Letter

Dark sector to restore cosmological concordance

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(Received 20 May 2021; accepted 27 September 2021; published 27 October 2021)

We develop a new phenomenological model that addresses current tensions between observations of the early and late Universe. Our scenario features: (i) a decaying dark energy fluid (DDE) with a transition at $z \sim 5,000$, to raise today's value of the Hubble parameter, and (ii) an ultralight axion (ULA), which starts oscillating at $z \gtrsim 10^4$, to suppress the matter power spectrum. Our Markov chain Monte Carlo analyses show that such a dark sector model fits a combination of cosmic microwave background (CMB), baryon acoustic oscillations, and Large Scale Structure (LSS) data slightly better than the ΛCDM model, while importantly reducing both the H_0 and S_8 tensions with late universe probes ($\lesssim 3\sigma$). Combined with measurements from cosmic shear surveys, we find that the discrepancy on S_8 is reduced to the 1.4σ level. Adding local supernovae measurements, we find that the H_0 and S_8 tensions are reduced to the 1.4σ and 1.2σ levels respectively, with a significant improvement $\Delta\chi^2 \simeq -18$ compared to the ΛCDM model. With this complete dataset, the DDE and ULA are detected at $\simeq 4\sigma$ and $\simeq 2\sigma$, respectively. We discuss a possible particle physics realization of this model, with a dark confining gauge sector and its associated axion, although embedding the full details within microphysics remains an urgent open question. Our scenario will be decisively probed with future CMB and LSS surveys.

DOI: 10.1103/PhysRevD.104.L081303

I. INTRODUCTION

Observations by the Planck satellite of the cosmic microwave background (CMB) indicate a Universe expanding today at a (Hubble) rate of $H_0 = 67.27 \pm 0.60$ km/s/Mpc [1], assuming the Λ cold dark matter (ΛCDM) model. This is in strong (4.4σ) tension with local measurements based on supernovae from the SH_0ES Collaboration [2], which report a faster rate of $H_0 = 74.03 \pm 1.42$ km/s/Mpc (see also [3]). The discrepancy between early and late Universe determinations of H_0 appears to be supported by several other probes [e.g., lensing time delays [4], and baryon acoustic oscillations (BAO) and BOSS galaxy clustering data analyzed with the Effective Field Theory of LSS [5–10] (EFTofLSS)].

Further disagreement arises in the determination of the amplitude of the matter power spectrum at late times, which is often parametrized by means of the combination $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$ (Ω_m and σ_8 being respectively the total relic abundance of nonrelativistic matter and the variance of matter fluctuations in a sphere of radius 8 Mpc$/h$ today). In particular, a recent combination of data from cosmic shear surveys finds $S_8 = 0.755^{+0.019}_{-0.021}$ [11,12], in 3.2σ tension with the value inferred by the Planck collaboration (see also [13–17] for other measurements).

A resolution of these tensions based on systematic errors is currently lacking. It is possible that the above discrepancies may be resolved instead by modifying the cosmological (ΛCDM) model used to infer values of parameters from early Universe probes. A notable attempt in this direction is the addition of an early dark energy (EDE) component [18] (see also [19,20]) that is very rapidly diluted after the epoch of matter radiation equality. This scenario significantly alleviates the Hubble tension when fitted to a combination of Planck, BAO, and supernovae data, but exacerbates the S_8 tension. Therefore, when cosmic shear as well as EFTofLSS data are included, the resolving power of EDE is reduced [21–25]. EDE also relies on a scalar field with a highly tuned potential [26]. A somewhat more particle-physics-oriented scenario is that of a strong first order phase transition in a weakly coupled scalar field at the eV scale, as proposed in the new early dark energy (NEDE) scenario [27–29]. However, this similarly increases the S_8 tension, while other well-motivated scenarios, such as decay through resonance [26] (see also [30]) or modified gravity models (see e.g., [31–37]) struggle to provide convincing solutions.

In this paper, we propose a new phenomenological dark sector (DS) model, which is instead able to more fully restore cosmological concordance by predicting both a larger expansion rate and a suppressed matter power

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spectrum at late times. Our model features both a decaying dark energy (DDE) component, which addresses the Hubble tension similarly to the EDE and NEDE scenarios, as well as an ultralight axion (ULA) field with a standard potential and generic initial conditions. By virtue of the misalignment mechanism, this axion contributes a fraction of the relic abundance of dark matter (DM) today. However, in contrast to CDM, it causes a suppression of power on small scales, due to the scale-dependent sound speed of its perturbations [38–40], and thus addresses the S_8 tension (see also [41] for a different ULA model with similar goals).

II. PHENOMENOLOGICAL MODEL

Our DS model is composed of two ingredients:

(1) A DDE fluid which undergoes a sharp transition at some redshift $z_{\rm dde}$, after which its equation of state parameter changes from $w = -1$ to $w = w_f > 1/3$.
(2) A ULA field a with a potential of the standard form $V = m_a^2 f_a^2 (1 - \cos a/f_a)$, where m_a and f_a are the axion mass and decay constant, respectively.

For the DDE fluid, we adopt the effective fluid modeling put forth in the NEDE scenario of [27,28] to perform a concrete numerical analysis. This model is general enough to capture the effective behavior of several possible microscopic scenarios. Its crucial features are: At the background level, the transition at $z_{\rm dde}$ is assumed to occur in much less than a Hubble time, and is thus modeled as instantaneous. The redshift $z_{\rm dde}$ is set by a subdominant "trigger" scalar field of mass $m_{\rm t}$ once the rolling condition $H \simeq m_{\rm t}$ is satisfied. Cosmological perturbations of the DDE fluid are initially set to vanish and then are reinitialized around $z_{\rm dde}$ by using the perturbations of the trigger field as initial conditions. Subsequently, they are treated as those of an ideal cosmic fluid with adiabatic sound speed $c_s^2 = w_f$. Overall, the NEDE/DDE fluid introduces four extra parameters to the ΛCDM model: (i) the fraction $F_{\rm dde}$ of the energy density in the DDE fluid at $z \geq z_{\rm dde}$, (ii) the mass of the trigger field, or equivalently, the redshift $z_{\rm dde}$ of the transition, (iii) the equation of state parameter w_f, and (iv) the precise value of the ratio $H/m_{\rm t}$, at which the trigger field starts rolling. However, the latter two parameters would be fixed once a particle physics model is specified. Thus, we fix $H/m_{\rm t} = 0.2$, justified by the dynamics of a generic scalar field. We also fix $w_f = 2/3$, as in [28], although our conclusions are not strongly affected by the precise value of w_f, as long as $w_f \gtrsim 0.5$, see also [20,28]. Overall, this leaves just two free parameters from the DDE component.

Let us now comment on the ULA component. At early times such an axion field behaves as dark energy with $w = -1$. Once $H \lesssim m_a$, the axion starts oscillating and eventually behaves as a dark matter component at late times, according to the misalignment mechanism. However, its effects on the growth of structures can deviate crucially from those of cold DM. In a Universe where the DM is made of ULAs, subhorizon matter perturbations with wavenumbers above the axion Jeans wave number $k_J/a = 6^{1/4}\sqrt{Hm_a}$ do not grow during matter domination, but rather oscillate [38–40] (see also [42]). In a Universe where a ULA makes up a fraction $r_a \equiv \Omega_a/\Omega_{\rm dm}$ of the DM, it can be shown that the suppression of the matter power spectrum is roughly $(\mathcal{P}^k_{a+cdm}/\mathcal{P}^k_{cdm})_{k>k_{J,0}} \sim (k_{J,\rm eq}/k)^{8(1-\gamma)}$ [42], where $\gamma = (-1+\sqrt{25-24r_a})/4$ and $k_{J,\rm eq}/a_0 \simeq 0.09\ {\rm Mpc}^{-1}(m_a/10^{-26}\ {\rm eV})$ is the Jeans wave number at equality. This estimate suggests that suppression of ∼7% of the matter power spectrum at the scales probed by the S_8 parameter can be obtained if the Universe contains an axion with $m_a \lesssim 10^{-26}$ eV and $r_a \sim 0.05$.

At the particle physics level, a ULA is fully described by the additional three parameters: (v) its mass m_a, (vi) its decay constant f_a, and (vii) its initial field value, $\theta_i = a_i/f_a$. However, this last parameter is most reasonably $\mathcal{O}(1)$, unless further tuning or model building is invoked. We choose a typical value $\theta_i = 2$, although the precise choice does not alter our conclusions. Once this parameter is fixed, m_a and f_a can be traded for the redshift at which axion oscillations begin, z_a, and r_a. This leaves us with two parameters from this component also.

III. DATASETS AND RESULTS

We have numerically implemented the DS model presented in the previous section, by merging two publicly available extensions of the Boltzmann code `CLASS` [43]: `TriggerCLASS` [44], developed in [27,28] to study the NEDE scenario, and `AxiCLASS` [45], developed in [46,47]. This latter code uses the state-of-the-art effective fluid model of [46] to compute the cosmological implications of ULAs. We have then performed an MCMC analysis of our DS model, using the `MontePython` sampler [48,49] also to find the χ^2, while we analyzed and plotted posterior distributions using `GetDist` [50,51].

After the choices described above, our DS model features four free parameters in addition to the six parameters of the ΛCDM model: $F_{\rm dde}$, $z_{\rm dde}$, r_a and z_a. In order to obtain reliable results, we find it necessary to fix the parameter z_a in the MCMC analysis (see also [46,52,53] for a similar strategy). We then choose $z_a \simeq 10^{4.2}$, which corresponds to $m_a \simeq 10^{-26}$ eV, since this alleviates cosmological tensions most significantly. We keep the remaining three parameters free to vary, and comment on how our results are affected by a different choice of z_a or by also fixing $z_{\rm dde}$ in (the Supplemental Material) [54]. In addition, we model neutrinos as two massless plus one massive species with $m_\nu = 0.06$ eV, following the Planck collaboration.

We consider four different combinations of cosmological datasets in this work:

(i) **P18 + BAO**: Planck 2018 high-ℓ and low-ℓTT, TE, EE, and lensing data [1]; BAO measurements from

TABLE I. The mean (best-fit) $\pm 1\sigma$ error of the cosmological parameters obtained by fitting our three-parameter DS model to the four cosmological datasets described in the text. The discrepancy of the inferred values of H_0 and S_8 (both for ΛCDM and for the DS model) with respect to SH_0ES and the combined analysis of [11], respectively, is shown, as well as the improvement in χ^2 with respect to ΛCDM [using the same datasets (the Supplemental Material) [54]].

Parameter	P18 + BAO		P18 + BAO + EFT		P18+BAO+EFT+S_8		P18+BAO+EFT+S_8+SN+H_0	
$100\omega_b$	$2.267(2.277)^{+0.022}_{-0.026}$		$2.265(2.289)^{+0.020}_{-0.027}$		$2.274(2.28)^{+0.020}_{-0.026}$		$2.303(2.295)^{+0.023}_{-0.025}$	
ω_{cdm}	$0.1241(0.1261)^{+0.0031}_{-0.0044}$		$0.1227(0.127)^{+0.0027}_{-0.0040}$		$0.1191(0.12)^{+0.0025}_{-0.0035}$		$0.1235(0.1238)^{+0.0030}_{-0.0029}$	
$\ln 10^{10}A_s$	$3.057(3.051)^{+0.015}_{-0.015}$		$3.054(3.058)^{+0.015}_{-0.015}$		$3.050(3.047)^{+0.015}_{-0.015}$		$3.062(3.057)^{+0.015}_{-0.015}$	
n_s	$0.9761(0.9784)^{+0.0074}_{-0.0089}$		$0.9743(0.9864)^{+0.0067}_{-0.0087}$		$0.9738(0.9748)^{+0.0065}_{-0.0083}$		$0.9860(0.9828)^{+0.0065}_{-0.0066}$	
τ_{reio}	$0.0565(0.0518)^{+0.0068}_{-0.0075}$		$0.0561(0.0551)^{+0.0068}_{-0.0075}$		$0.0557(0.0545)^{+0.0071}_{-0.0071}$		$0.0574(0.0562)^{+0.0069}_{-0.0077}$	
H_0[km/s/Mpc]	$69.3(69.3)^{+1.0}_{-1.4}$		$69.09(70.58)^{+0.86}_{-1.4}$		$69.37(70.02)^{+0.85}_{-1.4}$		$71.56(70.99)^{+0.98}_{-0.98}$	
F_{dde}	<0.137[95%](0.077)		<0.124[95%](0.11)		<0.127[95%](0.073)		$0.124(0.123)^{+0.034}_{-0.029}$	
z_{dde}	$5168(5452)^{+1100}_{-1300}$		$5193(5352)^{+1300}_{-1600}$		$5055(4440)^{+1300}_{-1600}$		$4749(4894)^{+640}_{-820}$	
$r_a \equiv \Omega_a/\Omega_{\rm dm}$	<0.032[95%](0.005)		<0.039[95%](0.014)		<0.069[95%](0.037)		$0.048(0.052)^{+0.017}_{-0.017}$	
$\log_{10} z_a$	Fixed to: 4.2		Fixed to: 4.2		Fixed to: 4.2		Fixed to: 4.2	
$m_a[10^{-26}$ eV]	(1.15)		(1.15)		(1.14)		(1.15)	
$f_a[10^{16}$ GeV]	<9.565[95%](3.816)		<10.438[95%](6.114)		<14.34[95%](9.908)		$11.2(12.0)^{+2.4}_{-1.9}$	
S_8	$0.827(0.838)^{+0.016}_{-0.013}$		$0.820(0.826)^{+0.017}_{-0.014}$		$0.788(0.783)^{+0.016}_{-0.015}$		$0.784(0.789)^{+0.014}_{-0.014}$	
	ΛCDM	DS	ΛCDM	DS	ΛCDM	DS	ΛCDM	DS
Tension with SH_0ES	4.4σ	2.7σ	4.3σ	3.0σ	4.0σ	2.8σ	3.7σ	1.4σ
Tension with S_8	3.3σ	3.1σ	3.2σ	2.8σ	2.6σ	1.4σ	2.2σ	1.2σ
$\chi^2_{DS} - \chi^2_{\Lambda\rm CDM}$	−4.0		−1.6		−7.7		−17.9	

6dFGS at $z = 0.106$ [55], SDSS MGS at $z = 0.15$ [56] (BAO smallz), and CMASS and LOWZ galaxy samples of BOSS DR12 at $z = 0.38$, 0.51, and 0.61 [57]. For the latter, we use the "consensus" BAO + FS likelihood which also includes measurement of the growth function $f\sigma_8(z)$ (FS) from the same samples.

(ii) **P18 + BAO + EFT**: the datasets above with the addition of information from the full shape of the power spectrum of galaxies in the BOSS/SDDS sample, extracted by means of the EFTofLSS [8–10]. This is implemented with the publicly available `PyBird` code [58,59] as a combined likelihood with BAO data from the same sample.

(iii) **P18 + BAO + EFT + S_8**: the datasets above with the addition of a split-normal prior on S_8, chosen according to the recent analysis of DES data in combination with KiDS/Viking [11], i.e., $S_8 = 0.755^{+0.019}_{-0.021}$.

(iv) **P18 + BAO + EFT + S_8 + SN + H_0**: the datasets above with the addition of the Pantheon Supernovae data sample [60] (SN) and the SH_0ES measurement of the Hubble parameter $H_0 = 74.03 \pm 1.42$ km/s/Mpc [2].

Before presenting our numerical results, an important caveat on the S_8 prior is in order. The use of such a prior as an approximation for the full weak-lensing likelihoods has been shown to be justified in the ΛCDM and EDE models [21]. For ULAs, assessing the impact of the full likelihoods requires a dedicated treatment of nonlinearities. Lacking such tools (see e.g., [61] for a discussion), we restrict our analysis to the linear power spectrum, except for nonlinearities computed in the `PyBird` likelihood, and assume that the use of a prior on S_8 correctly captures the constraints from the full DES and KiDS/Viking likelihoods on our DS model.

Our results for cosmological parameters are reported in Table I, while posterior distributions are plotted in Fig. 1. They have been obtained with at least eight chains per dataset, and $R - 1 < 0.03$ to satisfy the Gelman-Rubin criterion [62]. Detailed model comparisons and results for the matter and temperature anisotropy power spectra are reported in (the Supplemental Material) [54]. We assess tensions by computing $|A - B|/(\sqrt{\sigma_A^2 + \sigma_B^2})$, where A and B ($\sigma_{A,B}$) are the mean values (1σ errors) of H_0 (or S_8) inferred from the MCMC analysis and from the measurements, respectively (the Supplemental Material) [54].

Let us first comment on results obtained with the Planck + BAO dataset only: The abundances of both DS components are consistent with zero at 2σ, yet this dataset allows for a non-negligible fraction of the DM to be in the form of a ULA, up to ∼3% at 2σ (see [46,52] for previous similar bounds). The same is true for the DDE component, whose fraction of the total energy density at the redshift

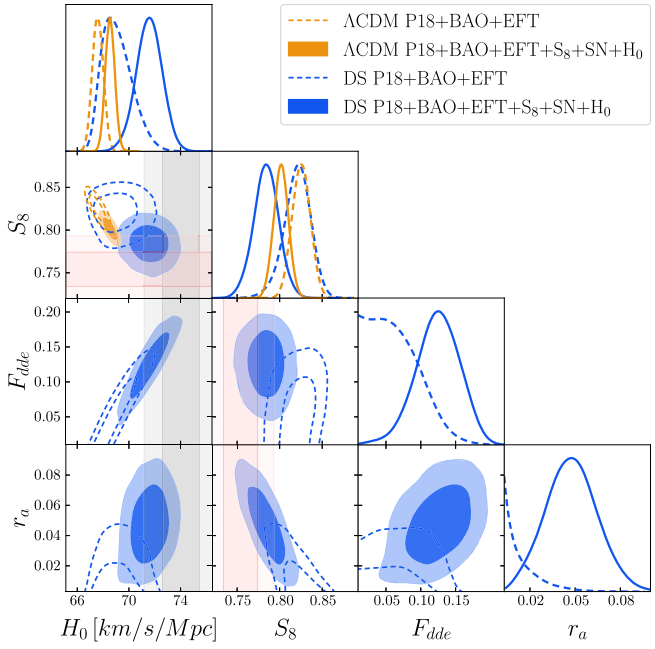

FIG. 1. Marginalized one-dimensional and two-dimensional posteriors for H_0 and S_8 in the ΛCDM and the DS models. For the latter, $F_{\rm dde}$ and r_a posteriors are also shown. In grey are shown the 1-σ (darker) and 2-σ (lighter) ranges for H_0 from $\mathrm{SH_0ES}$, and similarly the S_8 value from the joint analysis of [11] is shown in pink.

$z_{\rm dde} \gtrsim 5,000$ is allowed to be as large as $\sim$14% at 2σ, with a mild preference for $F_{\rm dde} \sim 7\%$. These features lead to a significant alleviation of the H_0 tension as compared to ΛCDM: the value of H_0 inferred in the DS model is only in 2.7σ tension with $\mathrm{SH_0ES}$, in contrast to 4.4σ for ΛCDM. At the same time, the S_8 tension is also ameliorated, albeit less dramatically. Overall, the DS model improves the fit to this dataset as compared to ΛCDM, although only very mildly, having $\Delta\chi^2 \simeq -4$ with three free extra parameters. The crucial point, however, is that in the DS model, both the H_0 and the S_8 tensions can be interpreted as moderate statistical fluctuations, weaker than in both the ΛCDM and EDE/NEDE models; see also (the Supplemental Material) [54]. This conclusion is only minimally altered by the addition of the EFT likelihood, with both tensions falling to the 3σ or below level in the combined dataset, $\Delta\chi^2 \simeq -2$, and the upper bound on r_a relaxed to 4%, (in agreement with [53], models with significantly lighter ULAs [41], are strongly constrained (the Supplemental Material) [54]), with a best-fit value of $r_a \sim 1\%$, which corresponds to $f_a \sim 6 \times 10^{16}$ GeV. These are the first important results of this work.

It therefore seems justified to combine the Planck + BAO + EFT dataset with a prior on S_8. Very interestingly, while the DDE component is almost unaffected by this addition, we notice that the best-fit value of r_a is raised to $\mathcal{O}(4\%)$, while fractions up to $\sim$7% are allowed at 95% C.L., see also (the Supplemental Material) [54]. As a consequence, we obtain the second important result of this work: the tension with cosmic shear measurements is very significantly reduced to 1.4σ level, as compared to 2.6σ under ΛCDM. Notice that the H_0 tension is also slightly relieved by these data, and the fit is significantly improved compared to ΛCDM ($\Delta\chi^2 \simeq -8$). These features are in stark contrast with previous attempts to restore cosmological concordance (see [21,22] and (the Supplemental Material) [54]).

Interpreting the residual 2.8σ tension on H_0 as a moderate statistical fluctuation, it therefore seems justified to also combine the previous dataset with the local measurements from $\mathrm{SH_0ES}$ and Pantheon. This leads to the third important result of this work, a significant improvement of the fit to data as compared to ΛCDM, $\Delta\chi^2 \simeq -18$ (with three extra parameters and z_a fixed), driven mainly by a dramatically better fit to $\mathrm{SH_0ES}$ and the S_8 prior. The DDE component is now detected at $\simeq 4\sigma$ (defined as 4× the 1σ interval), with a preference for $F_{\rm dde} \simeq 12\%$ at $z \sim 5,000$. The preference for the ULA component is also increased, with a vanishing relic abundance excluded at $\simeq 2\sigma$ in the posterior distributions, and its best-fit value being $r_a \sim 5\%$, which corresponds to $f_a \sim 10^{17}$ GeV, as expected from the earlier discussion of the model. These detections are the fourth important result of this work. With this combined dataset, both the S_8 and H_0 tensions are essentially resolved in our DS model, again in stark contrast with the ΛCDM and EDE/NEDE models (see (the Supplemental Material) [54] and [21–23]). Using the Akaike Information Criterium (AIC) [63] (see also [64]): $\Delta\mathrm{AIC} = \Delta\chi^2 + 2\Delta N$, where ΔN is the number of additional parameters compared to the ΛCDM model, we find $\Delta\mathrm{AIC_{DS}} = -11.9$ considering the three parameters of the DS model that we scan over in our MCMC analysis. By means of $p = \exp(-\Delta\mathrm{AIC}/2)$, we find that the DS model has strong evidence over ΛCDM according [65].

Overall, we conclude that our DS model can restore cosmological concordance when a wide combination of early and late time datasets is considered. Importantly, both the S_8 and H_0 tensions remain below the $\simeq 3\sigma$ level even when the model is confronted with early time datasets only.

IV. DISCUSSION

We would now like to explore whether the features of our phenomenological DS model can arise within a plausible particle physics scenario. The presence of ULAs with standard potentials is natural and appears to be a generic prediction of extra-dimensional ultraviolet (UV) theories such as String Theory, where the required $f_a \sim 10^{17}$ GeV is a reasonable value [66,67]. These would-be massless particles get their potential from nonperturbative physics, e.g., from instantons of a gauge theory that confines at some scale Λ_c. In this case, the natural expectation is

$m_a \simeq \Lambda_c^2/f_a$. The values of m_a and f_a obtained in our analysis then suggest the existence of a confining dark gauge theory with $\Lambda_c \sim 1$ eV. For a unified model, can this gauge theory play the role of the DDE fluid? To answer this question, we need to address two separate aspects: (I) Can a confining gauge sector behave as dark energy at early times, at least sufficiently before matter-radiation equality? (II) Can it then behave as a fluid with $w > 1/3$ below its confinement scale, at least for a sufficient amount of time after equality?

First, confining gauge sectors do indeed generically feature two very distinct behaviors in their cosmological history: On the one hand, for $T_{\rm DS} \gg \Lambda_c$ they are in a deconfined phase and their elementary constituents ("quarks" and "gluons") behave as relativistic components. On the other hand, for $T_{\rm DS} \ll \Lambda_c$ they are in the confined phase, where massive bound states ("hadrons") form. A PT normally occurs around the critical temperature $T_{{\rm DS},c} \lesssim \Lambda_c$.

Very interestingly, confinement PTs can be of first order kind in several simple examples (see e.g., [68,69]), in which case they may also naturally exhibit the phenomenon of strong *supercooling*, where the PT is delayed to $T_{\rm DS,n} \ll T_{{\rm DS},c}$. At temperatures $T_{\rm DS,n} \lesssim T_{\rm DS} \lesssim T_{{\rm DS},c}$, the confining sector is dominated by the vacuum energy gap between the two phases (see [69] and [70–72] for discussions in the context of strongly coupled solutions to the hierarchy problem). This can reproduce the required dark energy behavior of the DDE fluid up to sufficiently high redshifts. Further details on this possibility are provided in (the Supplemental Material) [54].

Having established that dark energy behavior is feasible at early times, we now turn to the required $w > 1/3$ behavior at late times. The generic expectation after a first order PT is that bubble collisions lead to an initially relativistic bath of DS states. Nonetheless, the authors of [28] have argued in favor of $w > 1/3$ after a first order PT as a consequence of subhorizon anisotropies and nonlinearities.

Here, we would like to suggest an alternative, albeit speculative, possibility. The equation of state (EoS) of a confining gauge theory can be affected by parameters beyond temperature; for instance, general arguments suggest that at very large "baryon" densities, the EoS can indeed be stiff [73], i.e., $c_s^2 > 1/3$ (see also [74,75] for a discussion in the context of neutron star cores, and e.g., [76,77] for holographic models). Furthermore, a recent holographic model with a cosmological first order confinement PT and a stiff EoS below the nucleation temperature was presented in [78], where it was found that the stiffness increases as the PT becomes strongly supercooled.

Yet another strategy is to realize the DDE fluid, abandoning the connection with the ULA potential, is to make use of one or more homogeneous scalar fields that approach a near vanishing potential, thus becoming kinetically dominated, leading to $w > 1/3$ at late times.

Whether these possibilities for $w > 1/3$ are viable is a very interesting question for future exploration.

Finally, let us discuss further the possible constraints/signatures of our DS model. For $m_a \sim 10^{-26}$ eV, the state-of-the-art constraint on r_a from the Lyman-α forest is $r_a \leq 0.18$ at 95% C.L. [42], which is far from the 2σ upper value obtained in our MCMC analysis. The presence of a ULA in our mass range can also affect halo formation. However, existing analyses of high-z galaxies do not constrain the axion DM fraction considered in this work [79] (see also [80,81]).

However, it is anticipated that future CMB-S4 can detect a fraction of DM in a ULA with $m_a \sim 10^{-26}$ eV at the percent level [82] (see also [83]). Future Large Scale Structure surveys, such as *Euclid* [84], DESI [85], WFIRST/Roman [86] and the Vera Rubin Observatory [87] will also further probe the existence of a DDE component. Hence upcoming observations should be able to confirm or rule out our DS model.

ACKNOWLEDGMENTS

We would like to thank Vivian Poulin for help in setting up `AxiCLASS`, Guido D'Amico for support with `PyBird` and Evan McDonough for discussions on the S_8 prior. We also thank Mark Alford for discussions on the equation of state of QCD matter in neutron stars. We thank Florian Niedermann and Martin Sloth for useful comments on a first version of this paper. We acknowledge use of Tufts HPC research cluster. The work of M. P. H. and F. R. is supported in part by National Science Foundation Grant No. PHY-2013953.

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