# Dark sector to restore cosmological concordance

Itamar J. Allali, Mark P. Hertzberg, and Fabrizio Rompineve

Phys. Rev. D **104**, L081303 — Published 27 October 2021

DOI: 10.1103/PhysRevD.104.L081303

# A Dark Sector to Restore Cosmological Concordance

Itamar J. Allali,* Mark P. Hertzberg,† and Fabrizio Rompineve‡
*Institute of Cosmology, Department of Physics and Astronomy, Tufts University, Medford, MA 02155, USA*

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), which undergoes a transition at $z \sim 5,000$, to raise today's value of the Hubble parameter – addressing the "$H_0$ tension," and (ii) an ultra-light axion (ULA), which starts oscillating at $z \gtrsim 10^4$, to suppress the matter power spectrum – addressing the "$S_8$ tension." 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 $1.4\sigma$ level, and the value of $H_0$ is further raised. Adding local supernovae measurements, we find that the $H_0$ and $S_8$ tensions are reduced to the $1.4\sigma$ and $1.2\sigma$ level 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.

**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 "ΛCDM model". This is in strong ($4.4\sigma$) tension with local measurements based on supernovae from the $\mathrm{SH_0ES}$ collaboration [2], which report a faster rate $H_0 = 74.03 \pm 1.42$ 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 Large Scale Structure [5–10] (EFTofLSS)).

Further disagreement arises in the determination of the amplitude of the matter power spectrum at late times, which is often parameterized by means of the combination $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$ ($\Omega_m$ and $\sigma_8$ being respectively the total relic abundance of non-relativistic 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 $3.2\sigma$ 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]. On the fundamental physics side, EDE relies on an ultra light 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 Letter, 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 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 ultra-light 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 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). We test our DS model against a wide array of cosmological datasets, by performing dedicated Markov Chain Monte Carlo (MCMC) analyses.

This phenomenological model is useful to demonstrate the ingredients that appear to be required for all

* itamar.allali@tufts.edu
† mark.hertzberg@tufts.edu
‡ fabrizio.rompineve@tufts.edu

observations to fit together. As an example, our DS model may arise microscopically within a dark gauge theory sector, which confines via a first order phase transition (PT) slightly above the eV scale. The associated axion then naturally receives a small mass from gauge instantons, very much like the well-known case of the QCD axion. Assessing whether the required rapid dilution of the DS after the PT can be realized in a fundamental physics scenario remains a very interesting and urgent task.

**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. An 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 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 re-initialized around $z_{\rm dde}$ by using as initial conditions the perturbations of the trigger field. 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[1], (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. To set ideas, 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 $w_f \gtrsim 0.5$, while for smaller values the model falls short of alleviating the $H_0$ tension, see also [20, 28]. Overall, this leaves just two free parameters from the DDE component. In our numerical analysis, this is treated exactly like the NEDE fluid of [27, 28], while its microphysical origin may be different; see the discussion, where we also present some tentative ideas to achieve $w_f > 1/3$.

Let us now comment on the ULA component. Similar to the DDE fluid above, 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 dark matter (DM). Indeed, the effective sound speed of ULA perturbations is scale-dependent [38–40]. Therefore, in a Universe where the DM is made of ULAs, sub-horizon matter perturbations with wavenumbers above the axion Jeans wavenumber $k_J/a = 6^{1/4}\sqrt{H\, m_a}$ do not grow during matter domination, but rather oscillate (see also [43] for a recent discussion). In a Universe where an 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 $\left(\mathcal{P}^k_{a+cdm}/\mathcal{P}^k_{cdm}\right)_{k>k_{J,0}} \sim (k_{J,{\rm eq}}/k)^{8(1-\gamma)}$ [43], 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 wavenumber at equality. This estimate suggests that suppression of $\sim 7\%$ 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, an 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 the fraction of the total energy density in the axion field at $z_a$. The latter can alternatively be replaced by $r_a$. This leaves us with two parameters from this component also.

The two ingredients that make up our DS should both feature a transition a little before the epoch of matter-radiation equality, if they are to address cosmological tensions. This opens up the possibility of a common fundamental origin, which we will discuss later.

**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` [44]: `TriggerCLASS`[2], developed in [27, 28] to study the NEDE scenario, and `AxiCLASS`[3], developed in [45, 46]. This latter code uses the state-of-the-art effective fluid model of [45] to compute the cosmological implications of ULAs. We have then performed an MCMC analysis of our DS model,

[1] Strictly speaking, $z_{\rm dde}$ also depends mildly on $H(z)$, which is affected by the presence of the DDE, but since $F_{\rm dde} \ll 1$, $z_{\rm dde}$ is nearly fixed once a value of $m_{\rm t}$ is specified. A similar remark applies to the ULA component.

[2] https://github.com/flo1984/TriggerCLASS

[3] https://github.com/PoulinV/AxiCLASS

| Parameter | P18+BAO | | P18+BAO+EFT | | P18+BAO+EFT+S$_8$ | | P18+BAO+EFT+S$_8$+SN+H$_0$ | |
|---|---|---|---|---|---|---|---|---|
| $100\omega_b$ | $2.267\ (2.277)^{+0.022}_{-0.026}$ | | $2.265\ (2.289)^{+0.020}_{-0.027}$ | | $2.274\ (2.28)^{+0.020}_{-0.026}$ | | $2.303\ (2.295)^{+0.023}_{-0.025}$ | |
| $\omega_{cdm}$ | $0.1241\ (0.1261)^{+0.0031}_{-0.0044}$ | | $0.1227\ (0.127)^{+0.0027}_{-0.0040}$ | | $0.1191\ (0.12)^{+0.0025}_{-0.0035}$ | | $0.1235\ (0.1238)^{+0.0030}_{-0.0029}$ | |
| $\ln 10^{10}A_s$ | $3.057\ (3.051)^{+0.015}_{-0.015}$ | | $3.054\ (3.058)^{+0.015}_{-0.015}$ | | $3.050\ (3.047)^{+0.015}_{-0.015}$ | | $3.062\ (3.057)^{+0.015}_{-0.015}$ | |
| $n_s$ | $0.9761\ (0.9784)^{+0.0074}_{-0.0089}$ | | $0.9743\ (0.9864)^{+0.0067}_{-0.0087}$ | | $0.9738\ (0.9748)^{+0.0065}_{-0.0083}$ | | $0.9860\ (0.9828)^{+0.0065}_{-0.0066}$ | |
| $\tau_{reio}$ | $0.0565\ (0.0518)^{+0.0068}_{-0.0075}$ | | $0.0561\ (0.0551)^{+0.0068}_{-0.0075}$ | | $0.0557\ (0.0545)^{+0.0071}_{-0.0071}$ | | $0.0574\ (0.0562)^{+0.0069}_{-0.0077}$ | |
| $H_0$ [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 | |
| $m_a\ [10^{-26}\ \rm eV]$ | (1.15) | | (1.15) | | (1.14) | | (1.15) | |
| $f_a\ [10^{16}\ \rm GeV]$ | $< 9.565$ [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$_0$ES | $4.4\sigma$ | $2.7\,\sigma$ | $4.3\sigma$ | $3.0\,\sigma$ | $4.0\sigma$ | $2.8\,\sigma$ | $3.7\sigma$ | $1.4\,\sigma$ |
| Tension with S$_8$ | $3.3\sigma$ | $3.1\,\sigma$ | $3.2\sigma$ | $2.8\,\sigma$ | $2.6\sigma$ | $1.4\,\sigma$ | $2.2\sigma$ | $1.2\,\sigma$ |
| $\chi^2_{DS} - \chi^2_{\Lambda CDM}$ | $-4.0$ | | $-1.6$ | | $-7.7$ | | $-17.9$ | |

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. Upper bounds are presented at 95% CL. The discrepancy of the inferred values of $H_0$ and $S_8$ (both for ΛCDM and for the DS model) with respect to SH$_0$ES and the combined analysis of [11] respectively is shown, as well as the improvement in $\chi^2$ with respect to ΛCDM (using the same datasets [42]).

using the `MontePython` sampler [47, 48][4] also to find the $\chi^2$, while we analyzed and plotted posterior distributions using `GetDist` [49][5].

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 [45, 50, 51] 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 [42]. 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:

- **P18+BAO**: Planck 2018 high-$\ell$ and low-$\ell$ TT, TE, EE, and lensing data [1]; BAO measurements from 6dFGS at $z = 0.106$ [52], SDSS MGS at $z = 0.15$ [53] (BAO smallz), and CMASS and LOWZ galaxy samples of BOSS DR12 at $z = 0.38$, $0.51$, and $0.61$ [54]. 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.

- **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 [55][6] as a combined likelihood with BAO data from the same sample.

- **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. $S_8 = 0.755^{+0.019}_{-0.021}$.[7]

- **P18+BAO+EFT+S$_8$+SN+H$_0$**: the datasets above with the addition of the Pantheon Supernovae data sample [56](SN) and the SH$_0$ES measurement of the Hubble parameter $H_0 = 74.03 \pm 1.42$ km/s/Mpc [2].[8]

[4] https://github.com/brinckmann/montepython_public
[5] https://getdist.readthedocs.io
[6] https://github.com/pierrexyz/pybird
[7] The joint analysis of KIDS1000+BOSS+2dfLenS [17] finds $S_8 = 0.766^{+0.02}_{-0.014}$. However, this is obtained using BOSS data and is thus not independent from the EFT and BAO likelihoods used in this work.
[8] Using instead the recent measurement $H_0 = 73.2 \pm 1.3$ km/s/Mpc [3] would not significantly alter our conclusions.

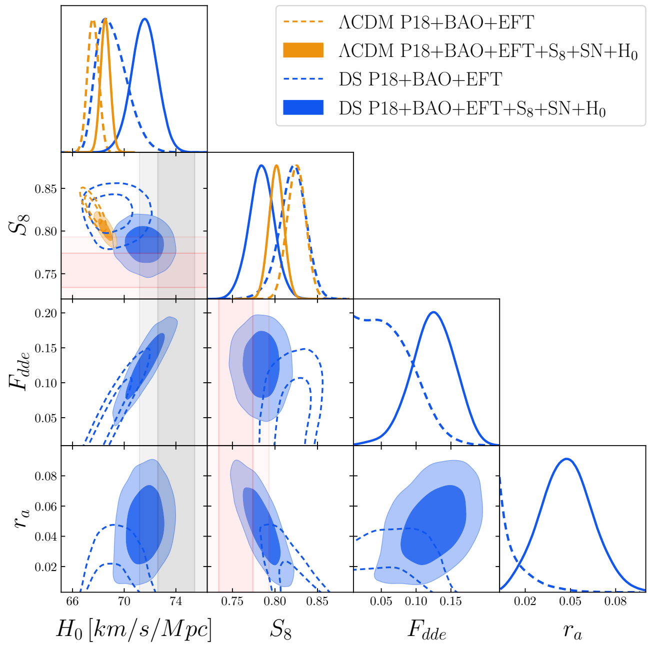


Figure 1. Marginalized 1D and 2D posteriors for $H_0$ and $S_8$ in the ΛCDM and the DS models, for two representative datasets. For the latter, $F_{\rm dde}$ and $r_a$ posteriors are also shown. In grey are shown the 1-$\sigma$ (darker) and 2-$\sigma$ (lighter) ranges for $H_0$ from SH$_0$ES, and similarly the $S_8$ value from the joint analysis of [11] is shown in pink.

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. [57] 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 [58]. Detailed model comparisons and results for the matter and temperature anisotropy power spectra are reported in the Supplemental Material [42]. We assess tensions by computing $|A-B|/(\sqrt{\sigma_A^2+\sigma_B^2})$, where $A$ and $B$ are the mean values of the parameter of interest ($H_0$ or $S_8$) inferred from the MCMC analysis and from the measurements respectively, while $\sigma_{A,B}$ are the $1\sigma$ errors in these values (for asymmetric errors, we use the upper and lower errors for $H_0$ and $S_8$ inferred from the MCMC analysis respectively, and the upper error from the $S_8$ prior) [42].[9]

Let us first comment on results obtained with the Planck+BAO dataset only: The abundances of both DS components are consistent with zero at $2\sigma$, yet this dataset allows for non-negligible fraction of the DM to be in the form of an ULA, up to $\sim 3\%$ at $2\sigma$ (see [45, 50] for previous similar bounds). The same is true for the DDE component, whose fraction of the total energy density at the redshift $z_{\rm dde} \gtrsim 5,000$ is allowed to be as large as $\sim 14\%$ at $2\sigma$, 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 $2.7\sigma$ tension with SH$_0$ES, in contrast to $4.4\sigma$ 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 [42]. This conclusion is only minimally altered by the addition of the EFT likelihood, with both tensions falling to the $3\sigma$ or below level in the combined dataset, $\Delta\chi^2 \simeq -2$, and the upper bound on $r_a$ relaxed to 4%,[10] 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% CL, see also [42]. As a consequence, we obtain the second important result of this work: the tension with cosmic shear measurements is very significantly reduced to $1.4\sigma$ level, as compared to $2.6\sigma$ 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 [42]).

Interpreting the residual $2.8\sigma$ tension on $H_0$ as a moderate statistical fluctuation, it therefore seems justified to also combine the previous dataset with the local measurements from SH$_0$ES and Pantheon. This leads to the third important result of this work, a

---

[9] This measure may overestimate the $H_0$ tension (when the $H_0$ prior is not included) in the DS model, since the $H_0$ posterior is somewhat non-Gaussian (as in EDE/NEDE). Alternative measures, see [59], would then further reduce the $H_0$ tension in our model.

[10] Previous constraints on ULAs were updated by [51], using a combination of BOSS and Planck 15 data. Our results are obtained with more recent CMB data. Models with significantly lighter ULAs than considered in our work, such as [41], are strongly constrained by the datasets above [42].

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 $4\times$ the $1\sigma$ 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 [42] and [21–23]). In order to further assess the improvement of the fit to this dataset, we use the Akaike Information Criterium (AIC) [60] (see also [61]): $\Delta\mathrm{AIC} = \Delta\chi^2 + 2\Delta N$, where $\Delta N$ is the number of additonal 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, and $\Delta\mathrm{AIC_{DS}} = -9.9$ if we also count $z_a$. Using $p = \exp(-\Delta\mathrm{AIC}/2)$, we find that the DS model has strong evidence over ΛCDM according to the revised Jeffreys' scale of [62].

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.

**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 UV theories such as String Theory, where the required $f_a \sim 10^{17}$ GeV is a reasonable value [63, 64]. These would-be massless particles get their potential from non-perturbative physics, e.g., from instantons of a gauge theory that confines at some scale $\Lambda_c$.[11] 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 $\Lambda_c \sim 1\,\mathrm{eV}$. 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, gauge theory 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.[12] 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 $T_{{\rm DS},c} \lesssim \Lambda_c$. Close to the PT, gauge theories can exhibit a wide range of phenomena and behaviors, depending on the gauge group and the matter content.

Very interestingly, confinement PTs can be of first order kind in several simple examples (see e.g. [66, 67]), 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 [67] and [68–70] 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 [42].

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. This is an interesting possibility which requires further investigation.

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 [71], i.e. $c_s^2 > 1/3$ (see also [72, 73] for a discussion in the context of neutron star cores, and e.g. [74, 75] for holographic models). Furthermore, a recent holographic model with a cosmological first order confinement PT and a stiff equation of state below the nucleation temperature was presented in [76], where it was found that the stiffness increases as the PT becomes strongly supercooled.

Yet another strategy 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 kinetic 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

[11] Non-perturbative UV contributions may also be present (see e.g. [63] and [65]).

[12] Here we use $T_{\rm DS}$ to denote the temperature of the confining DS, which can in general differ from that of the SM plasma.

$m_a \sim 10^{-26}$ eV, the state-of-the-art constraint on $r_a$ from the Lyman-$\alpha$ forest is $r_a \leq 0.18$ at 95% C.L. [43], which is far from the $2\sigma$ upper value obtained in our MCMC analysis. The presence of an 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 [77] (see also [78]). Nonetheless, these constraints may soon improve (see e.g. [79]).

However, it is anticipated that future CMB-S4 can detect a fraction of DM in an ULA with $m_a \sim 10^{-26}$ eV at the percent level [80] and that further improvements may be possible with intensity mapping of neutral hydrogen [81]. Future LSS surveys, such as *Euclid* [82], DESI [83], WFIRST/Roman [84] and the Vera Rubin Observatory [85] 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 MPH and FR is supported in part by National Science Foundation Grant No. PHY-2013953.

[1] **Planck** Collaboration, N. Aghanim et. al., *Planck 2018 results. V. CMB power spectra and likelihoods*, Astron. Astrophys. **641** (2020) A5, [arXiv:1907.12875].

[2] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri, and D. Scolnic, *Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond ΛCDM*, Astrophys. J. **876** (2019), no. 1 85, [arXiv:1903.07603].

[3] A. G. Riess, S. Casertano, W. Yuan, J. B. Bowers, L. Macri, J. C. Zinn, and D. Scolnic, *Cosmic Distances Calibrated to 1% Precision with Gaia EDR3 Parallaxes and Hubble Space Telescope Photometry of 75 Milky Way Cepheids Confirm Tension with ΛCDM*, Astrophys. J. Lett. **908** (2021), no. 1 L6, [arXiv:2012.08534].

[4] K. C. Wong et. al., *H0LiCOW – XIII. A 2.4 per cent measurement of H0 from lensed quasars: 5.3σ tension between early- and late-Universe probes*, Mon. Not. Roy. Astron. Soc. **498** (2020), no. 1 1420–1439, [arXiv:1907.04869].

[5] D. Baumann, A. Nicolis, L. Senatore, and M. Zaldarriaga, *Cosmological Non-Linearities as an Effective Fluid*, JCAP **07** (2012) 051, [arXiv:1004.2488].

[6] J. J. M. Carrasco, M. P. Hertzberg, and L. Senatore, *The Effective Field Theory of Cosmological Large Scale Structures*, JHEP **09** (2012) 082, [arXiv:1206.2926].

[7] M. P. Hertzberg, *Effective field theory of dark matter and structure formation: Semianalytical results*, Phys. Rev. D **89** (2014), no. 4 043521, [arXiv:1208.0839].

[8] T. Colas, G. D'amico, L. Senatore, P. Zhang, and F. Beutler, *Efficient Cosmological Analysis of the SDSS/BOSS data from the Effective Field Theory of Large-Scale Structure*, JCAP **06** (2020) 001, [arXiv:1909.07951].

[9] G. D'Amico, J. Gleyzes, N. Kokron, K. Markovic, L. Senatore, P. Zhang, F. Beutler, and H. Gil-Marín, *The Cosmological Analysis of the SDSS/BOSS data from the Effective Field Theory of Large-Scale Structure*, JCAP **05** (2020) 005, [arXiv:1909.05271].

[10] M. M. Ivanov, M. Simonović, and M. Zaldarriaga, *Cosmological Parameters from the BOSS Galaxy Power Spectrum*, JCAP **05** (2020) 042, [arXiv:1909.05277].

[11] M. Asgari et. al., *KiDS+VIKING-450 and DES-Y1 combined: Mitigating baryon feedback uncertainty with COSEBIs*, Astron. Astrophys. **634** (2020) A127, [arXiv:1910.05336].

[12] S. Joudaki et. al., *KiDS+VIKING-450 and DES-Y1 combined: Cosmology with cosmic shear*, Astron. Astrophys. **638** (2020) L1, [arXiv:1906.09262].

[13] C. Heymans et. al., *CFHTLenS tomographic weak lensing cosmological parameter constraints: Mitigating the impact of intrinsic galaxy alignments*, Mon. Not. Roy. Astron. Soc. **432** (2013) 2433, [arXiv:1303.1808].

[14] H. Hildebrandt et. al., *KiDS+VIKING-450: Cosmic shear tomography with optical and infrared data*, Astron. Astrophys. **633** (2020) A69, [arXiv:1812.06076].

[15] **DES** Collaboration, T. M. C. Abbott et. al., *Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing*, Phys. Rev. D **98** (2018), no. 4 043526, [arXiv:1708.01530].

[16] **HSC** Collaboration, C. Hikage et. al., *Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data*, Publ. Astron. Soc. Jap. **71** (2019), no. 2 Publications of the Astronomical Society of Japan, Volume 71, Issue 2, April 2019, 43, https://doi.org/10.1093/pasj/psz010, [arXiv:1809.09148].

[17] C. Heymans et. al., *KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints*, Astron. Astrophys. **646** (2021) A140, [arXiv:2007.15632].

[18] V. Poulin, T. L. Smith, T. Karwal, and M. Kamionkowski, *Early Dark Energy Can Resolve The Hubble Tension*, Phys. Rev. Lett. **122** (2019), no. 22 221301, [arXiv:1811.04083].

[19] P. Agrawal, F.-Y. Cyr-Racine, D. Pinner, and L. Randall, *Rock 'n' Roll Solutions to the Hubble Tension*, arXiv:1904.01016.

[20] M.-X. Lin, G. Benevento, W. Hu, and M. Raveri, *Acoustic Dark Energy: Potential Conversion of the Hubble Tension*, Phys. Rev. D **100** (2019), no. 6 063542, [arXiv:1905.12618].

[21] J. C. Hill, E. McDonough, M. W. Toomey, and S. Alexander, *Early dark energy does not restore cosmological concordance*, Phys. Rev. D **102** (2020), no. 4 043507, [arXiv:2003.07355].

[22] M. M. Ivanov, E. McDonough, J. C. Hill, M. Simonović, M. W. Toomey, S. Alexander, and M. Zaldarriaga, *Constraining Early Dark Energy with Large-Scale Structure*, Phys. Rev. D **102** (2020), no. 10 103502, [arXiv:2006.11235].

[23] G. D'Amico, L. Senatore, P. Zhang, and H. Zheng, *The Hubble Tension in Light of the Full-Shape Analysis of Large-Scale Structure Data*, arXiv:2006.12420.

[24] T. L. Smith, V. Poulin, J. L. Bernal, K. K. Boddy, M. Kamionkowski, and R. Murgia, *Early dark energy is not excluded by current large-scale structure data*, arXiv:2009.10740.

[25] R. Murgia, G. F. Abellán, and V. Poulin, *Early dark energy resolution to the Hubble tension in light of weak lensing surveys and lensing anomalies*, Phys. Rev. D **103** (2021), no. 6 063502, [arXiv:2009.10733].

[26] M. Gonzalez, M. P. Hertzberg, and F. Rompineve, *Ultralight Scalar Decay and the Hubble Tension*, JCAP **10** (2020) 028, [arXiv:2006.13959].

[27] F. Niedermann and M. S. Sloth, *New Early Dark Energy*, arXiv:1910.10739.

[28] F. Niedermann and M. S. Sloth, *Resolving the Hubble tension with new early dark energy*, Phys. Rev. D **102** (2020), no. 6 063527, [arXiv:2006.06686].

[29] F. Niedermann and M. S. Sloth, *New Early Dark Energy is compatible with current LSS data*, arXiv:2009.00006.

[30] N. Kaloper, *Dark energy, $H_0$ and weak gravity conjecture*, Int. J. Mod. Phys. D **28** (2019), no. 14 1944017, [arXiv:1903.11676].

[31] M.-X. Lin, M. Raveri, and W. Hu, *Phenomenology of Modified Gravity at Recombination*, Phys. Rev. D **99** (2019), no. 4 043514, [arXiv:1810.02333].

[32] J. Solà Peracaula, A. Gomez-Valent, J. de Cruz Pérez, and C. Moreno-Pulido, *Brans–Dicke Gravity with a Cosmological Constant Smoothes Out $\Lambda$CDM Tensions*, Astrophys. J. Lett. **886** (2019), no. 1 L6, [arXiv:1909.02554].

[33] J. Sakstein and M. Trodden, *Early Dark Energy from Massive Neutrinos as a Natural Resolution of the Hubble Tension*, Phys. Rev. Lett. **124** (2020), no. 16 161301, [arXiv:1911.11760].

[34] M. Zumalacarregui, *Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions*, Phys. Rev. D **102** (2020), no. 2 023523, [arXiv:2003.06396].

[35] G. Ballesteros, A. Notari, and F. Rompineve, *The $H_0$ tension: $\Delta G_N$ vs. $\Delta N_{\rm eff}$*, JCAP **11** (2020) 024, [arXiv:2004.05049].

[36] M. Braglia, M. Ballardini, W. T. Emond, F. Finelli, A. E. Gumrukcuoglu, K. Koyama, and D. Paoletti, *Larger value for $H_0$ by an evolving gravitational constant*, Phys. Rev. D **102** (2020), no. 2 023529, [arXiv:2004.11161].

[37] M. Braglia, M. Ballardini, F. Finelli, and K. Koyama, *Early modified gravity in light of the $H_0$ tension and LSS data*, Phys. Rev. D **103** (2021), no. 4 043528, [arXiv:2011.12934].

[38] M. Khlopov, B. A. Malomed, and I. B. Zeldovich, *Gravitational instability of scalar fields and formation of primordial black holes*, Mon. Not. Roy. Astron. Soc. **215** (1985) 575–589.

[39] W. Hu, *Structure formation with generalized dark matter*, Astrophys. J. **506** (1998) 485–494, [astro-ph/9801234].

[40] J.-c. Hwang and H. Noh, *Axion as a Cold Dark Matter candidate*, Phys. Lett. B **680** (2009) 1–3, [arXiv:0902.4738].

[41] L. W. Fung, L. Li, T. Liu, H. N. Luu, Y.-C. Qiu, and S. H. H. Tye, *Axi-Higgs Cosmology*, arXiv:2102.11257.

[42] See Supplemental Material at [] for further discussions on decaying dark energy from a confining gauge theory and for detailed model comparisons.

[43] T. Kobayashi, R. Murgia, A. De Simone, V. Iršič, and M. Viel, *Lyman-$\alpha$ constraints on ultralight scalar dark matter: Implications for the early and late universe*, Phys. Rev. D **96** (2017), no. 12 123514, [arXiv:1708.00015].

[44] D. Blas, J. Lesgourgues, and T. Tram, *The Cosmic Linear Anisotropy Solving System (CLASS) II: Approximation schemes*, JCAP **07** (2011) 034, [arXiv:1104.2933].

[45] V. Poulin, T. L. Smith, D. Grin, T. Karwal, and M. Kamionkowski, *Cosmological implications of ultralight axionlike fields*, Phys. Rev. D **98** (2018), no. 8 083525, [arXiv:1806.10608].

[46] T. L. Smith, V. Poulin, and M. A. Amin, *Oscillating scalar fields and the Hubble tension: a resolution with novel signatures*, Phys. Rev. D **101** (2020), no. 6 063523, [arXiv:1908.06995].

[47] B. Audren, J. Lesgourgues, K. Benabed, and S. Prunet, *Conservative Constraints on Early Cosmology: an illustration of the Monte Python cosmological parameter inference code*, JCAP **02** (2013) 001, [arXiv:1210.7183].

[48] T. Brinckmann and J. Lesgourgues, *MontePython 3: boosted MCMC sampler and other features*, Phys. Dark Univ. **24** (2019) 100260, [arXiv:1804.07261].

[49] A. Lewis, *GetDist: a Python package for analysing Monte Carlo samples*, arXiv:1910.13970.

[50] R. Hlozek, D. Grin, D. J. E. Marsh, and P. G. Ferreira, *A search for ultralight axions using precision cosmological data*, Phys. Rev. D **91** (2015), no. 10 103512, [arXiv:1410.2896].

[51] A. Laguë, J. R. Bond, R. Hložek, K. K. Rogers, D. J. E. Marsh, and D. Grin, *Constraining Ultralight Axions with Galaxy Surveys*, arXiv:2104.07802.

[52] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, L. Campbell, Q. Parker, W. Saunders, and F. Watson, *The 6dF Galaxy Survey: Baryon Acoustic Oscillations and the Local Hubble Constant*, Mon. Not. Roy. Astron. Soc. **416** (2011) 3017–3032, [arXiv:1106.3366].

[53] A. J. Ross, L. Samushia, C. Howlett, W. J. Percival, A. Burden, and M. Manera, *The clustering of the SDSS DR7 main Galaxy sample – I. A 4 per cent distance measure at $z = 0.15$*, Mon. Not. Roy. Astron. Soc. **449** (2015), no. 1 835–847, [arXiv:1409.3242].

[54] **BOSS** Collaboration, S. Alam et. al., *The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample*, Mon. Not. Roy. Astron. Soc. **470** (2017), no. 3 2617–2652, [arXiv:1607.03155].

[55] G. D'Amico, L. Senatore, and P. Zhang, *Limits on $w$CDM from the EFTofLSS with the PyBird code*, arXiv:2003.07956.

[56] D. M. Scolnic et. al., *The Complete Light-curve Sample of Spectroscopically Confirmed SNe Ia from Pan-STARRS1 and Cosmological Constraints from the*

*Combined Pantheon Sample*, Astrophys. J. **859** (2018), no. 2 101, [arXiv:1710.00845].

[57] R. Hložek, D. J. E. Marsh, D. Grin, R. Allison, J. Dunkley, and E. Calabrese, *Future CMB tests of dark matter: Ultralight axions and massive neutrinos*, Phys. Rev. D **95** (2017), no. 12 123511, [arXiv:1607.08208].

[58] A. Gelman and D. B. Rubin, *Inference from Iterative Simulation Using Multiple Sequences*, Statistical Science **7** (1992), no. 4 457 – 472.

[59] N. Schöneberg, G. Franco Abellán, A. Pérez Sánchez, S. J. Witte, V. Poulin, and J. Lesgourgues, *The $H_0$ Olympics: A fair ranking of proposed models*, arXiv:2107.10291.

[60] H. Akaike, *A new look at the statistical model identification*, IEEE Transactions on Automatic Control **19** (1974), no. 6 716–723.

[61] A. R. Liddle, *Information criteria for astrophysical model selection*, Mon. Not. Roy. Astron. Soc. **377** (2007) L74–L78, [astro-ph/0701113].

[62] R. Trotta, *Bayesian Methods in Cosmology*, 1, 2017. arXiv:1701.01467.

[63] P. Svrcek and E. Witten, *Axions In String Theory*, JHEP **06** (2006) 051, [hep-th/0605206].

[64] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, *String Axiverse*, Phys. Rev. D **81** (2010) 123530, [arXiv:0905.4720].

[65] A. Hebecker, T. Mikhail, and P. Soler, *Euclidean wormholes, baby universes, and their impact on particle physics and cosmology*, Front. Astron. Space Sci. **5** (2018) 35, [arXiv:1807.00824].

[66] R. D. Pisarski and F. Wilczek, *Remarks on the Chiral Phase Transition in Chromodynamics*, Phys. Rev. D **29** (1984) 338–341.

[67] P. Creminelli, A. Nicolis, and R. Rattazzi, *Holography and the electroweak phase transition*, JHEP **03** (2002) 051, [hep-th/0107141].

[68] B. von Harling and G. Servant, *QCD-induced Electroweak Phase Transition*, JHEP **01** (2018) 159, [arXiv:1711.11554].

[69] P. Baratella, A. Pomarol, and F. Rompineve, *The Supercooled Universe*, JHEP **03** (2019) 100, [arXiv:1812.06996].

[70] K. Agashe, P. Du, M. Ekhterachian, S. Kumar, and R. Sundrum, *Cosmological Phase Transition of Spontaneous Confinement*, JHEP **05** (2020) 086, [arXiv:1910.06238].

[71] Y. B. Zel'dovich, *The equation of state at ultrahigh densities and its relativistic limitations*, Sov. Phys. JETP **14** (1962) 1143–1147.

[72] M. G. Alford, S. Han, and M. Prakash, *Generic conditions for stable hybrid stars*, Phys. Rev. D **88** (2013), no. 8 083013, [arXiv:1302.4732].

[73] P. Bedaque and A. W. Steiner, *Sound velocity bound and neutron stars*, Phys. Rev. Lett. **114** (2015), no. 3 031103, [arXiv:1408.5116].

[74] C. Hoyos, N. Jokela, D. Rodríguez Fernández, and A. Vuorinen, *Breaking the sound barrier in AdS/CFT*, Phys. Rev. D **94** (2016), no. 10 106008, [arXiv:1609.03480].

[75] C. Ecker, C. Hoyos, N. Jokela, D. Rodríguez Fernández, and A. Vuorinen, *Stiff phases in strongly coupled gauge theories with holographic duals*, JHEP **11** (2017) 031, [arXiv:1707.00521].

[76] F. R. Ares, M. Hindmarsh, C. Hoyos, and N. Jokela, *Gravitational waves from a holographic phase transition*, arXiv:2011.12878.

[77] B. Bozek, D. J. E. Marsh, J. Silk, and R. F. G. Wyse, *Galaxy UV-luminosity function and reionization constraints on axion dark matter*, Mon. Not. Roy. Astron. Soc. **450** (2015), no. 1 209–222, [arXiv:1409.3544].

[78] D. J. E. Marsh, *Axion Cosmology*, Phys. Rept. **643** (2016) 1–79, [arXiv:1510.07633].

[79] B. Schwabe, M. Gosenca, C. Behrens, J. C. Niemeyer, and R. Easther, *Simulating mixed fuzzy and cold dark matter*, Phys. Rev. D **102** (2020), no. 8 083518, [arXiv:2007.08256].

[80] **CMB-S4** Collaboration, K. N. Abazajian et. al., *CMB-S4 Science Book, First Edition*, arXiv:1610.02743.

[81] J. B. Bauer, D. J. E. Marsh, R. Hložek, H. Padmanabhan, and A. Laguë, *Intensity Mapping as a Probe of Axion Dark Matter*, Mon. Not. Roy. Astron. Soc. **500** (2020), no. 3 3162–3177, [arXiv:2003.09655].

[82] L. Amendola et. al., *Cosmology and fundamental physics with the Euclid satellite*, Living Rev. Rel. **21** (2018), no. 1 2, [arXiv:1606.00180].

[83] **DESI** Collaboration, M. E. Levi et. al., *The Dark Energy Spectroscopic Instrument (DESI)*, arXiv:1907.10688.

[84] R. Akeson et. al., *The Wide Field Infrared Survey Telescope: 100 Hubbles for the 2020s*, arXiv e-prints (Feb., 2019) arXiv:1902.05569, [arXiv:1902.05569].

[85] **LSST** Collaboration, v. Ivezić et. al., *LSST: from Science Drivers to Reference Design and Anticipated Data Products*, Astrophys. J. **873** (2019), no. 2 111, [arXiv:0805.2366].