Sigma-8 tension is a drag

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Measurements of weak gravitational lensing at low redshifts ($z \lesssim 0.5$–1), quantified by the parameter S_8, favor weaker matter clustering than that expected from the standard Λ cold dark matter (ΛCDM) cosmological model with the parameters determined by cosmic microwave background (CMB) measurements. However, the amplitude of matter clustering at higher redshifts, as probed by lensing of the CMB, is consistent with ΛCDM. In the literature, it has been found that the tension can be resolved by introducing a friction between dark matter and dark energy without altering the tightly constrained expansion history. Here, we show that in order to get a low S_8 value consistent with the findings of cosmic shear under ΛCDM, cosmological measurements favor (at $\sim 3\sigma$, in this one parameter model) a nonzero drag leading to a suppression of low-redshift power right precisely around the transition from matter to dark-energy domination. Our results hint at a connection between the S_8 tension and the long-standing "cosmic coincidence problem." We suggest ways to further probe the scenario.

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I. INTRODUCTION

The concordance cosmological model, Λ cold dark matter (ΛCDM), provides an excellent description of increasingly precise measurements of the expansion history of the Universe and fluctuations in the matter density from observations of the cosmic microwave background (CMB) and the galaxy distribution. However, the increasing precision of observations and analyses has revealed tensions between the values of different parameters among different observables and experiments (see, e.g., Ref. [1] for a recent review).

Here, we focus on the tension related with the amplitude of the matter clustering in the late Universe, parametrized with the combination $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$, where σ_8 is the root mean square of the amplitude of matter perturbations smoothed over 8 h^{-1} Mpc, h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, and Ω_m is the matter density parameter today. Simply stated, the distribution of galaxies and matter in the late Universe (redshifts $z \lesssim 0.5$–1) as measured by low-redshift probes is smoother than expected from the evolution of the fluctuations observed in the CMB. These low-redshift probes include galaxy clustering[1] [2–6], galaxy weak lensing [7–11], galaxy clusters [12], CMB lensing tomography [13–16], and their combination and cross-correlations [17–20]; the derived values of S_8 systematically fall $\sim$2–3σ lower than the values obtained from the primary CMB anisotropies [21,22] and from the power spectrum of CMB lensing alone [23,24].[2] Furthermore, the deviation of σ_8 as measured from CMB lensing tomography from the ΛCDM prediction grows as the redshift decreases [15].

There are two features in the measurements that highly restrict potential solutions to this tension. First, the expansion history of the Universe is tightly constrained to follow the predictions of ΛCDM [21,25–28], so that background quantities such as Ω_m cannot be modified to resolve the tension (see Refs. [29,30] for an alternative view). Rather, a solution must decrease the clustering amplitude σ_8 [17,31,32]. Secondly, the auto power spectrum of the CMB lensing, the support kernel of which spans in redshift from today to recombination (with a very wide peak at $z \sim 1$–2), favors high values of S_8, compatible with those from the primary CMB anisotropies. This is also supported by eBOSS quasars data at high redshift $z \sim 1.5$, that are statistically compatible with *Planck* [33,34].

[1]See Ref. [2] for a discussion about the role of prior volume effect on the result.

[2]Note that CMB lensing tomography involves the cross-correlation of the CMB lensing and a low-redshift tracer of the large-scale structure, usually galaxy clustering. This cross-correlation in practice limits the support of the CMB lensing kernel to the redshift coverage of the galaxy sample employed.

These findings indicate that any physics beyond ΛCDM that may reconcile these measurements must be limited to the perturbation level, leaving the background evolution untouched, and must be effective[3] at $z \lesssim 1$. Coincidentally, this period corresponds to the epoch at which dark energy (DE) starts to dominate over dark matter (DM) in the total energy content of the Universe. This raises the question of whether the appearance of a new phenomenon at low-z that leads to low-σ_8 measurement could be tied to the beginning of DE domination, in turn providing us with new insight on the famous "cosmic coincidence" problem (see, e.g., Refs. [42–44]).

In the past, it has been shown that the σ_8 tension can be resolved by a drag force between DM and DE that becomes operational at low redshifts [45–52]. The drag slows the falling of DM into gravitational potential wells and thereby suppresses the growth of power. Here, we show that in order to obtain a low S_8 value, the effect must occur only at low redshifts, precisely when DE becomes dynamically important. This requires, of course, for there to be a preferred frame for the DE and thus, that the equation-of-state parameter be $w \neq -1$. Otherwise, the model leaves the expansion history unchanged (and thus, differs from ideas [53–57] on DE-DM interactions that affect the expansion history). Our work differs from prior works [45–52] (which provide microphysical models for the drag) in the articulation of the crucial role played by the CMB and galaxy weak lensing data, and in the use of powerful new datasets to constrain a minimal yet realistic model.

II. A COINCIDENCE OF TIME AND AMPLITUDE

A. Model of DM and DE drag

We begin by introducing the phenomenological model, similar to Refs. [45,49]. Working in Newtonian gauge, and following the notation of Ref. [58], we include the drag between DM and DE modifying the evolution equations for the velocity divergences θ as

$$\theta'_{\rm DM} = -\frac{a'}{a}\theta_{\rm DM} + k^2\psi + \Gamma_{\rm DMDE}(a)(\theta_{\rm DE} - \theta_{\rm DM}),$$
$$\theta'_{\rm DE} = -(1-3c_{s,\rm DE}^2)\frac{a'}{a}\theta_{\rm DE} + \frac{k^2 c_{s,\rm DE}^2}{(1+w_{\rm DE})}\delta_{\rm DE} + k^2\psi - \Gamma_{\rm DMDE}(a)R(\theta_{\rm DE} - \theta_{\rm DM}), \quad (1)$$

[3]Another avenue invokes modification restricted to small scales ($k \gtrsim 0.1$ h/Mpc), where current CMB data lose support, that may be active already at early-times, e.g., [35–37]. These models could be probed by Lyman-alpha data [38,39] or more accurate CMB lensing measurements at small scales [40]. Finally, we mention that it has been suggested that baryonic effects may be responsible for the low-S_8 estimates in cosmic shear data [32,41].

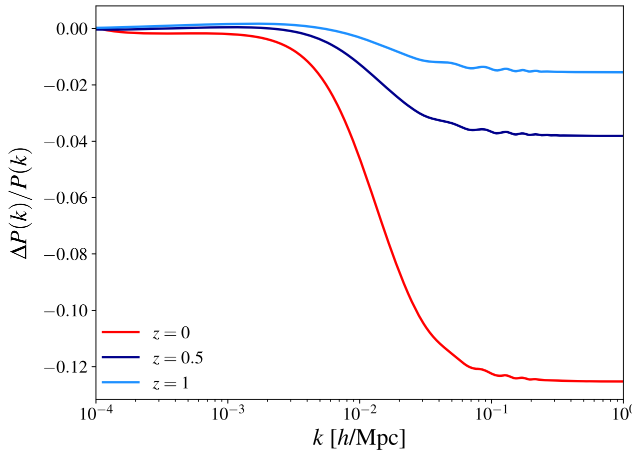

FIG. 1. Prediction for the power suppression in the best-fit wDMDE model to the full dataset including S_8 compared to ΛCDM, $(P(k)_{\rm DMDE} - P(k)_{\Lambda\rm CDM})/P(k)_{\Lambda\rm CDM}$ at $z = 0$, 0.5, 1.

where a is the scale factor, ψ is the gravitational potential, $'$ denotes a derivative with respect to conformal time, and $c_{s,\rm DE} \equiv 1$ and $w_{\rm DE}$ are the DE sound speed and equation-of-state parameter. We parametrize $\Gamma_{\rm DMDE}(a)$ and R as [45,49]

$$\Gamma_{\rm DMDE}(a) = \frac{a\Gamma_{\rm DMDE}}{\bar\rho_{\rm DM}(a)}, \qquad R = \frac{\bar\rho_{\rm DM}(a)}{(1+w_{\rm DE})\bar\rho_{\rm DE}(a)}, \quad (2)$$

with $\bar\rho_i$ the mean proper energy densities of DM and DE. The scaling of the interaction rate follows from assuming a time-independent coupling constant between the 4-velocity of DM and DE at the level of the equation of motions [49]. To gain some insight on the impact of this interaction, we illustrate the effect of the drag term on the matter power spectrum in Fig. 1 (setting the parameters to the best-fit values extracted from our analyses with[4] free $w_{\rm DE}$). The drag between DM and DE suppresses the matter power spectrum on scales that are within the horizon once the interaction becomes sizable. The suppression with respect to ΛCDM grows with time.

The most general setup involves a free DE equation of state parameter $w_{\rm DE}$, so $w_{\rm DE}$ and $\Gamma_{\rm DMDE}$ are the additional parameters of this model. However, type-Ia supernovae (SNeIa) and baryon acoustic oscillations (BAOs) constrain $w_{\rm DE} \simeq -1$ [21,25,34]. We therefore start by considering a fiducial scenario, where we set $w_{\rm DE} = -0.98$ (i.e., satisfying current constraints), leaving $\Gamma_{\rm DMDE}$ as our only extra parameter with respect to ΛCDM. We will later show that leaving $w_{\rm DE}$ free only has a minor impact on our conclusions.

[4]We find that the scales below which the suppression occurs are rather sensitive to the value of $w_{\rm DE}$ due to the divergence in the equation for the DE bulk velocity. However, the amplitude of the suppression, which is what matters most when computing S_8, is largely unaffected by the exact value of $w_{\rm DE}$.

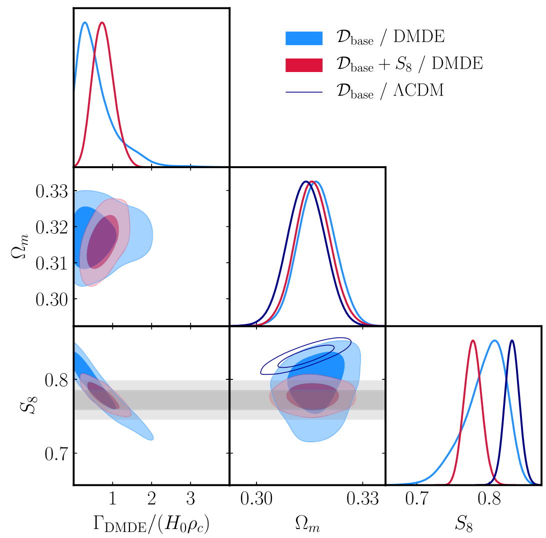

FIG. 2. 68% and 95% confidence level marginalized posterior distributions of the relevant cosmological parameters for ΛCDM (dark blue lines) and the model including the drag between DM and DE (filled contours), compared with the S_8 measurement from galaxy lensing (gray bands) averaged assuming two independent normal distributions.

B. Analytical argument for a new coincidence

The drag rate in the evolution equation of $\theta'_{\rm DM}$ becomes non-negligible when $\Gamma_{\rm DMDE}(a)/\mathcal{H}(a) \sim 1$, with $\mathcal{H}(a) \equiv a'/a$. We reexpress the ratio between these rates as [49]

$$\frac{\Gamma_{\rm DMDE}(a)}{\mathcal{H}} = \frac{\Gamma_{\rm DMDE}/(H_0\rho_c)}{E(a)\Omega_{\rm m}a^{-3}}, \tag{3}$$

where $\Omega_{\rm m} = \rho_{\rm m}/\rho_c$, with $\rho_c = (3H_0^2/8\pi G)$ the critical density, and $E(a) \equiv H(a)/H_0$. The amplitude of the drag rate $\Gamma_{\rm DMDE}$ is *a priori* unconstrained. Yet, a remarkable implication of this equation, is that for $\Gamma_{\rm DMDE} \sim H_0\rho_c$, the drag becomes effective for[5] $E(a)\Omega_{\rm m}a^{-3} = (\sqrt{\Omega_{\rm m}a^{-3} + \Omega_{\rm DE}(a)})\Omega_{\rm m}a^{-3} \sim 1$, where $\Omega_{\rm DE}$ is the DE density parameter. Assuming $w_{\rm DE} \sim -1$ and $\Omega_{\rm DE} = 1 - \Omega_{\rm m} \sim 0.7$, this is fulfilled specifically around $a_\Lambda \sim (\Omega_{\rm DE}/\Omega_{\rm m})^{-1/3}$. In other words, for this simple scaling of the amplitude of the momentum drag rate, the interaction and the effects of DE become relevant around the same time, indicating that the cosmic-coincidence problem may be connected to the low values of S_8 measured at low-z. As shown below, current observations indeed favor values of $\Gamma_{\rm DMDE}$ falling in this range.

[5]Here, we approximate $\Omega_m \sim \Omega_{\rm cdm}$ for simplicity, given that we are working at the order of magnitude level.

III. MONTE CARLO ANALYSIS

A. Analysis setup

To evaluate the success of the model under study, we perform a series of Markov chain Monte Carlo (MCMC) runs, using the public code Monte Python-v3[6] [59,60], which we interface with our modified version of CLASS[7] [61,62]. We use the Metropolis-Hasting algorithm assuming flat priors on $\{\omega_b, \omega_{\rm cdm}, 100\theta_s, \log(10^{10}A_s), n_s, \tau_{\rm reio}\} + \Gamma_{\rm DMDE}$. To test the convergence of the MCMC chains, we use the Gelman-Rubin [63] criterion $|R-1| \lesssim 0.01$. To postprocess the chains and plot figures, we use GetDist [64].

We adopt the *Planck* Collaboration convention in modeling free-streaming neutrinos as two massless species and one massive with $m_\nu = 0.06$ eV [65]. We do not include Halofit [66–68] to estimate the nonlinear matter clustering (which is critical to model galaxy-galaxy weak lensing correlation functions), as the presence of the drag term could affect nonlinear clustering. Accounting for the effects of the drag force on the nonlinear matter power spectrum is beyond the scope of this paper; therefore, to minimize the impact of this limitation, we consider (mostly) linear observables in our analysis.

We make use of the full *Planck* 2018 TT, TE, EE and lensing power spectra [21], BAO and $f\sigma_8$ (where f is the linear growth rate) measurements from BOSS DR12 & 16 at $z = 0.38, 0.51, 0.68$ [69–72], SDSS DR7 at $z = 0.15$ [73], and QSO measurements at $z = 1.48$ [33,74], as well as BAO-only measurements from 6dFGS at $z = 0.106$ [75] and Ly-α autocorrealation and cross-correlation with QSO at $z = 2.334$ [76]. We also include uncalibrated luminosity distances to SNeIa from Pantheon+ in the range $0.01 < z < 2.3$ [25]. We refer to this compilation of measurements as our fiducial dataset, denoted as $\mathcal{D}_{\rm base}$. We also consider cases including Gaussian priors on S_8 as measured by KiDS-1000x{2dFLenS + BOSS} ($S_8 = 0.766^{+0.02}_{-0.014}$) [17] and DES-Y3 ($S_8 = 0.776 \pm 0.017$) [16]. In future work, our results shall be confirmed including the modeling of the nonlinear matter power spectrum to consider the full galaxy weak lensing measurements in the analysis.

B. Results with *w* fixed

The results of our analyses with $w_{\rm DE} = -0.98$ are shown in Fig. 2. We show 68% and 95% confidence level marginalized posterior distributions of the relevant parameters for ΛCDM and the model including the drag between DM and DE; other parameters are unchanged with respect to the standard results assuming ΛCDM. As expected, $\Gamma_{\rm DMDE}$ is very degenerate with σ_8, which allows S_8 to reach values even lower than the measurements of low-z probes, while keeping $\Omega_{\rm m}$ effectively fixed: in particular, we find a

[6]https://github.com/brinckmann/montepython_public.
[7]https://lesgourg.github.io/class_public/class.html.

TABLE I. Mean (best-fit) and ±68% confidence level uncertainties of the marginalized cosmological parameters for ΛCDM and DMDE (with $w_{\rm DE} = -0.98$) using our fiducial data set, and including the prior on S_8 in the last column. The last row shows the χ^2 difference with respect to ΛCDM.

Model	ΛCDM	DMDE	DMDE w/S_8	wDMDE	wDMDE w/S_8
$\Gamma_{\rm DMDE}/(H_0\rho_c)$	⋯	$< 1.5(0.0)$	$0.75(0.73)^{+0.25}_{-0.29}$	$< 2.06(0.01)$	$0.82(1.11)^{+0.27}_{-0.36}$
$w_{\rm DE}$	-1	-0.98	-0.98	$< -0.95(-0.9999)$	$< -0.95(-0.9999)$
S_8	$0.831(0.831) \pm 0.011$	$0.796(0.830)^{+0.035}_{-0.018}$	$0.777(0.778)^{+0.012}_{-0.013}$	$0.794(0.829)^{+0.039}_{-0.017}$	$0.776(0.776)^{+0.012}_{-0.013}$
$\Omega_{\rm m}$	$0.3139(0.3141) \pm 0.0055$	$0.3170(0.3170)^{+0.0051}_{-0.0056}$	$0.3161(0.3162)^{+0.0051}_{-0.0053}$	$0.3170(0.3145)^{+0.0056}_{-0.0062}$	$0.3160(0.3130)^{+0.0056}_{-0.0059}$
$\Delta\chi^2_{\rm min}$(DMDE − ΛCDM)	⋯	$+0.5$	-9.5	0	-11.5

marginalized constraint of $S_8 = 0.745^{+0.074}_{-0.045}$ at 68% confidence level for our fiducial dataset.

In Table I, we show the mean and best-fit values of the parameters for each case, as well as the χ^2 statistics. While the results show no preference for the DM-DE drag force scenario with respect to ΛCDM for our fiducial dataset (both models present similar χ^2 values[8]), we find $\Delta\chi^2 = -9.5$ once we include the prior on S_8,[9] with no statistically significant degradation in other likelihoods.[10]

C. Results with w free

We now turn to the case where $w_{\rm DE}$ is let free to vary, as in full generality it is also a free parameter of the model. As previously, we report in Table I, the mean and best-fit values of the parameters $\{\Gamma_{\rm DMDE}/(H_0\rho_c), w_{\rm DE}, S_8, \Omega_{\rm m}\}$, as well as the χ^2 statistics, with and without including the S_8 prior. As expected, data constrain $w_{\rm DE} < -0.95$ at 95% CL (in good agreement with the literature [21,25]) but the ability of the model to resolve the S_8 tension is left unchanged. We compare the results further on Fig. 3, where we show the posterior distribution of the parameters of interest with and without letting $w_{\rm DE}$ free to vary. One can see that the impact of leaving $w_{\rm DE}$ free is minor given current strong constraints on deviations away from -1, and we find that the reconstructed value of $\Gamma_{\rm DMDE}$ (and S_8) is largely unaffected.

IV. DISCUSSION: IS THE σ_8 TENSION A COINCIDENCE?

Interestingly, irrespective of whether $w_{\rm DE}$ is kept fixed or varied, we find that $\Gamma_{\rm DMDE}$ must have values $\sim H_0\rho_c$ to reconcile S_8 from our fiducial dataset with the results from galaxy lensing. As discussed above, this shows a potential

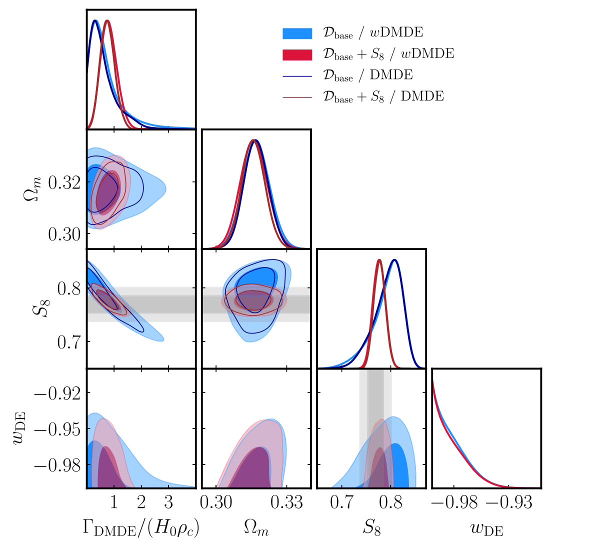

FIG. 3. Same as Fig. 2, but now comparing results of analyses with and without $w_{\rm DE}$ let free to vary.

connection between a low-S_8 value that is dynamically generated at low-z due to a DM-DE drag and the cosmic coincidence problem. Let us stress again that this coincidence is highly nontrivial because the free parameter[11] of the model $\Gamma_{\rm DMDE}$ is responsible for setting both the amplitude of the suppression (i.e., whether we can achieve the σ_8 measured by weak lensing) and the time at which $\Gamma \sim H$ (i.e., when the interaction becomes relevant), and $\Gamma_{\rm DMDE}$ is not *a priori* constrained. We illustrate this in Fig. 4: if $\Gamma_{\rm DMDE}$ were much larger, the interaction would have modified the evolution of perturbations at higher redshifts, potentially causing tension with the large-scale CMB lensing power spectrum (and even the integrated Sachs-Wolfe effect). On the other hand, a much lower $\Gamma_{\rm DMDE}$ would leave S_8 unaffected because the interaction would not be relevant at any time. DM-DE drag occurring right at the onset of DE domination can therefore explain why the only data that are affected are those probing

[8]The $+0.5$ degradation is coming from setting $w_{\rm DMDE} = -0.98$ in the DMDE case.

[9]We find a similar $\Delta\chi^2$ for the case in which $w_{\rm DE}$ also varies.

[10]Compared to analyses without the S_8 prior, we find increases in χ^2 of $+1.9$ for *Planck*TTTEEE + lowl data and $+0.6$ for BAO + $f\sigma_8$ measurements from BOSS (which, since $\Omega_{\rm m}$ does not vary, are due to small deviations in $f\sigma_8$), that are not statistically significant.

[11]We recall that we have shown background considerations enforce that $w_{\rm DE}$ does not play a role.

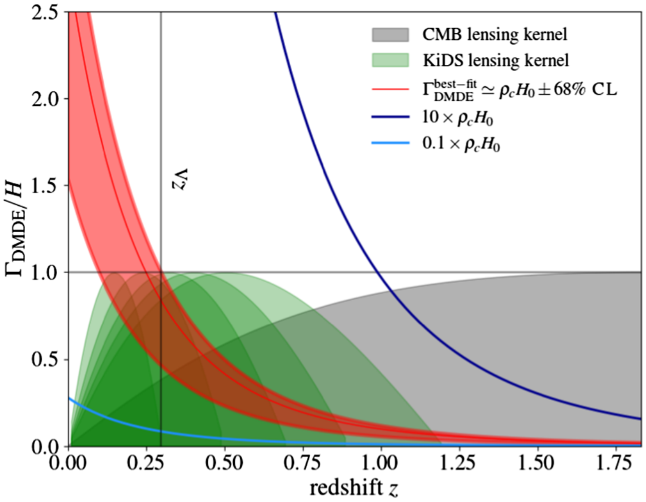

FIG. 4. Ratio of the interaction rate Γ_{DMDE} over the Hubble rate $H(z)$. We also show the CMB and galaxy weak lensing kernel functions (given the five z-bins of KiDS [77]) in the background. We indicate the redshift at which DE dominates, $z_\Lambda \equiv (\Omega_\Lambda/\Omega_{\text{m}})^{1/3} - 1$.

perturbations dynamics at $z < 0.5$, with the right amplitude of suppression, and not higher redshift ones, which are left unaffected. Hence, this scenario suggests that the transition to a DE-dominated epoch may have nontrivial implications for model building, potentially guiding future research, with some attempts already discussed in Refs. [45,49,52,53].

Importantly, this model can be further tested with future higher-accuracy measurements. Forthcoming CMB and galaxy surveys may be able to discriminate between the models. Additionally, the redshift-dependent σ_8 deviation from the prediction of ΛCDM can also be probed with CMB lensing tomography and $f\sigma_8$ measurements. Forthcoming

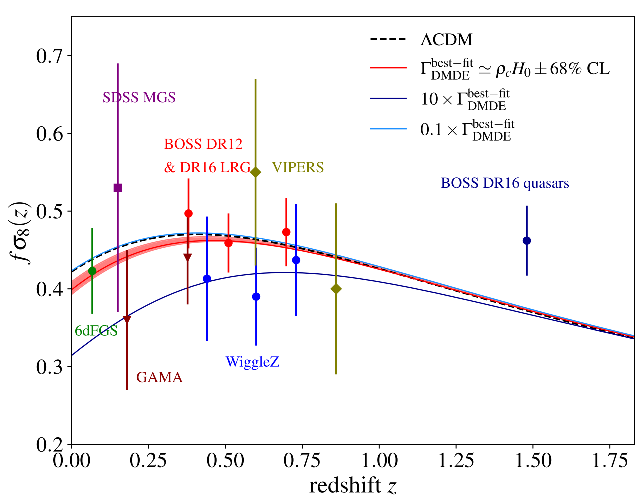

FIG. 5. Prediction for $f\sigma_8$ in the ΛCDM and DMDE models compared to a sample of data. Our analysis use 6dFGS, SDSS MGS, BOSS DR12, and 16 (LRG and quasars) data.

low-z clustering measurements, e.g., from the DESI bright galaxy sample [78], may detect the deviation in $f\sigma_8$ (see Fig. 5). Interestingly, the prediction for $f\sigma_8(z)$ is similar to that obtained in Ref. [79], in which authors studied a model where the growth index is left free to vary (and the background dynamics is identical to ΛCDM), showing that current data favor a deviation of the growth index from ΛCDM at 3.7σ. Similarly, improved cross-correlations between large-scale-structure surveys and CMB lensing will also weigh in on this.

Looking forward, there are additional observables in which the DM-DE drag would leave signatures that could be searched for to probe this scenario, if the effects are properly modeled. First, as mentioned above, this model shall be applied to the full set of measurements from galaxy lensing surveys, rather than just a prior on S_8. This will require improved modeling of the DM-DE drag, including nonlinear clustering (see, e.g., Refs. [47,80]). Meanwhile, similarly to the case of self-interacting DM [81], the friction between DM and DE would affect the intrinsic alignment of galaxies. Including the DM-DE drag in the formalism of intrinsic alignments (see, e.g., Ref. [82]) would allow us to use correlations of galaxy shapes to probe this model, distinguishing it from the effects of baryonic physics [83]. In addition, on larger scales, the suppression of the potential wells induced by the drag could lead to an interesting integrated Sachs-Wolfe signal (too small when considering the CMB TT power spectrum due to cosmic variance) but that could be picked-up when cross-correlating with CMB lensing or galaxy distributions. Finally, since baryons are unaffected by this interaction, it is expected that DM spirals down and collapses faster than baryons, leaving signatures like modified tidal streams, as well as potentially affecting probes of DM density profiles such as stellar-rotation velocities, and introducing a small velocity bias between DM and baryons that can be searched for in galaxy clustering measurements [84] and galaxy clusters [85]. Evaluating the scope of these searches and their sensitivity to the DM-DE drag provides very motivated targets for future studies. Let us also mention the possibility of extending the model to consider a drag between DE and baryons [86–88].

V. CONCLUSIONS

To conclude, we have explored a cosmological model that shows promise to resolve the tension in clustering between high-redshift and low-redshift probes. While further study is required, both modeling the nonlinear effects in the matter power spectrum and using additional cosmological and astrophysical probes, we have bolstered the motivation for this model. We showed that the required values to reconcile high-redshift measurements with the S_8 values preferred by galaxy-lensing observations naturally set the moment in which the DM-DE interaction becomes effective to be around DM-DE equality. Hence, this model involves interesting phenomenology not only for the dark sector of the Universe, but it may also imply that the last transition in the history of the Universe could have had nontrivial implications. We hope this work spurs interest in this family of solutions for the S_8 tension, both regarding model building and adding detail to the astrophysical and cosmological consequences of the friction to conclusively distinguish it from ΛCDM.

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