T₀ censorship of early dark energy and AdS

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Abstract

Present-day temperature T₀ of cosmic microwave background has been precisely measured by the FIRAS experiment. We identify why the early dark energy (EDE) (non-negligible around matter-radiation equality) scenario is compatible with the FIRAS result, while lifting the Hubble constant H₀. We perform Monte Carlo Markov Chain analysis to confirm our observations. We also present an α-attractor Anti-de Sitter (AdS) model of EDE. As expected, the existence of an AdS phase near recombination can effectively result in H₀ ≃ 73km/s/Mpc at 1σ region in the bestfit model.

PACS numbers:

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I. INTRODUCTION

The Hubble constant $H_0$, the present-day expansion rate of the Universe, sets the scale of the current Universe. Local measurements of $H_0$ yield $H_0 \gtrsim 73\text{km/s/Mpc}$ [1–5] (e.g. the SH0ES group reports $H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc}$ [5, 6]), which shows $> 4\sigma$ discrepancy [7] compared with the Planck result $H_0 = 67.72 \pm 0.78\text{km/s/Mpc}$ [8]. This discrepancy (called “Hubble tension”) can hardly be explained by systematic errors [9].

However, the analysis of Planck is based on $\Lambda$CDM and probes of high redshift physics, i.e. cosmic microwave background (CMB) and baryon acoustic oscillations (BAO). Thus the Hubble tension might be a hint of beyond-$\Lambda$CDM physics, specially before recombination [10–13]. One possibility is early dark energy (EDE) [14–23] (see also [24–26] for modified gravity). EDE is non-negligible only for a short period near matter-radiation equality and before recombination (the Universe after recombination is $\Lambda$CDM-like), which results in a suppressed sound horizon, and thus $H_0 \gtrsim 70\text{km/s/Mpc}$.

Recently, it has been found in Ref.[21] that the existence of Anti de-Sitter (AdS) vacua around recombination can effectively lift $H_0$ to $\sim 73\text{km/s/Mpc}$ at $1\sigma$ region. The cosmologies with an AdS phase at low-$z$ have been studied in Refs.[27–29]. The AdS vacua is ubiquitous in the landscape (consisting of all effective field theories with consistent UV-completion) [30, 31]. The AdS potential in Ref.[21] is only a phenomenological one, see also [32, 33] for inflation with multiple AdS vacua. Thus it is significant to explore AdS-EDE models originating from UV-complete theories.

Precise measurement of the present-day CMB $T_0$ from the COBE/FIRAS experiment, independent of Planck, yields [34, 35]

$$T_{0,\text{FIRAS}} = 2.72548 \pm 0.00057K.$$  \hspace{1cm} (1)

Based on $\Lambda$CDM, the Planck and BAO data yields $T_0 = 2.718 \pm 0.021K$ [36], consistent with $T_{0,\text{FIRAS}}$. However, the $T_0$ deduced from the Planck and SH0ES data, assuming $\Lambda$CDM, has $> 4\sigma$ discrepancy compared with $T_{0,\text{FIRAS}}$, called $T_0$ tension in Ref.[37], see also [38, 39] for recent studies. This might be yet another hint of new physics beyond $\Lambda$CDM.

In this paper, we identify, at the cosmological parameter level, why the EDE scenario can lift $H_0$, while staying compatible with $T_{0,\text{FIRAS}}$. We perform Monte Carlo Markov Chain (MCMC) analysis to confirm our observations. We also present a well-motivated AdS-EDE
model as well as the corresponding MCMC analysis. Low-z resolutions to the Hubble tension have also been discussed, see e.g.\cite{40–43} for different perspectives. As a contrast, we also show that \(w_{CDM}\) models with a constant equation of state parameter \(w \lesssim -1.3\) of dark energy at low-z seem incompatible with \(T_{0,FIRAS}\). Throughout this paper we assume a spatially flat Universe.

II. EARLY DARK ENERGY AND ADS

EDE may be non-negligible only for a short epoch decades before recombination \cite{14, 15}. The injection of EDE energy results in a larger Hubble rate \(H(z \gtrsim z_{rec})\) prior to recombination, so a suppressed sound horizon \(r_s = \int_{z_{rec}}^{\infty} dz/H(z)\). The spacing of CMB acoustic peaks perfectly sets the angular scale \(\theta_{CMB}\),

\[
\theta_{CMB} = \frac{r_s(z_{rec})}{D_A(z_{rec})},
\]

where

\[
D_A(z_{rec}) \equiv \int_{0}^{z_{rec}} \frac{dz}{H(z)} = \frac{1}{T_0} \int_{T_0}^{T_{rec}} \frac{dT}{H(T)}
\]

and \(z_{rec} \sim 1100\) is the recombination redshift. \(D_A(z_{rec})\) is the comoving angular distance, which is sensitive only to post recombination physics. Generally, \(D_A\) is anti-correlated with \(H_0\), so for constant \(\theta_{CMB}\), \(H_0 \sim r_s^{-1}\) will increase.

In the AdS-EDE model \cite{21}, initially the scalar field sits at the hillside of its potential \(V(\phi)\), and \(\rho_\phi\) is negligible. It will roll down the potential sometime near matter-radiation equality (when \(\rho_\phi/\rho_{tot} \sim 10\%)\), and roll into an AdS phase. In the AdS region, we have \(w_\phi = p_\phi/\rho_\phi > 1\), so that \(\rho_\phi \sim a^{-3(1+w)}\) will more quickly redshift away (in Refs.\cite{14, 15, 18} the dissipation of \(\rho_\phi\) is less effective by oscillation with cycle-averaged \(w < 1\), see also Refs.\cite{19, 23} for different mechanisms). This is crucial for having a larger injection of \(\rho_\phi (> 10\%)\), thus a higher \(H_0\). \(\rho_\phi\) injected must be dissipated rapidly enough so that it is negligible around recombination, or it will interfere with the fit of \(\Lambda CDM\) to CMB data. After that, the field will climb up to the \(\Lambda > 0\) region, and the Universe is settled to be \(\Lambda CDM\)-like until now.

The potential \(V(\phi)\) in Ref.\cite{21} is only a phenomenological one. Inspired by the \(\alpha\)-attractor \cite{44, 45}, we take \(V(\phi)\) as (see Fig-1)

\[
V(\phi) = V_0 \left[ 1 - \exp \left( -\gamma \tanh \left( \frac{\phi}{M_p \sqrt{6\alpha}} \right) \right) \right]^2 - V_0 + V_\Lambda.
\]
For $\phi \ll -M_p(6\alpha)^{1/2}$, we have a high plateau $V(\phi) \sim e^{2\gamma}V_0$ responsible for EDE. For $\phi \gg M_p(6\alpha)^{1/2}$, $V(\phi) = V_\Lambda$ behaves like a cosmological constant in the current Universe. In Ref. [45], the high plateau drives inflation in the early Universe, in which case $\gamma = \ln\left(\frac{H_{\text{inf}}}{H_\Lambda}\right) \gg 1$.

Here, the AdS-EDE model with potential (4) will be briefly called $\alpha\text{AdS}$. Initially, $\rho_{\phi_i} = V(\phi_i) \simeq (0.1\text{eV})^4$, roughly equal to height of the high plateau $e^{2\gamma}V_0$ if $\alpha \ll 1$. In the MCMC analysis, we choose $6\alpha = (0.15)^2 \ll 1$ for simplicity, thus only $V_0$, $\gamma$, $V_\Lambda$ are free parameters. The minima of potential (4) is $V_{\text{min}} = -V_0 + V_\Lambda$ at $\phi = 0$. The existence of an AdS phase requires $V_0 \gtrsim V_\Lambda$, i.e.

$$\gamma \lesssim \frac{1}{2} \ln \frac{V(\phi_i)}{V_\Lambda} \simeq 13,$$

where $V_\Lambda \sim (10^{-4}\text{eV})^4$ is the current dark energy scale. In the limit of large $\gamma$, the $\alpha\text{AdS}$ model reduces to a run-away model [16, 17] with $V(\phi > 0) \sim V_\Lambda$.

![Potential Diagram](image)

**FIG. 1:** Potential (4), plotted only for illustration. The scalar field initially sits at $\phi_i$ near the high plateau. It begins rolling down the potential around matter-radiation equality, passing through the AdS region near $\phi \simeq 0$ and finally climbs up the low plateau responsible for the current dark energy.
TABLE I: Mean and 1σ results of all the chains. All EDE models ($\phi^4$ [15], $\phi^4$AdS [21], $\alpha$AdS) are confronted with P18+BAO+SN+$H_0$ dataset.

III. $T_0$ CENSORSHIP OF BEYOND-$\Lambda$CDM MODELS

A. Dataset

Our dataset consists of the Planck18 high-$l$ and low-$l$ TT,EE,TE and lensing likelihoods (P18) [8], the BOSS DR12 [46] with its full covariant matrix for BAO measurements as well as the 6dFGS [47] and MGS of SDSS [48] for low-$z$ BAO, and the Pantheon data (SN) [49]. Recent SH0ES result $H_0 = 74.03 \pm 1.42$km/s/Mpc [5] is employed as a Gaussian prior ($H_0$).

We modified the Montepython-3.3 [50, 51] and CLASS [52, 53] codes to perform the MCMC analysis.

Here, we regard $T_0$ as an MCMC parameter. We sample the cosmological parameter set \{$\hat{T}_0^{-3} \omega_b, \hat{T}_0^{-3} \omega_{cdm}, H_0, \ln(10^{10} A_s T_0^{1+n_s}), n_s, \tau_{reio}, T_0$\} for $\Lambda$CDM, where $\hat{T}_0 \equiv T_0 / T_{0,FIRAS}$ and $\hat{\omega}_{b/\text{cdm}} T_0^{3}_{0,FIRAS} \equiv \hat{T}_0^{-3} \omega_{b/\text{cdm}}$ (reducing degeneracy between $H_0, \omega_{b/\text{cdm}}$ and $T_0$, see Ref.[37]).

The $w$CDM models introduce one more MCMC parameter $w$. Beyond that, the EDE-like models have additional parameters \{$\omega_{scf}, \ln(1 + z_c)$\}. As described in Refs.[14, 15, 21], $z_c$ is the redshift at which the field $\phi$ starts rolling and $\omega_{scf} = \rho_{\phi}/\rho_{\text{tot}}$ is the energy fraction of EDE at $z_c$. Moreover, the $\alpha$AdS model (4) has yet a parameter $\gamma$. Once \{$\omega_{scf}, \ln(1 + z_c), \gamma$\} are fixed, $V_\Lambda$ will be set by matching the budget equation $\Omega_{DE} = 1 - \Omega_m - \Omega_r$. The field initially sits around the high plateau $3 \omega_{scf} M_p^2 H^2(z_c) \sim e^{2\gamma}V_0$, so the minimal value $V_{\text{min}}$ of potential (4)

$$V_{\text{min}} \sim -3 \omega_{scf} M_p^2 H^2(z_c) e^{-2\gamma} + V_\Lambda$$

(6)
is roughly set by $\gamma$, $\omega_{\text{scf}}$, and $z_c$. When $\gamma \lesssim 13$, $V_{\text{min}} < 0$ is AdS-like, see (5).

B. Physical consideration

In our dataset, CMB and BAO play significant roles. Thus it is worthwhile to highlight their constraints on parameters $\{h_0, T_0, |w|, \bar{\omega}_m\}$, where $h_0 = H_0 \times (100\text{km/s/Mpc})^{-1}$, which helps to clarify the MCMC results in Sect-III C.

We assume a spatially-flat Universe, which is $w$CDM-like after recombination. We can Taylor expand $D_A(z_{\text{rec}})$ around a bestfit Planck $\Lambda$CDM model (by performing partial derivatives with respect to one of $\{h_0, T_0, |w|, \bar{\omega}_m\}$) to estimate its dependence on $\{h_0, T_0, |w|, \bar{\omega}_m\}$.

Using $\Omega_m \approx 0.3$ and $\Omega_{DE} \approx 0.7$, for fixed $\theta_{CMB}$ in (2), we have

$$ (r_s T_0) h_0^{0.19} T_0^{0.21} |w|^{-0.09} \bar{\omega}_m^{0.4} = \text{const.} \quad (7) $$

The BOSS experiment [46] sets the BAO angular scales as

$$ \theta_{BAO}^\parallel = r_d H(z_{\text{eff}})/(1 + z_{\text{eff}}) \quad \text{and} \quad \theta_{BAO}^\perp = \frac{r_d}{D_A(z_{\text{eff}})}, \quad (8) $$

where $z_{\text{eff}}$ is the effective redshift bins of BOSS DR12 data (i.e. $z_{\text{eff}} = 0.38, 0.51, 0.61$ [46]), and $r_d$ is the comoving sound horizon at the baryon drag epoch. Here, we take $z_{\text{eff}} = 0.61$ (the results at different $z_{\text{eff}}$ only exhibit slight difference). And for fixed $\theta_{BAO}^\parallel$ and $\theta_{BAO}^\perp$, we have

$$ \theta_{BAO}^\parallel : (r_d T_0) h_0^{0.51} T_0^{-0.27} |w|^{-0.26} \bar{\omega}_m^{0.24} = \text{const.} \quad (9) $$

$$ \theta_{BAO}^\perp : (r_d T_0) h_0^{0.75} T_0^{-0.63} |w|^{-0.17} \bar{\omega}_m^{0.12} = \text{const.} \quad (10) $$

C. $T_0-H_0$ in MCMC results

Table-I presents the MCMC results for $\Lambda$CDM and beyond-$\Lambda$CDM models, see also the corresponding $T_0-H_0$ contours in Fig-2. In Appendix-A, we also focus on the $\alpha$AdS model, and present the posterior distributions and marginalized contours of all the cosmological parameters and the bestfit $\chi^2$ values per experiment. As expected, the existence of an AdS phase near recombination can effectively lift $H_0$ to $\sim 73\text{km/s/Mpc}$ at $1\sigma$ region.

In Fig-2, we see that the $\Lambda$CDM+P18 contour respects Eq.(7) (the $\theta_{CMB}$ line). The $\Lambda$CDM+P18 contour intersects with the SH0ES band at $T_0 \sim 2.6K$, which is inconsistent
FIG. 2: Marginalized 1σ and 2σ contours in the $T_0$-$H_0$ plane. The gray band is the 1σ and 2σ SH0ES result $H_0 = 74.03 \pm 1.42$ km/s/Mpc [5]. The thick yellow line depicts the FIRAS 1σ region [34, 35]. Only the EDE models simultaneously lift $H_0$ and remain compatible with $T_{0,FIRAS}$.

However, the EDE scenario not only lifts $H_0$, but also is compatible with $T_{0,FIRAS}$. This can be explained as follows. In CMB and BAO constraints (7), (9) and (10), we have $|w| = 1$ for EDE scenarios. The Universe after recombination is $\Lambda$CDM-like, and $r_d \sim r_s$, since the physics at and after recombination must not be affected by EDE. Thus we (approximately) solve Eqs.(7), (9) and (10) for $T_0 = T_{0,FIRAS}$, and have

$$r_s h_0 \simeq const., \quad \bar{\omega}_m^{-1} h_0^2 \simeq const.$$  

Thus though $h_0$ is lifted due to $h_0 \sim r_s^{-1}$ (essence of the EDE idea), $T_0 = T_{0,FIRAS}$ needs
not to be shifted. The expense of compatibility with $T_{0,FIRAS}$ is that

$$\bar{\omega}_m = \left( \frac{h_0^2}{h_{0,\Lambda}^2} \right) \bar{\omega}_{m,\Lambda}$$  \hspace{1cm} (12)$$

must be magnified. According to (12), we actually have $\Omega_m \simeq \text{const}$ (equivalently $\Omega_m \simeq \Omega_{m,\Lambda}$), since $\omega_m = \Omega_m h_0^2$. As a consistency check of (12), for $h_{0,\Lambda} \sim 0.68$ and $\bar{\omega}_{m,\Lambda} \sim 0.14$ in $\Lambda$CDM (see Table-I), we will have $\bar{\omega}_m \sim 0.16$ in AdS-EDE models ($h_0 \sim 0.73$), consistent with the results in Table-I. We plot contours of $\{H_0, T_0, \bar{\omega}_m\}$ in Fig-3. As expected, $H_0$ is lifted respecting Eq.(12).

![Figure 3: Marginalized 1σ and 2σ contours of the EDE models in the \{T_0 - \bar{\omega}_m - H_0\} space. $T_{0,FIRAS}$ and $H_0$ are plotted as described in Fig-2. The $\omega_m T_0^{-3} - H_0$ contours of all EDE models respect Eq.(12) (dashed line).](image)

In $\Lambda$CDM, $\omega_m$ is difficult to adjust since it is well constrained by Planck, but in EDE $\omega_m$ can be consistently tuned due to the scalar field perturbations, see Appendix-B. This
seems to cause a slight larger $\sigma_8$, so-called $S_8$ tension, e.g.[54], see also [55–57]. However, this tension is also present in $\Lambda$CDM with $\sim 2\sigma$ significance (inherited but not significantly exacerbated in EDE, as argued in [23, 58]), which might be related with systematic error or possible intrinsic inconsistency of Planck data itself [59, 60].

The low-$z$ resolutions beyond $\Lambda$CDM have been also studied in e.g.[28, 61–68]. It is usually thought that $w$CDM models with $w \simeq -1.3$ might resolve the Hubble tension, e.g.[40, 61, 69], though it is disfavored by the full BAO data. However, in Fig-2, we see that such a solution seems also incompatible with $T_{0,FIRAS}$.

The $w$CDM model, like $\Lambda$CDM, does not alter the physics around and before recombination, so $rST_0$ is constant [37]. It is well-known that $w$CDM with $w < -1$ is not supported by the full BAO data, e.g.recent Ref.[69], so we only solve Eqs.(7) and (10), and have

$$h_0^{-3}|w| \simeq \text{const.}, \quad T_0^{-8}|w| \simeq \text{const.}$$

(13)

Note (13) is conflicted with BAO constraint (9), see the black line in Fig-4. Here, if $|w| > 1$, $h_0 \propto |w|^{1/3}$ will be lifted. However, $T_0 \propto |w|^{1/8}$ must also be magnified, which will make $T_0$ inconsistent with the result (1) of $T_{0,FIRAS}$. Though we can fix $T_0 = T_{0,FIRAS}$, and have $h_0 \sim |w|^{9/19}$ for the CMB constraint (7), it is obviously conflicted with BAO constraints (9) and (10). As a consistency check of (13), for $h_0 \sim 0.68$ in $\Lambda$CDM, we will have $w \simeq -1.3$ in $w$CDM ($h_0 \sim 0.74$) but

$$T_0 \simeq T_{0,FIRAS}|w|^{1/8} \sim 2.8K,$$

(14)

which is consistent with the $w$CDM results in Table-I. Here, we confront $w$CDM with P18 and perpendicular BAO data ($\theta_{BAO}$). The contours of $\{H_0, T_0, w\}$ is plotted in Fig-4, which clearly shows the inconsistency of $w$CDM with $T_{0,FIRAS}$. As expected, $T_0$ is lifted respecting Eq.(14).

IV. CONCLUSION

It is well-known that $H_0$ and $T_0$ are basic cosmological parameters (specially not dimensionless). Precisely measured value $T_{0,FIRAS}$ of $T_0$ can be regarded as a censorship of beyond-$\Lambda$CDM models resolving the $H_0$ tension.

We, based on Eqs.(7), (9) and (10) (i.e. CMB and BAO constraints), identified why EDE is compatible with $T_{0,FIRAS}$, while lifting $H_0$. As a contrast, we also showed that $w$CDM
FIG. 4: Marginalized 1σ and 2σ contours of the $wCDM$ model in the $\{w-T_0-H_0\}$ space. $T_{0,FIRAS}$ and $H_0$ are plotted as described in Fig-2. Upper panel: The rainbow line plots compatible intersections of (7) and (10) at different $T_0$, with a color coding for $T_0$. As expected, the contour of the $wCDM$ model spreads along the predicted line. The black line plots the $\theta_{\parallel BAO}$ constraint (9) at $T_0 = 2.77 K$ (see Table-I), which suggests that $wCDM$ with $w \lesssim -1.3$ is not actually favored by BAO data. Lower Panel: In addition, such a $wCDM$ model is also inconsistent with $T_{0,FIRAS}$. Models with $w \lesssim -1.3$ seem inconsistent with $T_{0,FIRAS}$. We performed MCMC analysis for the corresponding models to confirm our observations. It has been pointed out in Ref.[37] that for $\Lambda$CDM, $T_0$ yielded by the Planck and SH0ES data has $>4\sigma$ discrepancy compared with $T_{0,FIRAS}$. However, we showed that EDE is compatible with not only $T_{0,FIRAS}$, but also local measurements of $H_0$. Our result suggests that even if EDE is not the final story restoring cosmological concordance, it might be on the right road. Relevant issues are worth studying.

Inspired by the $\alpha$-attractor [44, 45], we also presented a well-motivated AdS-EDE model.
In the MCMC analysis, we do not assume AdS \textit{in priori}, but in Fig-5 we see that the MCMC result weakly hints the existence of an AdS phase, with the bestfit cosmology having AdS depth $V_{\text{min}} \sim -(0.001 \text{ eV})^4$. The bestfit model allows $H_0 \sim 73 \text{ km/s/Mpc}$ at 1$\sigma$ range, which indicates that the existence of AdS phase around recombination helps to significantly lift $H_0$. Our result again highlights an unexpected point that AdS vacua, ubiquitous in consistent UV-complete theories, might also play a crucial role in our observable Universe.

**FIG. 5:** Marginalized contour of $T_0$ with respect to $V_{\text{min}}/\Lambda$. The axis $-\ln(1 - V_{\text{min}}/\Lambda)$ is chosen such that it is log scale when $-V_{\text{min}}/\Lambda \ll 1$ (deep in the AdS phase) and $V_{\text{min}}/\Lambda \to 1$, while it is linear around $V_{\text{min}} \sim 0$. Dashed line labels $V_{\text{min}} = 0$. Yellow band represents $T_{0,FIRAS}$.

**Acknowledgments** This work is supported by the University of Chinese Academy of Sciences. Y.S.P. is supported by NSFC, Nos. 11575188, 11690021. The computations are performed on the TianHe-II supercomputer.
Appendix A: MCMC results of the $\alpha$AdS model

In the MCMC analysis we sample over \{$\omega_b/T_0^{3}, \omega_{cdm}/T_0^{3}, H_0, \ln(10^{10}A_s T_0^{1+n_s}), n_s, \tau_{reio}, T_0, \omega_{scf}, \ln(1+z_c), \gamma$\}. We use flat priors for additional EDE parameters (Table-II). Here, we do not assume AdS \textit{in priori} in the MCMC analysis, since the $\gamma$ prior in Table-II covers non-AdS region of the potential, see Eq.(5). Posterior distributions and marginalized contours of all cosmological parameters are plotted in Fig-6. The mean and bestfit values are shown in Table-III. We also report the bestfit $\chi^2$ values per experiment in Table-IV.

Appendix B: Scalar field perturbations in EDE and $\omega_m$

When the EDE becomes non-negligible, the gravitational perturbation $\Psi$ will be suppressed by the EDE perturbations [55]. In order to preserve the fit to the CMB data, $\omega_m$...
FIG. 6: Posterior distributions and marginalized 68% and 95% contours of all model parameters in the \( \alpha \)AdS model confronted with the full datasets P18+BAO+SN+\( H_0 \).

must increase accordingly to compensate for the slight suppress in \( \Psi \).

We plot the evolution of \( \Psi \) in Fig-7. Two EDE lines are nearly identical at high-\( z \) due to the same cosmological parameters except for \( \omega_{cdm} \). However, they will not coincide any longer when EDE becomes non-negligible. \( \Psi \) in the \( \phi^4 \)AdS model with fixed \( \omega_{cdm} = 0.122 \) is suppressed compared with that in the bestfit \( \phi^4 \)AdS model. This is because in the bestfit \( \phi^4 \)AdS model such suppression will be compensated by the gravity of extra dark matter
TABLE IV: bestfit $\chi^2$ per experiment

| Experiment               | $\chi^2$  |
|--------------------------|-----------|
| Planck high $l$          | 2347.44   |
| Planck low $l$           | 416.89    |
| Planck lensing           | 11.79     |
| BAO BOSS DR12            | 0.66      |
| BAO low $z$              | 2.46      |
| Pantheon                 | 1026.94   |
| SH0ES                    | 1.33      |

FIG. 7: Evolution of $\Psi$ with $k = 2\pi/r_s$, which roughly corresponds to the first acoustic peak, plotted for the bestfit models of $\Lambda$CDM and $\phi^4$AdS. The green line is produced by a $\phi^4$AdS model with reduced $\omega_{cdm}$ while fixing all other parameters to the bestfit.

abundance, which lifts $\Psi$ at recombination to the $\Lambda$CDM value (dashed line), so produces
correct power in the CMB TT spectrum.

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