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Suppression without Thawing:
Constraining Structure Formation and Dark Energy with Galaxy Clustering

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We present a new perturbative full-shape analysis of BOSS galaxy clustering data, including the full combination of the galaxy power spectrum and bispectrum multipoles, baryon acoustic oscillations, and cross-correlations with the gravitational lensing of cosmic microwave background measured from *Planck*. Assuming the ΛCDM model, we constrain the matter density fraction $\Omega_m = 0.3154 \pm 0.0089$, the Hubble constant $H_0 = 68.34 \pm 0.77\,\mathrm{km\,s^{-1}Mpc^{-1}}$, and the mass fluctuation amplitude $\sigma_8 = 0.686 \pm 0.027$ (equivalent to $S_8 = 0.704 \pm 0.031$). Cosmic structure at low redshifts appears suppressed with respect to the *Planck* ΛCDM concordance model at 4.5σ. We explore whether this tension can be explained by the recent DESI preference for dynamical dark energy (DDE): the BOSS data combine with DESI BAO and PantheonPlus supernovae competitively compared to the CMB, yielding no preference for DDE, but the same $\sim 10\%$ suppression of structure, with dark energy being consistent with a cosmological constant at 68% CL. Our results suggest that either the data contains residual systematics, or more model-building efforts may be required to restore cosmological concordance.

Introduction. — Observational and theoretical efforts over the last three decades have led to the establishment of the standard model of cosmology: ΛCDM. This model can successfully fit a wide range of cosmological data, in particular the various correlators of cosmological fluctuations traced by the cosmic microwave background (CMB) anisotropies and large-scale structure of the Universe [e.g., 1, 2].

Despite its phenomenological successes, the ΛCDM model suffers from significant theoretical questions. Many of its core ingredients, such as cosmic inflation, dark matter, and dark energy are, at best, highly exotic. The latter is particularly puzzling from the theoretical viewpoint. The simplest explanation for dark energy is the famous cosmological constant, which gives rise to the naturalness paradox that shatters the fundamental pillars of physics: symmetry-based selection rules and dimensional analysis [3, 4]. Whilst anthropic [5] and landscape [6] explanations are possible, the cosmological constant problem still poses a formidable conceptual challenge in fundamental physics. This challenge is particularly relevant given the possible ($\gtrsim 2.5\sigma$) evidence for dynamical dark energy (DDE, also known as $w_0 w_a$CDM) recently reported by the Dark Energy Survey Instrument (DESI) collaboration [7–9].

In addition to DDE, the data contain other anomalies whose presence could signal the breakdown of cosmological concordance. The most prominent is the Hubble tension, *i.e.* the apparent disagreement between the direct and indirect measurements of the Hubble constant H_0, a proxy for the age of the Universe [10]. Another important anomaly is the disagreement of the direct and indirect probes of the growth of structure encoded by the mass fluctuation amplitude σ_8, or the related structure growth parameters $S_8 \equiv (\Omega_m/0.3)^{1/2}\sigma_8$ and $f\sigma_8$ (where f is the redshift-dependent logarithmic growth factor) [11, 12]. This discrepancy is observed in multiple independent low-redshift datasets [13] (a selection of which are shown in Fig. 1): cluster counts [e.g., 14, 15], weak lensing measurements [e.g., 16, 17], CMB lensing cross-correlations [e.g., 18, 19], and galaxy clustering in redshift space [e.g., 12, 20–24], though there exist some outliers [25–33]. In general relativity the expansion history and growth of structure are intricately related through the equations of

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motion, and the accumulation of cosmological tensions raise a natural question: do they all point to a particular new physics model in a correlated fashion? This *Letter* addresses this question focusing on the case of DDE and the σ_8 tension.

We present an independent reanalysis of the galaxy clustering data from the Baryon acoustic Oscillation Spectroscopic Survey (BOSS) in combination with *Planck* CMB lensing, in an attempt to link the possible σ_8 tension found in these data with the hints of DDE reported by DESI. Using methodologies developed in previous works [20, 21, 38–41], we measure the BOSS three-dimensional redshift-space power spectrum and bispectrum multipoles, and post-reconstructed BAO data. We also include the angular cross correlation between the BOSS galaxies and *Planck* CMB lensing following [42] (see also [34, 42–48]). For the first time, we consistently analyze all of these observables within the effective field theory (EFT)-based full-shape (FS) framework [23, 38, 49]. Our first important result is that, when combined with a BBN prior on the baryon density, this dataset yields a measurement of matter clustering amplitude σ_8 discrepant with the *Planck* concordance value at the 4.5σ level (cf. Fig. 1). This represents the strongest evidence for the σ_8 tension from the BOSS dataset to date.

In the second part of this *Letter*, we study whether the σ_8 tension can be explained by the DDE model suggested by the combination DESI+Supernovae (SNe) and CMB. Specifically, we analyze a combination of the BOSS data described above (both FS and BAO), including the galaxy-CMB lensing correlations, the DESI BAO data at redshift $z > 0.8$, and PantheonPlus SNe data assuming the DDE model. We find that DDE does not restore concordance between galaxy clustering data and the primary CMB. The optimal values of σ_8 in our DDE analysis is still in a 4.5σ tension with *Planck*, though the H_0 is consistent with *Planck*, but not with the value implied by the Cepheid-calibrated distance ladder [10] (though in better agreement with [50]). In addition, our dataset constrains DDE competitively compared to DESI BAO but does not display any evidence for DDE. The combination of the above results suggests that internal tensions between the datasets seem to pull cosmological parameters in directions uncorrelated with each other; this could motivate more efforts from the model building perspective, as well as searches for systematic effects in the full combination of the large-scale structure data.

Data. — Our primary dataset is the clustering of galaxies from the twelfth data release of the BOSS survey [51, 52]. These galaxies are observed in both the northern (NGC) and southern (SGC) galactic caps and are composed of the `LOWZ` and `CMASS` samples, each of which are restricted to the redshift ranges $0.15 < z < 0.43$ and $0.43 < z < 0.70$ in order to avoid overlap.[1] Combining both galactic caps, the `LOWZ` and `CMASS` catalogs cover $8,579$ and $9,493$ deg^2 with $361,762$ and $777,202$ galaxies, respectively. The complete DR12 catalogs also contain galaxies in two chunks `LOWZE2` and `LOWZE3` selected using different criteria than the main `LOWZ` sample. These are often combined with the main samples in order to maximize the survey volume, but, since the different selections imply different galaxy properties, we will instead omit them in this work (this choice was made also in pre-DR16 BOSS analyses [e.g., 53], leading to a smaller area in the `LOWZ` sample compared to `CMASS`).

To characterize the clustering of the above galaxy samples, we utilize the power spectrum and bispectrum statistics, measured using the window-free estimators derived in [20, 54, 55] (now implemented in the PolyBin3D code [56]). We include the standard systematic and FKP weights constructed by BOSS [51], which imply that the power spectrum probes clustering at an effective redshift $z_{\rm eff} = \int dV\, z\bar{n}^2(z)/\int dV \bar{n}^2(z)$, equal to 0.316 (0.555) for the `LOWZ` (`CMASS`) sample, where $\bar{n}$ is the weighted galaxy number density. The same weights applied to the bispectrum would result in a different effective redshift (instead weighted by $\bar{n}^3$); to ameliorate this, we an additional redshift weight $w_B(z) \equiv \bar{n}(z)^{-1/3}$ when computing the bispectrum. We additionally include the real-space power spectrum proxy Q_0 (equal to the power spectrum perpendicular to the line of sight) is estimated from the redshift space multipoles [40].

In addition to the power spectrum and bispectrum, we also include post-reconstruction BAO measurements from the BOSS galaxies. Since this signal does not depend strongly on galaxy properties, we will use measurements of the BAO scale from the *combined* BOSS sample covering the full survey area and redshift range, including the `LOWZE2` and `LOWZE3` samples omitted in the above

[1] Unlike our previous works [e.g., 21], we split the sample by their physical type rather than imposing a redshift-cut [e.g., 25].

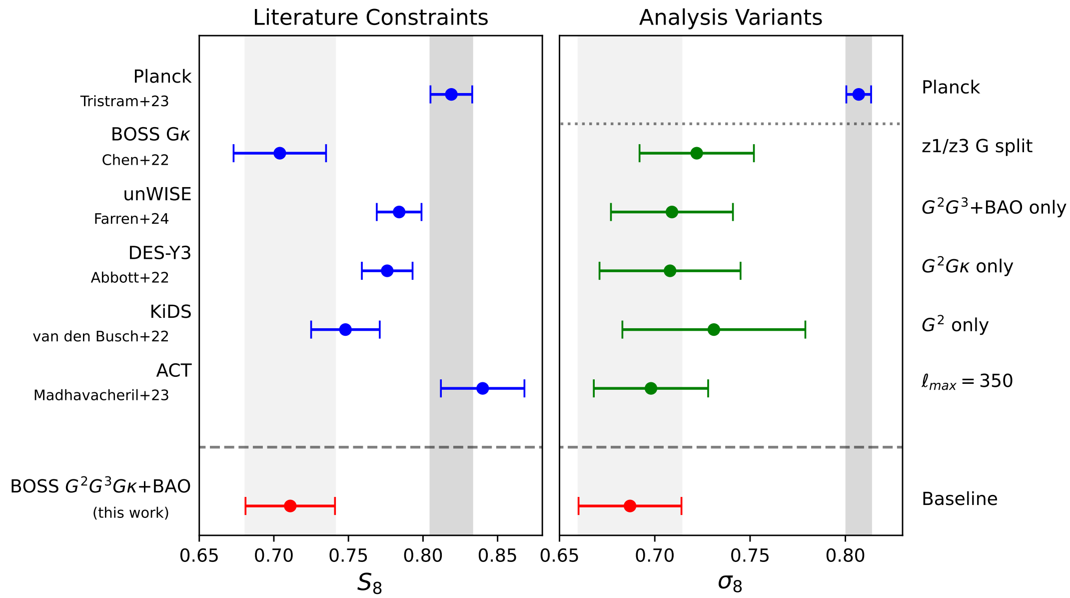

FIG. 1. **Left**: A comparison on various S_8 results available in the literature [17, 32, 34–37], with our measurement (bottom) including galaxy two- and three-point information (G^2 and G^3), cross-correlation with lensing ($G\kappa$), and BAO. **Right**: Dependence of our results on analysis choices including choice of galaxy split, dataset, and maximum cross-correlation scale.

full-shape analysis (specifically, those from [41]). This combined sample is split into non-overlapping redshift bins $0.2 < z < 0.5$ (**z1**) and $0.5 < z < 0.75$ (**z3**) chunks following [25, 57] with effective redshifts of $z_{\rm eff} = 0.38$ and 0.59, respectively. We compute the total covariance of the above measurements using measurements from the 2048 public MultiDark Patchy mocks [58, 59].

In order to measure the lensing cross correlation with galaxies we use publicly-available CMB lensing maps reconstructed from *Planck* data. Specifically, we use the PR4 map introduced in [60], which uses the updated `NPIPE` pipeline and slightly more data than previous releases, leading to a 20% improvement in signal-to-noise compared to PR3. We compute the cross-correlations of the lensing convergence κ with the `LOWZ` and `CMASS` galaxies using the `NaMaster` algorithm [61] adopting the same numerical choices (including filters and apodization) as described in [42]—to which we direct the interested reader for further details including extensive systemaics tests—except that we split the cross correlations according to galactic cap. In particular we use `NaMaster` to compute the bandpower window $M_{L\ell}$ relating the observed bandpowers in bin L to the unbinned theory $\hat{C}_L = M_{L\ell}C_\ell$, as well as an analytic (Gaussian) covariance matrix using the theory predictions for the measured C_ℓ's. We treat this covariance independently from that derived from the three-dimensional clustering of galaxies since the mode overlap is negligible [62]. Similarly to the bispectrum, we re-weight the galaxies when computing the cross correlation $C_\ell^{\kappa g}$ by the ratio of the galaxy and CMB lensing kernels in order to homogenize the effective redshifts probed with the galaxy power spectrum [34].

Finally, in addition to BOSS-volume data, we will supplement our analysis with constraints on cosmological expansion at lower and higher redshfts obtained from Supernovae Type Ia (SNIa) and external BAO data. For the former we adopt the PantheonPlus dataset [63, 64] (which constrains the redshift-dependence of luminosity distances) and BAO likelihoods for the 6-degree Field Galaxy Redshift Survey (6dFGS) [65] and the Main Galaxy Sample (MGS) in SDSS DR7 [66], as implemented in `MontePython` [67, 68]. For the latter, we use all galaxy BAO measurements from DESI with $z > 0.8$ [7] as well as the DESI Lyα measurement [8]. We also adopt the BBN baryon density constraint from the primordial deuterium abundance $\Omega_b h^2 = 0.02268 \pm 0.00038$ [38, 69], and fix[2] the spectral tilt to the *Planck* best-fit value

[2] Alternatively, one can free n_s in the fit or use the Harrison-

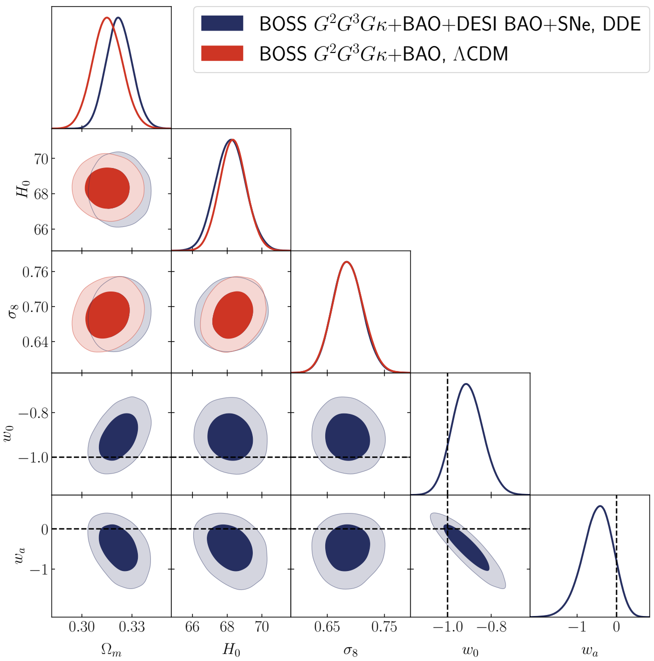

FIG. 2. Constraints on cosmological parameters from our baseline dataset (BOSS two- and three-point galaxy clustering correlations, cross correlations of galaxies and CMB lensing and BAO; BOSS $G^2G^3G\kappa$+BAO) on the standard ΛCDM model (red), as well as those on the dynamical dark energy (DDE) model from the baseline data in addition to DESI BAO (at $z > 0.8$) and PantheonPlus supernovae (blue). Dashed lines mark the ΛCDM values of the dark energy equation of state parameters w_0 and w_a, corresponding to the cosmological constant.

$n_s = 0.9649$.

Theoretical model. — We begin with a short overview of the theory model used for galaxy clustering. At the background level, we adopt either a baseline ΛCDM model, or the popular dynamical dark energy (DDE) extension, which is parametrized according to the equation of state $w(a) = w_0 + w_a(1-a)$ [70]. We compute predictions for the redshift-space power spectrum and bispectrum, as well as the real-space matter-galaxy cross power spectrum, using the effective field theory of large scale structure (EFT) [71–73] as implemented in the `CLASS-PT` code [74] in a modification to the public likelihoods.[3] Our modeling follows the the conventions of [74–76], to which we refer the reader for further details. Briefly, the galaxy power spectrum is computed to one-loop in perturbation theory while the bispectra are computed using the same bias parameters up to quadratic order. The lensing cross correlation probes the real-space cross power spectrum of galaxies with matter P_{mg} perpendicular to the line of sight; we evaluate P_{mg} to one-loop order including an additional counterterm for the matter field. In all cases the effects of long-wavelength displacements on the BAO wiggles in the linear power spectrum are resummed following [77–81] (see also [82, 83]).

To make contact with observations, we rescale the wavenumbers in the redshift-space power spectrum and bispectrum to correct for the mismatch of the true cosmology and the fiducial cosmology (with $\Omega_m = 0.31$) used to convert the angles and redshifts in the galaxy catalogs to rectilinear coordinates. Following this conversion, the power spectrum and bispectrum are then converted into the measured multipoles by integrating over the requisite angles [84, 85] and combined into the measured k-bins, including weights to correct for discreteness effects as described in [20]. No such conversions are needed for the angular power spectrum multipoles which are given in the Limber approximation by [86, 87]

$$C_\ell^{\kappa g} = \int \frac{d\chi}{\chi^2}\Big(W^\kappa(\chi) W^g(\chi)\ P_{mg}\big(k = \frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\big) + W^\kappa(\chi)W^\mu(\chi)(2\alpha-1)P_{mm}\big(k = \frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\big)\Big),$$

where χ is comoving distance and the CMB lensing and galaxy density kernels are given by

$$W^\kappa(\chi) = \frac{3}{2}H_0^2\Omega_m(1+z)\frac{\chi(\chi_*-\chi)}{\chi_*},\ W^g(\chi) = \frac{dN}{d\chi}.$$

We evaluate P_{mg} at the effective redshift rather than parameterizing its redshift evolution since the galaxy redshift distribution is very narrow. Furthermore, W^μ is the galaxy lensing kernel and α is the magnification bias—the latter contribution was studied extensively in [88] and we use the values of α measured for `LOWZ` and `CMASS` therein. Unlike the $\kappa-g$ term, the magnification bias contribution probes the matter power spectrum to non-linear scales, though its support at the smallest scale is curtailed since $W^{\kappa,\mu}$ fall to zero at short distances. As this term gives only a small contribution, but one dependent on non-perturbative physics, we model it via the one-loop P_{mm} EFT prediction supplemented with a phenomenological

Zeldovich theoretical value $n_s = 1$. These choices have a marginal impact on our results.

[3] https://github.com/oliverphilcox/full_shape_likelihoods

"resummed" version of the counterterm whose parameters were fitted from HMcode [89]. We stress that the choice of non-linear corrections for the magnification bias has a negligible impact on final results.

Our baseline analysis of BOSS (which we dub $G^2G^3G\kappa$+BAO) uses redshift-space scale cuts $k_{\max}^{P_\ell} = 0.2\,h\mathrm{Mpc}^{-1}$ and $k_{\max}^{B_\ell} = 0.08\,h\mathrm{Mpc}^{-1}$, and real-space scale cuts for Q_0 and P_{mg} at $k_{\max}^{\mathrm{real}} = 0.4\,h\mathrm{Mpc}^{-1}$ (corresponding to angular cuts $\ell_{\max}^{\mathtt{LOWZ,CMASS}} = 400, 600$) validated in [20, 34, 38, 40, 75, 76, 90–93].

Parametrization and priors. — In this *Letter*, we follow the EFT parametrization in [20, 38, 76, 93]. Briefly, galaxy clustering is described by one linear, two quadratic, and one cubic bias parameters, along with three counterterms and three stochastic terms up to k^2 in scale dependence. In addition to these contributions we include a next-order finger-of-god (FoG [94]) term $k^4\mu^4P_{\mathrm{lin}}$ to account for the effect leading to larger dynamical non-linearities than other effects [74]. The tree-level bispectrum is described by these bias parameters up to quadratic order and two additional stochastic terms associated with the non-Gaussianity and density-dependence of short modes and, like the power spectrum, a phenomenological FoG term. The real-space clustering of matter requires an additional real space counterterm $P_{mg}^{\mathrm{c.t.}} = 2b_1c_0k^2P_{\mathrm{lin}}(k)$, for which we use the Gaussian prior $\mathcal{N}(0, 10^2)$ in units $[h^{-1}\mathrm{Mpc}]^2$, resulting in 14 free parameters per sample.[4]

Results. — We start by analyzing the BOSS FS and BAO data within the baseline ΛCDM model. Our results are displayed in Fig. 2 and Tab. I. We find that the optimal values of cosmological parameters are consistent with the *Planck* baseline CMB values [1], except for σ_8, which shows a 4.5σ disagreement. The tension with the ACT CMB lensing results [36] has a similar strength: 4.3σ. For the S_8 parameter, the discrepancy is somewhat weaker, 3.8σ, though our results appear in agreement with weak lensing measurements by DES [17], KiDS [16], and HSC [28, 29], see Fig. 1.

Notably, the tension remains for different subsets of the underlying data (see Fig. 1). Our tests include: (a) adopting a more conservative choice of $\ell_{\max} = 350$ for the lensing data (which yields $\sigma_8 = 0.698^{+0.03}_{-0.03}$); (b) fitting only the galaxy power spectrum multipoles using the Lagrangian EFT with the velocileptors code[5] [23, 95–97] ($\sigma_8 = 0.731^{+0.048}_{-0.048}$); (c) fitting only the multipoles plus CMB-lensing cross correlation ($\sigma_8 = 0.708^{+0.037}_{-0.037}$) as in ref. [22][6]; (d) removing the galaxy-CMB lensing cross correlation ($\sigma_8 = 0.709^{+0.031}_{-0.033}$); (e) analyzing the z1/z3 split of the BOSS data including LOWZE2/LOWZE3 samples omitted in our main FS analysis ($\sigma_8 = 0.722^{+0.03}_{-0.03}$). We find consistent results in all cases (Fig. 1).

Parameter	ΛCDM	DDE
Ω_m	$0.3155\ (0.3103)^{+0.0087}_{-0.0090}$	$0.3223\ (0.3232)^{+0.0079}_{-0.0081}$
H_0	$68.54\ (68.54)^{+0.77}_{-0.81}$	$68.19\ (67.47)^{+0.89}_{-0.89}$
σ_8	$0.687\ (0.704)^{+0.026}_{-0.028}$	$0.686\ (0.691)^{+0.026}_{-0.028}$
S_8	$0.704\ (0.716)^{+0.031}_{-0.031}$	$0.711\ (0.717)^{+0.029}_{-0.029}$
w_0	-1	$-0.907\ (-0.971)^{+0.072}_{-0.073}$
w_a	0	$-0.49\ (-0.05)^{+0.42}_{-0.34}$

TABLE I. Cosmological parameters and their 68% confidence limits (with best-fit values shown in parentheses), from the full BOSS dataset under the ΛCDM model (left) and from BOSS+DESI+SNe under the DDE model (right).

Another important observation is that the preference for low σ_8 is not a prior effect (see e.g. [38, 76, 98] for related studies), as previous studies have shown that the preference for a low σ_8 value in the BOSS data is present at the level of the raw χ^2 statistic [23, 76]. The tension also remains when more informative reasonably narrow priors are applied. It will be interesting to see if informative simulation-based priors [99] can sharpen our constraints further.

Secondly, we analyze the full combination of BOSS clustering, DESI BAO, and SNe data assuming the DDE model. Our results are shown in Fig. 2 and Tab. I. The inferred H_0 value is consistent with previous CMB and LSS measurements based on the ΛCDM model, confirming the standard lore that DDE cannot resolve the Hubble tension [11]. Turning to the σ_8 tension, we find nearly identical constraints in the DDE model as in ΛCDM, im-

[4] Part of this counterterm also enters the galaxy power spectrum, but the counterterm combinations that appear in $P_{0,2,4}$ are linearly independent from that of P_{gm}, leading to four parameters for four independent spectra.

[5] https://github.com/sfschen/velocileptors/

[6] https://github.com/sfschen/BOSSxPlanck

plying that DDE cannot resolve the σ_8 discrepancy in the BOSS galaxy clustering data. Finally, we observe that the $w_0 - w_a$ posterior is consistent with the ΛCDM values $(-1, 0)$ within 68% CL.

Notably, the FS data provides an independent channel to extract ω_m (and Ω_m), relevant for the DDE constraints [38, 98]. Our analysis suggests that the inclusion of this information leads to a non-detection of DDE, compared to the weak preference found in Appendix A of [9], which used only the BAO data from BOSS/eBOSS. The BOSS FS data delivers constraints on the matter density whose precision rivals that of the *Planck* CMB, which when combined with DESI and PantheonPlus, cf. [9], *i.e.* BOSS FS can competitively replace the CMB in breaking degeneracies inherent in BAO data. This remains true if we vary the spectral tilt n_s in the fit; as such, our results do not require any input from the CMB.[7]

Conclusions. — In this *Letter*, we have presented a novel analysis of public galaxy clustering and CMB lensing data from *Planck* and BOSS, representing the most complete combination of galaxy correlators yet performed. Our results suggest a value of the mass fluctuation amplitude in tension with the best-fit ΛCDM value predicted by *Planck* CMB anisotropies, which cannot be accounted for by dynamical dark energy (DDE); furthermore, the combination of BOSS with BAO data from DESI and expansion data from supernovae does not yield any evidence for DDE. Our results have several important implications.

From the phenomenological perspective, it would be interesting to build a model that can resolve this σ_8 tension. There exist many proposals that can readily produce some suppression on small scales, such as massive neutrinos [39, 100], ultralight axions [101, 102], light but massive relics [103], baryon-dark matter scattering [104], dark sector interactions [105–107], and beyond; however, it is unclear whether these can account for the part of the suppression in BOSS that is present on large scales $k \lesssim 0.1\,h\mathrm{Mpc}^{-1}$ [23, 76]. In addition, such a model should keep cosmic structure at $z \gtrsim 1$ unsuppressed, as suggested by eBOSS quasar [108, 109] and Lyman-α data [110, 111].

The σ_8 tension is generated by data that effectively measure the cross-correlation between the galaxy field and a probe of matter, through either CMB lensing or redshift-space distortions (which probe the velocity field): σ_8 is extracted from the ratio between the relevant cross- (*i.e.* the quadrupole and P_{gm}) and auto- galaxy power spectrum (*i.e.* the monopole). An additive foreground, arising for example due to contaminants in the photometric selection of target galaxies, would enhance the auto-spectrum but cancel in both cross-correlations, leading to smaller ratios between them and consequently lower σ_8. If such a systematic correction is present, it will affect these two seemingly independent measurements of σ_8 in a correlated fashion. That said, the addition of the bispectrum, which instead probes structure growth through cancelling quadratic and linear terms in the redshift-space galaxy density, is also found to reduce the measured σ_8, though we caution that the impact of foreground systematics on the 3-point function is less well-explored. In any case, we expect the coming generation of galaxy surveys, which feature more robust data and updated treatments of foreground systematics, to shed light on this issue.

Finally, it will be important to understand if the tensions in the expansion history, particularly due to deviations away from a cosmological constant, that appear from different combinations of the LSS data from BOSS and DESI are physical, and if there is a new physics model that can account for them in a consistent manner. Such effects, as well as further examination of the low-σ_8 discrepancy, will certainly be illuminated with future full-shape analyses of galaxy clustering data from DESI [112] and beyond.

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[7] In this case, we find $\sigma_8 = 0.655\ (0.683)^{+0.031}_{-0.034}$, $w_0 = -0.887\ (-0.875)^{+0.075}_{-0.08}$, $w_a = -0.80\ (-0.65)^{+0.52}_{-0.42}$.

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