the thick black solid line in Figure 2 and Table 1. A distinct non-Gaussian distribution can be found in the ln (1 + z_e) - ω_{scf} plane, which is because in the low z_e and low ω_{scf} region θ_i is so small that the field would not climb out of AdS well (we called it AdS bound). However, our best-fit point is not close to this region, so we do not need to worry about it. H_0 and ω_{scf} are positively correlated, which is exactly what we expect, i.e. larger EDE fraction brings a larger H_0. Meanwhile, ω_{scf} and S_8 are negatively correlated, since larger ω_{cdm} is required to balance the extra EDE, we’ll discuss it in detail in section 6. The negative correlation between z_e and H_0 is due to very little effect of the EDE peak on r_s when EDE is far away from the recombination time.

Unlike other EDE solutions (such as [49] for the same dataset), CMB data alone has strong preference of non-zero EDE, at least for our model and dataset combination. The posterior distributions of H_0 and S_8 are all consistent with direct measurements at 1σ level. The best value of H_0 is even slightly larger than R19. However, the uncertainty of H_0 is very large.

5.2 Planck_lowℓ + SPT + BAO + Pantheon

BAO measured H(z)r_s^{drag} (line of sight direction) and D_M(z)/r_s^{drag} (perpendicular to the line of sight direction), or average angle, constrained to D_V(z)/r_s^{drag} for the late Universe, and (uncalibrated) supernova luminosity distances constrain the shape of D_L(z), and thus the shape of H(z). Their combination sets the constraint for H_0r_s^{drag}. Recent studies have already pointed out that the Hubble tension is actually relevant with the deviations of both H_0 and r_s, e.g.[79-81], so it is necessary to compare the compatibility of model with BAO+SN observations. We add the data of BAO+Pantheon in our Planck_lowℓ+SPT
dataset and present the posterior distribution of the parameters in Figure 3, see also Table 1.

![Figure 3](image)

**Figure 3.** Planck\_low$\ell$+SPT (+BAO+Pantheon) constraints on each parameter under AdS-EDE (68% and 95% confidence range). We also plot the R19 constraint to $H_0$ [5] and the KiDS+VIKING-450+DES-Y1 constraint to $S_8$ [78] in light gray.

With the addition of BAO+Pantheon, the uncertainty of the parameters is much reduced, however the difference from the results without BAO+Pantheon stays within 1$\sigma$. This is an indication that BAO+Pantheon is compatible with our CMB dataset. $H_0 = 71.92$ is consistent with R19 at 1.1$\sigma$ level, and is 3.7$\sigma$ higher than that in $\Lambda$CDM model. The value of $\sigma_8$ is slightly raised, but is still 2.1$\sigma$ consistent with the KiDS+VIKING-450+DES-Y1 (WL) result. The best-fit values of EDE fraction is slightly decreased after the addition of BAO+Pantheon.
We also compare the posterior distribution of the parameters in Figure 4 for our CMB dataset with those using the full Planck data (i.e., Planck2018 high-\(\ell\) TT TE EE spectrum, low-\(\ell\) TT EE spectrum and lensing spectrum) as CMB data, see also Table 5. The full Planck data has less parameter uncertainties, but its \(S_8\) differs from the WL measurements by 4.9\(\sigma\). \(H_0\) in the full Planck data is slightly larger than that in our dataset, however, our EDE parameters, namely \(\ln(1 + z_c), \omega_{\text{scf}}\), have larger uncertainties.

**Figure 4.** Constraints on each parameter for different combinations of CMB datasets + BAO + Pantheon (+SH0ES) under AdS-EDE (68\% and 95\% confidence range). We also plot the R19 constraint to \(H_0\) [5] and the KiDS+VIKING-450+DES-Y1 constraint to \(S_8\) [78] in light gray.
To further clarify the role of BAO+Pantheon, we follow [52] by approximating $H(z)$ as a five-point natural cubic spline function and fitting the BAO+Pantheon data with MCMC, constrain $\beta_{\text{BAO}} \equiv c / H(z) r_{\text{drag}}$: $\beta_{\text{BAO}} = 29.769^{+0.379}_{-0.372}$. This constraint is model-independent (except for the flatness assumption). We compare the parameter constraints on the $r_{\text{drag}}-H_0$ plane under AdS-EDE with model-independent BAO+Pantheon in Figure 6.

It can be seen that the $r_{\text{drag}}-H_0$ distribution under AdS-EDE (without BAO+Pantheon data) is 1σ consistent with the overlap region of model-independent $r_{\text{drag}}-H_0$ constraint and R19. However, for $\Lambda$CDM (see e.g. [79]), its posterior distribution is far from the

![Figure 5](image-url)
Figure 6. 1σ and 2σ posterior distributions for different model and dataset combinations in the $r_s^{\text{drag}}-H_0$ plane. The horizontal gray line is the R19 constraint on $H_0$ [5]. The skewed gray line is the BAO+Pantheon constraint on $H_0 r_s^{\text{drag}}$ in a model-independent way. The middle colored scatters are the parameters ranges in AdS-EDE constrained by Planck $\text{low} \ell + \text{SPT} + \text{BAO} + \text{Pantheon}$. 

| Data set                | $\Lambda$CDM | AdS-EDE |
|-------------------------|--------------|---------|
| Planck TT, $30 \leq \ell < 1000$ | 405.96       | 409.71  |
| Planck TT, $\ell < 30$ | 22.35        | 20.38   |
| Planck EE $\ell < 30$  | 395.68       | 395.92  |
| SPTpol                  | 145.56       | 144.92  |
| SPTlen                  | 4.91         | 4.97    |
| BOSS DR12 BAO           | 3.55         | 3.60    |
| BAO low-z               | 2.30         | 2.09    |
| Pantheon                | 1026.91      | 1027.27 |
| Total                   | 2007.23      | 2008.86 |

Table 2. $\chi^2$ of $\Lambda$CDM and AdS-EDE for the Planck $\text{low} \ell + \text{SPT} + \text{BAO} + \text{Pantheon}$ best-fit values.

overlap region, and the degeneracy direction is orthogonal to the distribution of the model-independent constraint. Similar to $\Lambda$CDM, the direction of $\Omega_m$ in AdS-EDE is orthogonal to the model-independent $r_s^{\text{drag}}-H_0$ constrained degeneracy direction. This can be understood as following. It is well-known that CMB almost fixed $\theta_s$, and

$$\theta_s = \frac{r_s}{D_A} = \frac{r_s H_0}{\int dz \frac{dz}{H(z)}} \int \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)} dz .$$  \hspace{1cm} (5.1)

This suggests that $\Omega_m$ will be determined by $r_s H_0$. Therefore, the addition of BAO+Pantheon data constrains $\Omega_m$ to larger values, so $S_8$. 

– 11 –
\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Data set & $\Lambda$CDM & AdS-EDE \\
\hline
Planck TT, $30 \leq \ell < 1000$ & 407.06 & 407.97 \\
Planck TT, $\ell < 30$ & 20.95 & 20.34 \\
Planck EE $\ell < 30$ & 395.70 & 396.27 \\
SPTpol & 142.93 & 145.07 \\
SPTlen & 5.65 & 5.09 \\
BOSS DR12 BAO & 7.96 & 4.31 \\
BAO low-z & 4.39 & 2.89 \\
Pantheon & 1027.46 & 1027.04 \\
SH0ES & 8.96 & 0.27 \\
\hline
Total & 2021.07 & 2009.25 \\
\hline
\end{tabular}
\caption{$\chi^2$ of $\Lambda$CDM and AdS-EDE best fits to Planck low-$\ell$+SPT+BAO+Pantheon+SH0ES.}
\end{table}

We present in Table 2 the $\chi^2$ of the best fits of $\Lambda$CDM and AdS-EDE. The AdS-EDE fit is slightly worse than the fit in $\Lambda$CDM: $\Delta \chi^2 = 1.63$. However, since the difference in $\chi^2$ is slight, it is not statistically significant.

5.3 Planck low-$\ell$ + SPT + BAO + Pantheon + SH0ES

Including the R19 prior, we present the posterior parameters in Table 1. We also present a comparison of the parameter posterior distribution before and after the addition of R19 data and with $\Lambda$CDM model in Figure 5, and a comparison with the parameter posterior distribution using the full Planck data as CMB data instead in Figure 4.

We see that $H_0$ is restricted to a higher value of $H_0 = 73.29$ (consistent with R19 within 1σ), and $S_8 = 0.816$. However, the uncertainty of $H_0$ does not enlarge significantly, which indicates that there is no significant inconsistency with R19 data. Thanks to the larger uncertainty of $H_0$ toward higher values without R19 prior for Planck low-$\ell$+SPT dataset, $H_0$ is raised more than that for full Planck data (see Appendix Appendix B). Here, $\omega_{\text{scf}}$ is slightly raised and $z_c$ is constrained to be closer to the recombination epoch to lift $H_0$. However, this constraint on the EDE parameters is not as drastic as other EDE models, since AdS-EDE already brings a larger $H_0$ even without the $H_0$ prior.

Similarly, we present the $\chi^2$ of the $\Lambda$CDM and AdS-EDE best-fit values with R19 data in Table 3. After the addition of R19 data, the fit of $\Lambda$CDM to the BAO and Pantheon is bad due to the previously described deviation in the $r_s$-darg-$H_0$ plane. However, AdS-EDE is fully compatible with the $H_0$ prior. And due to its reduced $r_s$, the fit to the BAO and Pantheon measurements is also well. Due to the rapid decay of AdS-EDE, the spoil to the CMB fit is slight. Totally, we get $\Delta \chi^2 = -11.82$ for AdS-EDE compared to $\Lambda$CDM, indicating that AdS-EDE significantly fits relevant observations better than $\Lambda$CDM.

5.4 Planck low-$\ell$ + SPT + BAO + Pantheon + SH0ES + RSD + WL

Finally, we add RSD and WL measurements to make the relationship with direct $S_8$ measurements clear. Results are presented in Figure 7 and Table 1.
Including RSD+WL, we get $S_8 = 0.785$, the difference with direct $S_8$ measurement is only $1.3\sigma$, while we have $H_0 = 71.87$, which is only slightly lower compared to that without RSD+WL. Compared with the result of full Planck data, Planck_lowl+SPT allows higher $z_c$, so that less $\omega_{cdm}$ is added to balance EDE, allowing to achieve a lower $S_8$. This is different from compromise of lowering EDE fraction when the full Planck data is considered. Our results indicate that AdS-EDE is not excluded by the current WL measurements. As a contrast, we also present the result using EFTofLSS in Appendix Appendix A.

Figure 7. Posterior distribution of each parameter under AdS-EDE after adding RSD and WL measurements (68% and 95% confidence range). We also plot the R19 constraint to $H_0$ [5] and the KiDS+VIKING-450+DES-Y1 constraint to $S_8$ [78] in light gray.
Figure 8. Parameters distribution on the plane \((S_8, H_0)\) for Planck\textsubscript{lowl}+SPT+BAO+Pantheon and fullPlanck+SPT+BAO+Pantheon in AdS-EDE. The gray bands represents constraints from direct \(H_0\) [5] and \(S_8\) [78] measurements.

6 Discussion

The \(S_8-H_0\) relation for our datasets is presented in Figure 8. We can find that EDE has a different relationship from \(\Lambda\)CDM (see e.g. Figure 5). Precise CMB \(\theta_s\) measurement constrains \(\omega_{\text{cdm}} H_0^2\) and the heights of peaks constrain \(\omega_m\), and they actually constrain \(\omega_{\text{cdm}} H_0\) [3]. \(\omega_{\text{cdm}}\) controls the late matter fluctuation, this is the reason of the negative relation in Figure 5.

However, this is not the case for EDE, since the relation of \(S_8-H_0\) is mainly controlled by EDE’s fraction \(\omega_{\text{scf}}\), see left plane of Figure 8. In EDE scenario, since larger EDE fraction brings higher \(H_0\), larger \(\omega_{\text{cdm}}\) required to balance early ISW effect (see middle panel of Figure 8), which is common in any early resolution (relevant with energy injection) for the Hubble tension. And the approximate relationship is \(\frac{\delta H_0}{H_0} \sim 0.5 \frac{\delta \omega_{\text{cdm}}}{\omega_{\text{cdm}}}\) [83]. It is this higher \(\omega_{\text{cdm}}\) that bring larger \(S_8\).

Besides difference with \(\Lambda\)CDM, there is also difference between different CMB datasets, where Planck\textsubscript{lowl}\(\ell\)+SPT favors the region consistent with direct \(H_0\) and \(S_8\) measurements. This is relevant with \(\Omega_m = \omega_m h^{-2}\) (see the right panel of Figure 8). As we have mentioned, BAO+SN data will precisely set \(\Omega_m\). However, this is the case only when \(\theta_s\) is fixed. It can be found in Figure 9 that Planck\textsubscript{lowl}\(\ell\)+SPT favors a smaller \(\theta_s\), which will bring less \(\Omega_m\). It seems that the slightly less \(\Omega_m\) than Planck has been indicated [84–88]. Here, the change of \(n_s\) is the natural results of higher \(H_0\) [83].

To clarify the effect of different CMB datasets, we plot their best-fit values and residuals to Planck 2018 on TT and EE spectrum in Figure 10 and Figure 11. It can be found in Figure 11 that SPTpol polarization spectrum has smaller uncertainty than Planck at \(\ell > 1000\) and can extend to higher \(\ell\). The different oscillation phases can be observed and the fullPlanck case is closer to the baseline model (as our baseline model contains fullPlanck data), which are indications for different \(\theta_s\). This different \(\theta_s\) is due to the oscillation-like residuals in Planck’s TT spectrum, which cause high-low \(\ell\) inconsistency and lensing anomaly 3. It also comes from oscillation-like residuals in Planck’s TE and EE spectrum, which have not still detected in ACT or SPT observation [24].

\(^3\)However, it is worth noting that our model also captures \(800 < \ell < 1000\) residual peaks of Planck TT.
Figure 9. Posterior distribution of parameters in AdS-EDE using different CMB datasets.

Figure 10. AdS-EDE best-fit values for Planck_low + SPT + BAO + Pantheon + SH0ES and fullPlanck + BAO + Pantheon + SH0ES on TT spectrum, and residual and uncertainty of different CMB observations (light error bars is the unused data). The reference value is the best-fit result to full Planck data (i.e. base_pikHM_TTTEEE_lowl_lowE_lensing) under ΛCDM model. Cosmological variance is showed in light gray background. Note different ℓ range to other figures.

Regardless of which CMB dataset is used, compared with the ΛCDM model larger \( n_s \) brings a deficit in the \( \ell < 30 \) multipoles. And this deficit does exist in Planck’s observations of the TT spectrum, which is one of the sources of its high and low \( \ell \) inconsistency \(^{[44]}\). This leads to a better fit of AdS-EDE to this part of data, although not significant due to extremely large cosmological variance here.

We also compare the residuals of AdS-EDE with the cosmological variance, see Fig-
Figure 11. AdS-EDE best-fit values for Planck \(_{\text{low} \ell} +\text{SPT} +\text{BAO} +\text{Pantheon} +\text{SH0ES}\) and fullPlanck +BAO+Pantheon+SH0ES on EE spectrum, and residual and uncertainty of different CMB observations (light error bars is the unused data). The reference value is the best-fit result to full Planck data (i.e. \text{base}_\text{plikHM} \text{TTTEEE}_{\text{lowl}} \text{lensing}) under \Lambda \text{CDM} model.

Figure 12. The residuals of the TT spectrum can only be within the cosmological variance for scales that can be observed at present \((\ell \leq 4000)\), however, the residuals of the EE spectrum is larger than the cosmological variance at small scales \((2500 \lesssim \ell \leq 4000)\). This suggests that the polarization spectrum will be a significant tool for constraining AdS-EDE from CMB, a range that also lies outside Planck’s multipoles. Due to the larger \(n_s\), the AdS-EDE effect on very small scales also far exceeds the cosmological variance.

7 Conclusion

Currently, the EDE is a popular resolution for the Hubble tension. In AdS-EDE model, the existence of AdS phase can make the energy injected before recombination decay faster, which avoids degrading the CMB fit, and thus allow a higher EDE fraction. However, like other EDE models, this brings a larger late matter density fluctuation, worsening the tension between Planck data and LSS observations. Thus it is significant to revisit the constraining power of LSS on the AdS-EDE model using the different CMB dataset.

It is well-known that the Planck data itself also present the outstanding anomalies, such as the discrepancy between high and low \(\ell\) and the over-smoothing of the acoustic peak by the gravitational lensing. Thus for CMB data, we conservatively discard the high \(\ell\) part of Planck TT spectrum as well as the polarization spectrum and replace the corresponding data with SPTpol observations, as in Refs.[48, 49]. We verify the compatibility of this combined CMB dataset under AdS-EDE.
We get $H_0 = 74.7 \text{ km/s/Mpc}$ when using our combined CMB dataset alone (Planck$_\text{low}$+$\text{SPT}$), and $H_0 = 71.92 \text{ km/s/Mpc}$ when using Planck$_\text{low}$+$\text{SPT}$+$\text{BAO}$+$\text{Pantheon}$ dataset, respectively. Here, the Hubble tension is substantially relieved, even without any prior of direct measurements. And it is consistent with the age constraints of the oldest astrophysical objects [89] (see also [90–93] for other age constraints). Unlike other works (e.g. [37, 49]), we can see a preference for the non-zero AdS-EDE, with the best-fit value $\omega_{\text{scf}} \approx 0.1$. This is actually a straight result of the AdS bound in AdS-EDE model, which is not present without the AdS phase.

We also investigated the role of different CMB datasets. We find that the direction of solving both $H_0$ tension and $S_8$ tension is controlled by $\Omega_m$, which is related to $\theta_s$. The oscillation-like residual at high-$\ell$ part of Planck data, which is relative to lensing anomaly and high-low $\ell$ inconsistency, results in the corresponding discrepancy of $\theta_s$. The residual analysis shows that the small-scale polarization spectrum is essential for identifying EDE models. Ground-based CMB experiments such as SPT-3G [94] and Advanced ACTPol [95] might observe effects of EDE on the CMB, while the upcoming high-precision small-scale CMB experiments Simons Observatory [96] and CMB-S4 [97] can help us to reestimate the anomaly at Planck’s high-$\ell$ part.

It should be also pointed out that the observations of LSS such as Euclid satellite [98], LSST [99], DESI [100] will not only further constraint on the resolution of the $H_0$ tension,

\footnote{With the $H_0$ prior from SH0ES, we get $H_0 = 73.29 \text{ km/s/Mpc}$. Inclusion of the RSD and WL measurements leads to $S_8 = 0.785$, which is $1.3\sigma$ consistent with direct $S_8$ measurement.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure12}
\caption{The AdS-EDE best-fit values for Planck$_\text{low}$+$\text{SPT}$+$\text{BAO}$+$\text{Pantheon}$+$\text{SH0ES}$ compared with the best-fit values for the $\Lambda$CDM model based only on full Planck data (i.e., base.plikHM.TTTEEE.lowl.lowE.lensing) in term of the ratio of residuals to cosmological variance on the CMB TT and EE spectra.}
\end{figure}
but also enable us to judge whether the $S_8$ tension actually implies new physics or not.

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A Results with Planck low$\ell$ + SPT + BAO + Pantheon + SH0ES + EFTofLSS

Effective Field Theory of Large-Scale Structure (EFTofLSS) [101, 102] can extract information on moderate nonlinear scales, by characterizing the nonlinear effects on small scales as effective parameters on large scales. Since LSS is 3-dimensional, it will have larger number of modes than the 2-dimensional CMB, and thus can have a smaller cosmological variance and theoretically better constrain cosmological parameters.

Here, our BOSS DR12 BAO data are replaced with the data of BOSS DR12 containing three regions [103]: CMASS NGC, CMASS SGC and LOWZ NGC, as well as the covariance matrix between them. In principle, this statistical constraint on BAO data selection is worse than the ‘consensus’ final result used in our text. We consider the similar model-independent approach to obtain this BAO+Pantheon constraint on $r_s^{\text{drag}} H_0$: $\beta_{\text{BAO}} = 29.684_{-0.386}^{+0.390}$. There is no significant difference from the analysis result in the text, which indicates that it is safe to use this BAO alternative. The EFTofLSS is implemented by pybird [104]. The nuisance parameter of EFTofLSS is partially marginalized, and the rest are the same as [104], independent on echo area.

A comparison of the posterior distribution of the parameters before and after including EFTofLSS is presented in Figure 7 and Table 4. It can be seen that the degradation of the parameters is smaller than RSD+WL. Including EFTofLSS, we have $H_0 = 72.34$ km/s/Mpc, the discrepancy with R19 is only 0.8$\sigma$, the $S_8$ is only reduced by less than 1$\sigma$, and the uncertainty does not increase significantly.

| parameters          | Planck low$\ell$ + SPT + BAO + Pantheon + SH0ES | Planck low$\ell$ + SPT + BAO + Pantheon + SH0ES + EFTofLSS |
|---------------------|-----------------------------------------------|----------------------------------------------------------|
| $\omega_{\text{scf}}$ | $0.122(0.116)_{-0.021}^{+0.024}$             | $0.114(0.108)_{-0.016}^{+0.024}$                       |
| $\ln(1 + z_c)$      | $8.39(8.30)_{-0.23}^{+0.17}$                 | $8.39(8.50)_{-0.19}^{+0.24}$                           |
| $H_0$               | $73.08(73.29)\pm 0.96$                       | $72.68(72.34)\pm 0.91$                                 |
| $n_s$               | $0.9965(0.9990)_{-0.00065}^{+0.0083}$         | $0.9938(0.9945)_{-0.0063}^{+0.0079}$                   |
| $\omega_b$          | $0.02368(0.02375)_{-0.00027}^{+0.00033}$     | $0.02355(0.02373)_{-0.00025}^{+0.00029}$               |
| $\omega_{\text{cdm}}$ | $0.1316(0.1308)\pm 0.0041$                 | $0.1304(0.1292)\pm 0.0032$                            |
| $\ln 10^{10}A_s$    | $3.045(3.046)_{-0.011}^{+0.016}$            | $3.027(3.030)_{-0.016}^{+0.028}$                      |
| $\tau$              | $0.0462(0.0470)_{-0.0072}^{+0.011}$         | $0.0382(0.0434)_{-0.0077}^{+0.015}$                   |
| $100\theta_s$       | $1.03955(1.03965)\pm 0.00073$               | $1.03963(1.04010)\pm 0.00070$                         |
| $\sigma_8$          | $0.831(0.832)_{-0.013}^{+0.017}$            | $0.821(0.819)_{-0.013}^{+0.015}$                      |
| $S_8$               | $0.820(0.816)_{-0.017}^{+0.020}$            | $0.811(0.810)_{-0.016}^{+0.018}$                      |

Table 4. Constraints on the parameters of AdS-EDE for Planck low$\ell$ + SPT + BAO + Pantheon + SH0ES (+ EFTofLSS), including mean values and $\pm 1\sigma$ regions, with best-fit values in parentheses.
B Results with fullPlanck+BAO+Pantheon

| parameters | fullPlanck+BAO+Pantheon |
|------------|--------------------------|
| $\omega_{scf}$ | 0.1124(0.1084)$^{+0.0046}_{-0.0070}$ |
| $\ln(1+z_c)$ | 8.153(8.147)$^{+0.075}_{-0.084}$ |
| $H_0$ | 72.52(72.46) ± 0.51 |
| $n_s$ | 0.9964(0.9949)$^{+0.0047}_{-0.0041}$ |
| $\omega_b$ | 0.02341(0.02331)$^{+0.00018}_{-0.00016}$ |
| $\omega_{cdm}$ | 0.1346(0.1336)$^{+0.0016}_{-0.0018}$ |
| $\ln 10^{10}A_s$ | 3.079(3.072) ± 0.015 |
| $\tau$ | 0.0545(0.0523)$^{+0.0071}_{-0.0079}$ |
| $100\theta_s$ | 1.04108(1.04132) ± 0.00029 |
| $\sigma_8$ | 0.8604(0.8554) ± 0.0074 |
| $S_8$ | 0.863(0.856) ± 0.011 |

Table 5. Constraints on the parameters of AdS-EDE for fullPlanck+BAO+Pantheon, including mean values and $\pm 1\sigma$ regions, with best-fit values in parentheses.

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