

Multiprobe constraints on early and late time dark energy

Alexander Reeves^{1,*}, Simone Ferraro^{2,3}, Andrina Nicola⁴, and Alexandre Refregier¹

¹*Institute for Particle Physics and Astrophysics, ETH Zürich,
Wolfgang-Pauli-Strasse 27, CH-8093 Zürich, Switzerland*

²*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*

³*Department of Physics, University of California, Berkeley, California 94720, USA*

⁴*Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy,
The University of Manchester, Manchester M13 9PL, United Kingdom*



(Received 7 November 2025; accepted 23 March 2026; published 7 May 2026)

We perform a multiprobe analysis combining cosmic microwave background (CMB) data from *Planck* and the Atacama Cosmology Telescope (ACT), ACT CMB lensing, and large-scale structure (LSS) measurements from the Dark Energy Spectroscopic Instrument (DESI), including DESI Legacy Imaging Survey (LS) galaxies and baryon acoustic oscillations (BAOs). We present the first 5×2 pt analysis of ACT DR6 lensing, DESI LS, and *Planck* Integrated Sachs-Wolfe (ISW). Within Λ CDM, this yields $S_8 = \sigma_8(\Omega_m/0.3)^{0.5} = 0.819 \pm 0.016$, in good agreement with primary CMB inferences and provides a sound-horizon-free Hubble constant constraint of $H_0 = 70.0 \pm 4.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Then, combining with CMB primary and BAO, we reconfirm a CMB–BAO discrepancy in the $\Omega_m - \frac{D_v}{r_d}$ plane, which is heightened when combining BAO with the 5×2 pt data vector. We explore two dark-energy extensions that may reconcile this: an early-time modification, early dark energy (EDE), and late-time dynamical dark energy (DDE) parametrized by $w_0 w_a$. For CMB primary + BAO + 5×2 pt, we find a 3.3σ preference for DDE over Λ CDM, while EDE is modestly favored at 2.3σ . The models address different shortcomings of Λ CDM: DDE relaxes the neutrino mass bound ($M_\nu < 0.17 \text{ eV}$ vs $< 0.050 \text{ eV}$ under Λ CDM), making it compatible with neutrino oscillation measurements, while EDE raises the Hubble constant to $H_0 = 70.5 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$, easing the discrepancy with SH0ES. However, neither model resolves both issues simultaneously. Our analysis indicates that both DDE and EDE remain viable extensions of Λ CDM within current uncertainties and demonstrates the capacity of combined probes to place increasingly stringent constraints on cosmological parameters.

DOI: 10.1103/w737-nk6r

I. INTRODUCTION

Multiprobe techniques are at the forefront of modern cosmological analysis. Such analyses offer significant advantages over single-probe measurements. These include the ability to identify and mitigate systematic effects that do not correlate between datasets and the breaking of parameter degeneracies to provide tight constraints on cosmological models. In recent years, numerous studies in this direction have been performed, including the 3×2 pt analysis of large-scale structure (LSS) galaxy surveys combining galaxy clustering and weak lensing measurements [1–3], a similar combination but exchanging cosmic microwave background (CMB) lensing for galaxy weak

lensing [4], and comprehensive analyses combining CMB and several LSS tracers (see, e.g., Refs. [5–9]).

Recent analysis of the second data release of the baryon acoustic oscillation (BAO) data from the Dark Energy Spectroscopic Instrument (DESI DR2) shows a $\sim 3\sigma$ preference for an evolving dark energy equation of state when combined with CMB data from *Planck* [10,11]. This is driven by an internal $\sim 2\sigma$ tension between CMB and BAO data when analyzed under Λ CDM [10]. While dynamical dark energy (DDE) is a plausible model to explain these data, the evidence is not yet conclusive. In particular, several recent papers have suggested that altering prerecombination physics, for example, via an early dark energy (EDE) component [12,13] or by a modified recombination history [14,15], while keeping a cosmological constant, can also partially resolve this discrepancy.

In this work, we confront these recent hints with LSS and CMB data using a multiprobe approach. Building on the framework introduced in Refs. [7,16] and incorporating new datasets, we analyze, for the first time, a 5×2 pt LSS combination of Atacama Cosmology Telescope (ACT)

*Contact author: areeves@phys.ethz.ch

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](#). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

DR6 CMB lensing, Legacy Imaging Survey (LS) galaxy clustering, and *Planck* PR3 ISW, measuring all autocorrelation and cross-correlation. The 2×2 pt subset of this data vector, comprising the LS autocorrelations and their cross-correlations with CMB lensing, has already been shown to place strong constraints on the lensing amplitude S_8 within Λ CDM [17–19]. Moreover, Ref. [20] demonstrated that this subset, when combined with type Ia supernova (SNe) data, provides robust evidence for a DDE scenario even in the absence of primary CMB data.

We begin by deriving Λ CDM constraints, including deriving a sound horizon-free H_0 value and assessing goodness of fit under this model. We then combine with primary CMB data from *Planck* PR4 and ACT DR6 and DESI DR2 BAO measurements to explore two extensions in the dark energy sector that can reconcile the mild tensions between these data observed under Λ CDM. The extensions represent modifications to early- and late-time physics respectively: an early-Universe modification exemplified by an axionlike EDE model and a dynamical dark energy model with a time-evolving equation of state (denoted hereafter by DDE). In particular, we ask whether contemporary LSS and BAO data favor an evolving $w(z)$ or an EDE component when analyzed alongside the CMB; how these extensions affect derived parameters such as S_8 and the neutrino mass sum; and what changes arise when we confront these models with external data from Pantheon+SNe [21] and local distance ladder H_0 inferences from SH0ES [22]. We further aim to clarify the phenomenological drivers of any improvement in fit beyond Λ CDM.

The rest of this paper is organized as follows: In Sec. II, we introduce the datasets and measurements used in our analysis. In Sec. III, we describe our analysis pipeline, including details of the likelihoods, modeling assumptions, covariance estimation, and inference framework. Section IV presents the theoretical models behind the extensions to Λ CDM under consideration. We report our results in Sec. V, first discussing the constraints on Λ CDM parameters from the 5×2 pt data and goodness of fit. We then combined with CMB primary and BAO data and examine the EDE and DDE dark energy extensions and determine the model preference from the relative goodness of fit. We also discuss these findings in the context of additional external datasets (supernovae data and external priors on H_0 or S_8). Finally, Sec. VI summarizes our conclusions and outlines future prospects for distinguishing early vs late-time new physics with upcoming data.

II. DATASETS

In this section, we briefly outline the datasets used in this analysis.

A. DESI legacy imaging survey

We use the LS luminous red galaxy (LRG) catalogue [23], drawn from the $g r z$ imaging of the LS

DR9 [24] for the photometric clustering part of our analysis. The images were taken with DECam on the CTIO 4m Blanco telescope, the Bok 2.3m telescope, and the 4m Mayall telescope (MzLS), providing $\sim 20,000 \text{ deg}^2$ of uniform photometry with well-characterized selection functions and photometric redshifts. We use the “Main LRG sample,” which covers $16,700 \text{ deg}^2$ on the sky, and comprises approximately 12 million galaxies. The redshift distributions are characterized using 2.3 million spectroscopic redshifts from DESI’s Survey Validation [25]. The data are distributed in four tomographic redshift bins in the range $0.2 \lesssim z \lesssim 1.4$. A detailed description of the photometric selection criteria is given in Ref. [23].¹

B. ACT DR6 CMB primary and lensing

For the ACT DR6 primary CMB, we use the P-ACT combination adopted by the ACT Collaboration as their baseline dataset. This dataset incorporates the *Planck* 2018 temperature and polarization spectra, covering the multipole ranges $30 < \ell < 1000$ for TT (temperature) and $30 < \ell < 650$ for TE and EE (temperature-polarization cross-correlation and polarization auto-correlation, respectively), combined with ACT DR6 data at high multipoles [27]. Following the ACT Collaboration, we also add the SRoll2 low- ℓ EE likelihood [28]. For the $2 < \ell < 30$ TT part of the likelihood, we use the compressed likelihood from Ref. [29] which is based on the *Planck* PR3 Commander-derived likelihood; the latter is used in the official ACT analysis, while the former was shown to produce identical constraints with reduced computational overhead [29]. We adopt the compressed “ACT-lite” CMB-only likelihood where foregrounds are premarginalized. This has been shown by the ACT Collaboration to yield cosmological parameters consistent with the baseline MFLike likelihood (which explicitly varies foreground parameters) while significantly reducing the computational cost [27].

In addition, we use the gravitational-lensing convergence maps reconstructed from the same ACT DR6 data, covering a total sky area of approximately 9400 deg^2 [30]. The lensing pipeline applies both quadratic and iterative estimators to multifrequency temperature and polarization maps to reconstruct the CMB lensing potential. The ACT DR6 public release includes the reconstructed lensing maps, their associated masks, and simulations of the noise properties.²

C. *Planck* primary CMB anisotropies

When deriving constraints, we compare results by exchanging between the CMB primary likelihood of

¹These data are publicly available here [26].

²The ACT DR6 lensing data are available at this URL: https://lambda.gsfc.nasa.gov/product/act/actadv_dr6_lensing_maps_info.html.

ACT DR6 and *Planck* PR4. The *Planck* PR4 processing (“NPIPE”) delivers improved calibration and foreground mitigation relative to earlier releases [31]. We adopt the HiLLiPoP version of the *Planck* PR4 likelihood [32]. We use a compressed version of the likelihood described in Appendix A, which has an order of magnitude fewer data points and allows for faster inference while producing identical cosmological constraints. We make the rewritten JAX version of this likelihood (including the corresponding compression matrix) publicly available.³

For our ISW analysis, we use the *Planck* PR3 temperature maps.⁴ We use the Commander maps, as these are the recommended maps for measurements on large angular scales.⁵

D. DESI DR2 baryon acoustic oscillations

The second public release of the Dark Energy Spectroscopic Instrument (DESI) survey provides more than 14 million spectroscopic redshifts gathered with the 5000-fiber DESI spectrograph on the 4m Mayall Telescope at Kitt Peak National Observatory [33]. DR2 covers $\sim 7500 \text{ deg}^2$ and is split into four tracer classes—0.3 million Bright Galaxy Survey galaxies ($0.1 < z < 0.4$), 2.14 million LRGs ($0.4 < z < 1.1$), 2.43 million emission line galaxy (ELGs) ($0.8 < z < 1.6$), and 0.86 million quasars ($0.8 < z < 2.1$)—yielding BAO measurements across $0.1 < z < 2.1$ [10]. In this work, we use the public DESI DR2 BAO likelihood, comprising 13 distance measurements at seven effective redshifts spanning $0.30 \leq z_{\text{eff}} \leq 2.33$ [Bright galaxy survey (BGS), LRG1, LRG2, LRG3 + ELG1, ELG2, QSO, Ly α]. The likelihood consists of measurements of $\{D_M/r_d, H r_d\}$ for all tracer classes except BGS, where D_V/r_d is used [10].

E. Pantheon + type Ia supernovae

When adding SNe to our data combination, we employ the Pantheon+ compilation of 1550 spectroscopically confirmed SNe Ia spanning $0.001 < z < 2.26$ and comprising 1701 light curves [21]. To mitigate sensitivity to host-galaxy peculiar velocities and local bulk flows at very low redshift, we remove the 111 SNe with $z < 0.01$; our working sample therefore contains 1439 SNe (1590 light curves) over $0.01 < z < 2.26$ [21].

III. MODELING, DATA VECTOR, COVARIANCE, AND INFERENCE PIPELINE

A. Modeling

Our modeling pipeline closely follows the framework developed in Refs. [7,16]. For the LS LRGs, ISW cross-

correlations, and ACT DR6 CMB-lensing cross-correlations, we define our own modeling choices. All other elements of the framework—primary CMB TTTEEE, DESI BAO, CMB lensing autocorrelation and Pantheon + distances—are instead implemented using JAX translations of the official publicly available likelihoods from Cobaya [34].

1. Theoretical predictions

To produce theoretical predictions for the LSS tracers (CMB lensing, galaxy clustering, ISW) in this pipeline, we employ the FKEM [35] beyond Limber algorithm as implemented in CCL v3.1 [36] (see also Ref. [37] for a recent JAX-based beyond Limber implementation). This computes the full 3D angular power spectrum projection integral,

$$C_{\ell}^{XY} = \int_0^{\infty} d\chi \int_0^{\infty} d\chi' W^X(\chi) W^Y(\chi') \times \int_0^{\infty} \frac{2}{\pi} k^2 dk P(k; \chi, \chi') j_{\ell}(k\chi) j_{\ell}(k\chi'), \quad (1)$$

where $P(k; \chi, \chi')$ is the unequal time matter power spectrum, j_{ℓ} is the spherical bessel function, χ is the comoving distance, and $W^{X/Y}$ are window functions specific to the probes in the pipeline. We use this full computation for multipoles $\ell < 60$. For $\ell \geq 60$, we set up CCL to transition to the standard Limber approximation [38],

$$C_{\ell}^{XY} = \int \frac{d\chi}{\chi^2} P\left(k = \frac{\ell + \frac{1}{2}}{\chi}, \chi\right) W^X(\chi) W^Y(\chi). \quad (2)$$

We chose the transition at $\ell = 60$ based on Fig. 4 of Ref. [17] where the Limber approximation is shown to be inaccurate at $>1\%$ for $\ell \lesssim 60$ for LS LRG autocorrelations.

For the LS projected galaxy overdensity, we adopt a linear galaxy bias b_i fit independently in each of the four tomographic bins, include magnification using the standard magnification kernel with a free number-count slope parameter s_i per bin, and add a constant projected shot-noise term with one free parameter per bin, following Ref. [17]. We adapt the CCL code to enable the use of the AxICLASS [39] backend Boltzmann solver with the appropriate parameter settings in order to make theoretical predictions for the EDE model.

For the CMB primary, we compute TT, TE, and EE spectra with CLASS [40] (or AxICLASS [39] in the case of EDE) using the precision settings detailed in Appendix A of Ref. [41]. The precision settings are required to ensure unbiased constraints when using the high- ℓ ACT DR6 CMB primary likelihood. DESI BAO and Pantheon + SN distances and sound horizon predictions are produced from the same CLASS evaluation.

2. Scale cuts

The scale cuts used in this analysis are summarized in Table I. For galaxy clustering—both in autocorrelations

³<https://github.com/alexander-reeves/jax-loglike>.

⁴We do not expect any significant change to our results upon exchanging with the PR4 NPIPE temperature map, as the large-scale temperature signal is essentially unchanged in this reprocessing [31].

⁵Available at the Planck Legacy Archive, <https://pla.esac.esa.int/>.

TABLE I. Multipole ranges and binning for LSS autocorrelations and cross-correlations..

Spectrum	ℓ range	No. of bins
LSS autocorrelations		
$\delta_{g1}\delta_{g1}$	30–185	5
$\delta_{g2}\delta_{g2}$	30–215	5
$\delta_{g3}\delta_{g3}$	30–235	5
$\delta_{g4}\delta_{g4}$	30–245	5
$\kappa_{\text{CMB}}\kappa_{\text{CMB}}$	40–1300	18
LSS cross-correlations		
$\delta_{g1}\kappa_{\text{CMB}}$	40–185	5
$\delta_{g2}\kappa_{\text{CMB}}$	40–215	5
$\delta_{g3}\kappa_{\text{CMB}}$	40–235	5
$\delta_{g4}\kappa_{\text{CMB}}$	40–245	5
$\delta_{g1}T$	20–90	4
$\delta_{g2}T$	20–90	4
$\delta_{g3}T$	20–90	4
$\delta_{g4}T$	20–90	4
$\kappa_{\text{CMB}}T$	40–90	4

and crosscorrelations—we restrict to scales where a linear-bias description is adequate. Concretely, in each redshift bin, we set ℓ_{max} by mapping angular to three-dimensional modes with the Limber approximation. We then require $k < 0.1h \text{ Mpc}^{-1}$, ensuring the analysis remains safely within the linear regime, where the difference between the linear and nonlinear matter power spectrum is $\lesssim 1.5\%$ (we estimate this using CLASS [40] in the best-fit *Planck* ΛCDM cosmology). The minimum multipole is conservatively fixed to $\ell_{\text{min}} = 30$ for galaxy autocorrelations to mitigate the impact of large-scale redshift-space distortions [42] and to suppress box-size effects in the simulation-based covariance matrix.

For ACT DR6 CMB lensing, we analyze the autospectrum over the extended range $40 \leq L \leq 1300$, which the collaboration deemed reliable after unblinding, following a simulation-based reevaluation of potential foreground-induced biases [43,44]. Finally, for each cross-correlation we adopt the more conservative of the two scale cuts defined by the probes entering the cross-spectrum, except for ISW cross-correlations where we use $\ell_{\text{min}} = 20$ to enhance the signal-to-noise ratio, which peaks on larger scales. We checked that the recovered ISW covariance matrix matches an analytic estimate within 5% on the diagonals, showing that we are not significantly affected by box-size effects.

3. Neural-network emulators

As in our previous work [7,16], we employ JAX-based neural-network emulators to produce rapid theoretical predictions at each sampled point in parameter space. We draw 10^6 points in a Latin hypercube in the

cosmological parameter space and train dense feed-forward networks to emulate the outputs of our theoretical predictions module (see Sec. III A 1). The pipeline mirrors Ref. [7], with only a single change for the EDE runs where we replace baseline CLASS with AxICLASS.

Each neural network emulator is a multilayer perceptron with four hidden layers and 512 units per layer, using the custom activation function,

$$f(\vec{x}) = (\vec{\gamma} + (1 + \exp(-\vec{\beta} \cdot \vec{x}))^{-1}(1 - \vec{\gamma})) \cdot \vec{x}, \quad (3)$$

where $f(\vec{x})$ is the activation function that describes how the input vector $\vec{x}$ is mapped to the output vector in each layer and $\vec{\beta}$ and $\vec{\gamma}$ are trainable parameters following the approach in Ref. [45]. We produce separate emulators for C_{ℓ}^{TT} , C_{ℓ}^{TE} , C_{ℓ}^{EE} , $C_{\ell}^{\kappa_{\text{CMB}}\kappa_{\text{CMB}}}$, BAO sound horizon-distance ratios, and SNe distances. For the remaining LSS probes, we train a single joint emulator whose target is the concatenated vector of all binned LSS spectra. The networks are trained using TensorFlow [46]. We subsequently translate the weights and biases to the JAX ecosystem using Flax [47].

B. Data vector

1. Mask deconvolution

In this pipeline, we deal with projected maps of both simulations and observational data, which have a survey mask that generally couples modes together. The survey mask introduces mode coupling between multipoles. We can relate the ensemble-averaged cut-sky power spectrum $\langle \tilde{C}_{\ell}^{XY} \rangle$ to the full-sky spectrum C_{ℓ} through a mode coupling matrix $M_{\ell\ell'}$,

$$\langle \tilde{C}_{\ell}^{XY} \rangle = \sum_{\ell'} M_{\ell\ell'} C_{\ell'}. \quad (4)$$

Recovery of the full-sky C_{ℓ} from cut-sky data by inverting the coupling matrix is generally not possible due to information loss from partial sky coverage. To make progress, we employ the MASTER algorithm [48], implemented in NaMaster [49], which approximates the true angular power spectrum as a piecewise constant over multipole bins. This approximation enables inversion of the binned mode coupling matrix, providing unbiased estimates of the full-sky bandpowers. To address pixelization effects, we use the window function obtained from HEALPY's `pixwin` function as an effective “beam” in the NaMaster `NmtField` object for each map.⁶

⁶This pixelization correction approach is applicable at high ℓ/NSIDE only when the source density is sufficiently high (see Appendix A of Ref. [50]). Alternative methods that circumvent pixelization entirely and thereby avoid these issues are discussed in Refs. [51,52].

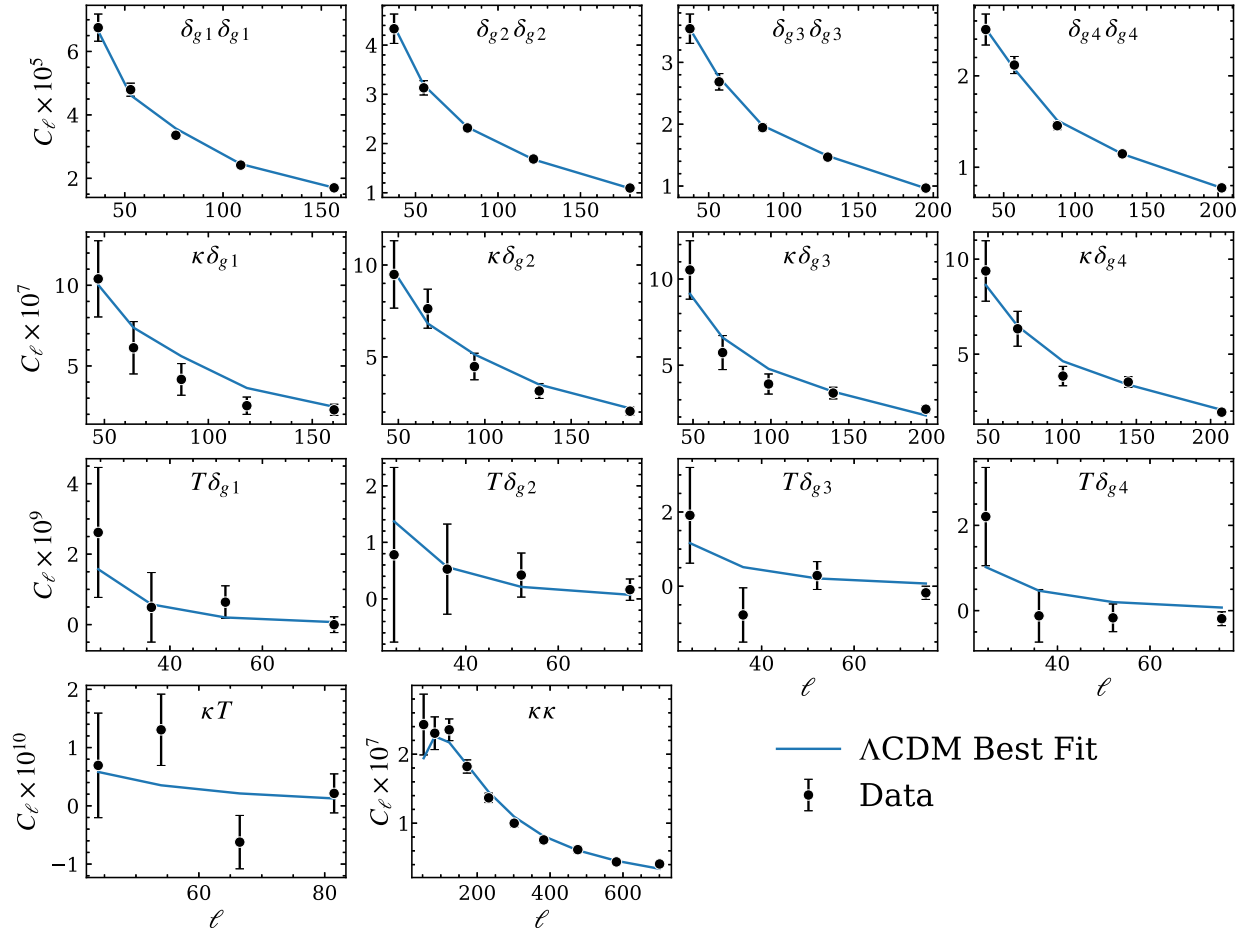


FIG. 1. The measured 5×2 pt data vector with corresponding simulation-based error bars. We show also the best-fit prediction for these spectra under Λ CDM.

2. Measuring the data vector

To produce the 5×2 pt data vector, we follow Ref. [7], starting from galaxy maps for the LS LRGs, the ACT DR6 lensing convergence map, and the *Planck* PR3 Commander-derived temperature map. Each of the maps are produced at HEALPix NSIDE = 2048 with the respective survey masks applied. We then use NaMaster to compute mask-deconvolved bandpowers following the procedure outlined in Sec. III B 1. For CMB lensing autocorrelations, we instead make use of the official ACT DR6 lensing bandpowers instead of deriving our own data vector directly from the convergence map. For the ACT DR6 lensing cross-correlations, we apply a Monte Carlo normalization correction following the procedure outlined in Appendix F. Our measured data vector can be seen in Fig. 1.

C. Covariance matrix

We build the low- z covariance from 2000 mock map-level realizations based on 200 independent N -body light cones. Each light cone is generated with PKDGRAV3 [53] in the *Planck* 2018 fiducial cosmology (Table II) with a boxsize of $L_{\text{BOX}} = 2250 \text{ Mpc}/h$ and 2080^3 particles.

The resulting light cones are postprocessed with the publicly available UFalcon software⁷ [16,54] to generate correlated galaxy density, ISW and CMB lensing signal maps at NSIDE = 2048.

We add noise realizations separately for each probe. For DESI galaxies, the noise is added as a Poisson draw of random positions inside the DESI mask. For the ISW maps, we add FFP10 end-to-end simulations containing both CMB signal and noise components to the ISW signal maps following Ref. [16]. While this adds an additional ISW signal component to the simulated maps, this is entirely subdominant to the other contributions, so it has a negligible impact. This method was shown to produce covariances that agree well (within 5% on the diagonals) with analytically derived Gaussian ISW covariance matrices in Ref. [16]. For CMB lensing, we create noise-only maps from the public ACT DR6 simulations by subtracting the input signal $a_{\ell m}$ s from the full simulated $a_{\ell m}$ s and converting the residuals to HEALPix maps at NSIDE = 2048 with the `alm2map` routine from HEALPY. Treating the

⁷<https://cosmology.ethz.ch/research/software-lab/UFalcon.html>.

TABLE II. Fiducial Cosmological parameters used in simulations for the covariance matrix. This matches the best-fit parameters from *Planck* 2018 [55].

Parameter	Value
Ω_m	0.315
A_s	2.1×10^{-9}
n_s	0.9649
Ω_b	0.0493
H_0 (Km/s/Mpc)	67.3
M_ν (eV)	0.06

noise as additive in this way is accurate to better than 3.5% in the noise power spectrum [5], which is adequate for covariance estimation.

We apply the respective survey masks to each simulation before we measure pseudo- C_ℓ s following the same procedure outlined in Sec. III B 1. The covariance matrix is then estimated from the ensemble of the 2000 pseudo- C_ℓ mock realizations of the data vector. When inverting this matrix for parameter inference, we correct for finite-sample bias with the Hartlap factor [56]. Finally, we replace the simulated ACT lensing autocovariance block with the covariance matrix supplied by the ACT Collaboration while retaining the simulation-derived cross-covariance blocks (i.e., the $\langle C_\ell^{\text{K}_{\text{CMB}} \text{K}_{\text{CMB}}} C_\ell^{XY} \rangle$ parts where X, Y represent two other probes in the pipeline).

We checked that the resulting covariance matrix is well converged by varying the number of simulations used and computing the mean relative difference of the diagonals of the matrix. We find that after ~ 1500 realizations the relative differences are $\lesssim 1\%$ implying sufficient convergence for cosmological analysis. We also checked that the simulation-based covariance agrees within 10% along the diagonal with an independent analytical calculation for the same matrix and produces nearly identical constraints (see Appendix D).

D. Likelihood

In our joint analyses, we form the sum the likelihood contributions from the CMB primary, BAO, SNe, and the combined 5×2 pt LSS data vector, under the assumption that interprobe cross-covariances are negligible. For the CMB primary likelihoods, this approximation is justified because the cross-correlation with LSS tracers is small compared to the dominant primary CMB power spectra [57] (this statement may require reexamination for future high-precision surveys [58,59]). For the BAO–LSS cross-covariance, we test this approximation explicitly in Appendix B and find that the BAO information content in the LSS data vector is negligible compared to the information content of the reconstructed BAO likelihood.

When combining CMB lensing with primary CMB power spectra, we follow Ref. [4] and forward model the linear response of the lensing reconstruction to the

measured primary spectra, updating to first order the estimator normalization and reconstruction biases (e.g., $N^{(0)}, N^{(1)}$). This is required for a consistent analysis, as these quantities necessarily depend on the given CMB primary realization. When the primary CMB power spectra are not included, we adopt a *CMB-marginalized* covariance matrix for the CMB lensing autospectrum. In this setup, uncertainties in the CMB two-point functions are propagated as an additional contribution to the covariance.

E. Inference and minimization

The priors used in this analysis are presented in Table III. For cosmological parameters, we generally employ wide flat priors. For the galaxy nuisance parameters, we follow the prescription in Ref. [17] in placing uniform priors on the galaxy bias and Gaussian priors based on the measured values from Ref. [23] on the shot noise and magnification-slope parameters. Following the recent DESI DR2 EDE analysis of Ref. [12], we adopt a Gaussian prior on $\log_{10} a_c$ centered at the scale factor near matter-radiation equality. This choice reduces prior volume in low-likelihood regions corresponding to EDE transitions that occur much later or much earlier than equality [60,61]. Our baseline results without placing the Gaussian prior on $\log_{10} a_c$ are shown in Appendix E, where we find that using a flat prior makes a negligible difference to our conclusions.

We use the EMCEE package [62] for performing cosmological inference. We leverage JAX's natural vectorization via vmap and GPU acceleration to greatly accelerate our inference. Running on a single NVIDIA A100 Tensor Core GPU allows for converged chains in under four hours for every analysis setup explored in this work with most taking under 30 minutes (see also Ref. [63] for a similar approach). We deem our Markov Chain Monte Carlo chains to be converged by verifying that the autocorrelation time τ [62] stabilized and that each walker satisfied $N_{\text{steps}} > 100\tau$ for all parameters.

To find the best-fit parameters and χ^2_{min} values, we first use a simulated annealing approach [64–66]. That is, we first sample the full posterior with EMCEE, then *whiten* the parameter space by rescaling each direction by its posterior standard deviation. Twelve starting points are drawn from a small Gaussian ball (0.1σ in every dimension) around the posterior mode. From each starting point, we launch a simulated-annealing chain whose acceptance probability at an effective temperature T is

$$P_{\text{acc}}(\theta \rightarrow \theta') = \min \left[1, \exp \left(-\frac{\Delta E}{T} \right) \right], \quad (5)$$

where $\Delta E = E(\theta') - E(\theta)$ and $E = -\ln \mathcal{L}$. The temperature is lowered in four linear steps from $T = 0.75$ to $T = 0.01$ and run a maximum of 2.5×10^4 steps at each rung, transitioning to the next rung when this limit is reached or earlier if the best fit does not improve in a window of 200

TABLE III. Parameters varied in the analysis and associated priors. Unless stated otherwise, priors are flat and uninformative. CMB-foreground nuisance parameters in the ACT DR6 and HILLIPOPP likelihoods are *not* listed; for those we follow, the respective collaboration prescriptions. Shot-noise and magnification-slope priors follow [17] as described in the text.

Parameter	Description	Prior/fixed value
Base Λ CDM		
ω_c	Physical cold dark matter density	$\mathcal{U}(0.08, 0.20)$
ω_b	Physical baryon density	$\mathcal{U}(0.01875, 0.02625)$
$\ln(10^{10} A_s)$	Primordial amplitude	$\mathcal{U}(2.5, 3.5)$
n_s	Scalar spectral index	$\mathcal{U}(0.84, 1.10)$
h	Hubble parameter	$\mathcal{U}(0.4, 1.0)$
LSS nuisance (galaxy/baryonic)		
$b_{g,i}$ ($i = 1..4$)	Linear galaxy bias per bin	$\mathcal{U}(0.1, 5.0)$
$\text{SN}^{2D}(z_i)$	Projected shot noise (per bin)	Bin 1: $\mathcal{N}(4.07, 1.22)$
		Bin 2: $\mathcal{N}(2.25, 0.675)$
		Bin 3: $\mathcal{N}(2.05, 0.615)$
		Bin 4: $\mathcal{N}(2.25, 0.675)$
$s_\mu(z_i)$	Number-count (magnification) slope (per bin)	Bin 1: $\mathcal{N}(0.972, 0.0972)$
		Bin 2: $\mathcal{N}(1.044, 0.1044)$
		Bin 3: $\mathcal{N}(0.974, 0.0974)$
		Bin 4: $\mathcal{N}(0.988, 0.0988)$
$\log_{10} T_{\text{AGN}}$	Baryonic feedback amplitude	$\mathcal{U}(7.1, 8.5)$
Extended cosmology		
$\log_{10} a_c$	EDE critical scale factor	$\mathcal{N}(-3.531, 0.10)^b$
$f_{\text{EDE}}(a_c)$	EDE fraction at a_c	$\mathcal{U}(0, 0.8)$
θ_i	Initial field displacement	$\mathcal{U}(0.1, \pi)$
w_0	DE equation of state (EoS) (today)	$\mathcal{U}(-3.0, 0.5)$
w_a	Time variation of DE EoS	$\mathcal{U}(-3.0, 2.0)$
$M_\nu = \sum m_\nu$	Sum of neutrino masses	$\mathcal{U}(0, 1.5) \text{ eV}^a$

^aWhen not varied, the sum of neutrino masses is fixed to $M_\nu = 0.06 \text{ eV}$.

^bGaussian prior on $\log_{10} a_c$ as described in the text (see also Ref. [12]).

steps. After the annealing ladder is finished, the best candidate from each chain is further optimized using Adam [67], a first-order gradient-based stochastic optimizer, which is implemented in the OPTAX package in JAX [68]. We checked that the typical spread between the minimum χ^2 of the 12 different starting points is $\sigma(\chi^2_{\min}) \lesssim 0.2$ in each case.

F. Assessing model preference using Wilks' theorem

Following the methodology of recent DESI analyses (see, e.g., Ref. [10]), we assess model preference between Λ CDM and extensions using Wilks' theorem. Two models are said to be *nested* when the simpler model is obtained as a special case of the extended one for specific parameter values. In our case, taking $f_{\text{EDE}} \rightarrow 0$ and $(w_0, w_a) \rightarrow (-1, 0)$ for the EDE and DDE models, respectively, recovers the Λ CDM predictions. Wilks' theorem [69] states that, under the assumptions of large sample size, regularity of posteriors, and that the simpler (nested) model is the true underlying model, the test statistic

$$\Delta\chi^2 = -2 \ln \left(\frac{\mathcal{L}_{\Lambda\text{CDM}}}{\mathcal{L}_{\text{ext}}} \right) \quad (6)$$

asymptotically follows a chi-squared distribution with degrees of freedom equal to the difference in the number of free parameters between the two models. We can then assess model preference for the extended model by quantifying how unlikely it would be to observe the measured decrease in χ^2 if Λ CDM were the true underlying model.

IV. THEORY MODELS

In this work, we explore two extensions of the dark energy sector that can help to reconcile CMB and BAO data.

A. EDE

The simplest EDE model comprises an ultralight scalar field displaced from the minimum of its corresponding potential. The field is initially frozen by Hubble friction, leading to an enhanced expansion rate in the prerecombination Universe. Once the Hubble rate drops below its effective

mass, the field rolls down the potential and oscillates around its minimum. The canonical EDE model features a pseudo-scalar (axionlike) field with the following potential:

$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right) \right]^n, \quad (7)$$

where m and f are the mass and decay constant of the EDE field.⁸ With this choice of potential, once the field becomes dynamical, it decays as a fluid with an effective equation of state $\langle w_\phi \rangle = (n-1)/(n+1)$. Throughout this work, we fix $n = 3$, which has been shown to produce a cosmologically viable model [39,76]. This choice means the energy density will dilute at a rate, $\rho_{\text{EDE}} \propto (1+z)^{4.5}$, that is faster than matter, meaning the effect of EDE is localized in time to the period just prior to recombination.

The particle physics parametrization m and f can be traded for the phenomenological parameters f_{EDE} and a_c : at scale factor a_c , EDE's fractional contribution to the energy density, f_{EDE} , is maximal. The physics of our EDE model is then governed by four parameters: f_{EDE} , a_c , n , and the initial misalignment angle $\theta_i = \phi_i/f$, with ϕ_i the initial field value. Increasing f_{EDE} raises the early-Universe expansion rate $H(z)$ and thereby reduces the characteristic sound horizon scales [both the BAO ruler at the drag epoch, r_{drag} , and the sound horizon at recombination, $r_s(z_*)$]. The CMB very precisely measures the acoustic angular scale,

$$\theta_* \equiv \frac{r_s(z_*)}{D_A(z_*)}, \quad (8)$$

where $D_A(z_*)$ is the angular diameter distance to the surface of last scattering. Consequently, if $r_s(z_*)$ decreases, maintaining the observed θ_* requires a smaller $D_A(z_*)$, which in turn drives a higher inferred H_0 (for fixed physical densities). We adopt the EDE model implementation in the modified CLASS [40] code `AXICLASS`⁹ [39,76] for deriving the numerical results reported here.

B. Dynamical dark energy

We consider a dynamical dark energy model with the Chevallier–Polarski–Linder (CPL) form [77,78],

$$w(a) = w_0 + w_a(1-a), \quad (9)$$

where w_0 is the present-day equation of state, and w_a describes its linear redshift evolution. Theoretically, CPL can be thought of as a first-order expansion about $a = 1$ that provides a controlled, accurate approximation to broad classes of smooth quintessence dynamics near the present epoch: for canonical scalar fields with either thawing or freezing evolution, the late-time distance and linear-growth

histories over $0 \lesssim z \lesssim 2$ are well captured by the CPL parametrization [78]. This is further motivated by the limits of current data; a recent DESI DR2 extended analysis, which analyzed nonparametric reconstructions (such as binning and Gaussian processes) for the evolution of $w(z)$, found consistent behavior between methods and concluded that the two-parameter $w_0 w_a$ description captures the dominant late-time evolution constrained by these data [11].

V. RESULTS

A. Λ CDM

We display the Λ CDM constraints of our 5×2 pt LSS data combination in Fig. 2. From the 5×2 -point data vector alone, we obtain

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3} = 0.819 \pm 0.016, \quad (10)$$

which is in excellent agreement with both the *Planck* PR4 `HiLLiPoP` value, $S_8 = 0.819 \pm 0.014$ [32], and the ACT DR6 P-ACT value, $S_8 = 0.830 \pm 0.014$ [27]. Our measurement also agrees with the latest KiDS-Legacy weak-lensing result, $S_8 = 0.815 \pm 0.012$ [79], as well as with a recent multiprobe (3×2 pt) analysis combining *Planck* and ACT DR6 lensing with unWISE galaxies, which found $S_8 = 0.816 \pm 0.015$ [4]. Our result is also consistent (within 1σ) with a recent DESI-DR1 joint 3D clustering + LS galaxy $\times$ CMB-lensing analysis which finds $S_8 = 0.808 \pm 0.017$ [80].

We further compare our results to several recent analyses using the 2×2 pt subset of our data vector (CMB-lensing $\times$ galaxy and galaxy auto), which excludes the ACT autospectrum. Reference [17] reports $S_8 = 0.790^{+0.024}_{-0.027}$ from the *ACT-only* cross and $S_8 = 0.775^{+0.019}_{-0.022}$ when combining ACT with *Planck* lensing (see also the companion paper Ref. [19] who also find a lower amplitude of fluctuations compared to CMB primary inferences). Reference [18], using a DESI LS catalogue that was *not* calibrated using DESI Spectra from [81], finds $S_8 = 0.772 \pm 0.040$ for ACT-only lensing and 0.765 ± 0.032 for ACT + *Planck* lensing. In Appendix C, we show that the 2×2 pt subset of our pipeline yields fully consistent constraints with the publicly available chains from Ref. [17]. The multiprobe constraints therefore yield a slightly higher S_8 inference at the $\sim 1\text{--}1.5\sigma$ level compared to the 2×2 pt analysis, especially when the latter are derived with the ACT + *Planck* lensing map. This is consistent with the general finding that the ACT DR6 lensing autopower-spectrum analysis favors an S_8 close to the primary-CMB prediction (the ACT Collaboration finds $S_8 = 0.840 \pm 0.028$ when combining ACT DR6 lensing with BAO measurements from SDSS and 6dF [82]), so including it alongside galaxy clustering lifts the central value of the joint S_8 relative to the 2×2 pt constraint.

⁸For examples of other EDE(like) models, see Refs. [70–75].

⁹<https://github.com/PoulinV/AxiCLASS>.

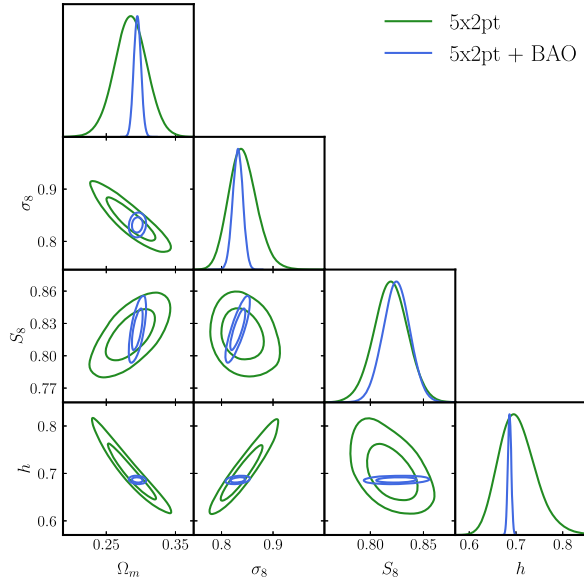


FIG. 2. Contours for Λ CDM model with LSS data. Green contours: 5×2 pt refers to the combination of ACT DR6 lensing, LS LRGs clustering and *Planck* ISW. Blue contours: same 5×2 pt combination as before with added DESI DR2 BAO data. Note for the constraints shown here, we fix $n_s = 0.9649$, and $\omega_b = 0.02236$.

Note for the above results and Fig. 2, we fix the poorly constrained baryon density and spectral tilt to their respective *Planck* best-fit values [55] ($n_s = 0.9649$ and $\omega_b = 0.02236$). If we instead allow ω_b and n_s to vary with a flat prior from Table III, we find a slightly broader constraint of $S_8 = 0.827 \pm 0.020$. Adding the DESI BAO likelihood, keeping n_s and ω_b fixed as before, sharpens the constraints by providing a strong constraint on Ω_m and hence breaking degeneracy, yielding

$$\sigma_8 = 0.832 \pm 0.010, \quad (11)$$

$$\Omega_m = 0.295 \pm 0.005. \quad (12)$$

Overall, these results demonstrate the power of combining CMB lensing with LSS tracers to produce competitive cosmological constraints without recourse to primary-CMB anisotropies. The results suggest that the (mostly linear)

TABLE IV. Goodness of fit for Λ CDM. We show the reduced χ^2 and corresponding probability-to-exceed (PTE) values for the baseline 5×2 pt data vector and for the combination with DESI DR2 BAO. In both cases, the fit is statistically acceptable, with PTE values in the expected range.

Dataset	n_{data}	χ^2_{red}	PTE
5×2 pt	78	0.98	0.36
5×2 pt + DESI DR2 BAO	91	0.96	0.44
P-ACT ^a + 5×2 pt + DESI DR2 BAO	481	1.0112	0.36

^aP-ACT here is without additional $\ell < 30TT/EE$ *Planck* likelihoods as these are non-Gaussian as described in the text.

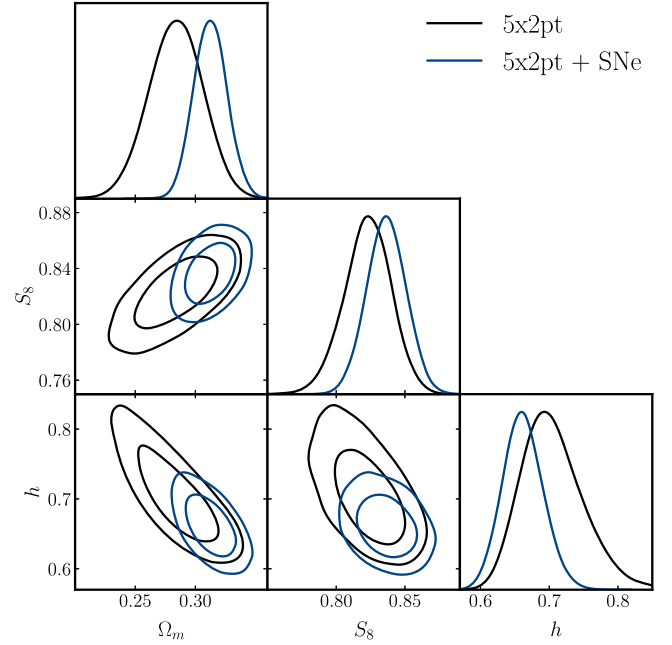


FIG. 3. Sound horizon free H_0 measurements. The 5×2 pt + SNe contour combines the Pantheon+ SNe dataset with our LSS data combination. A Gaussian prior is placed on the spectral tilt, and ω_b is varied in a flat uniform prior as described in the text.

scales and redshifts probed by our analysis do not exhibit the “lensing is low” trend seen in some previous galaxy weak lensing cross-correlation studies [1–3,83].

1. Sound horizon-free H_0

With our 5×2 pt dataset alone, we are able to weakly constrain the Hubble parameter (see Fig. 3)

$$H_0 = 70.0 \pm 4.0 \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad (13)$$

This broad constraint is consistent within 1σ with both the value of H_0 preferred by CMB primary inferences and local measurements of H_0 from SH0ES [22]. We note that this constraint is found assuming a fixed $n_s = 0.9649$ and $\omega_b = 0.02236$, when instead allowing ω_b to vary within a wide flat prior from Table III and imposing a conservative n_s prior centered on, but ten times broader than, the *Planck* constraint [55] ($n_s \sim \mathcal{N}(0.9649, 0.04)$), we find a slightly broader constraint of

$$H_0 = 70.0 \pm 4.4 \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad (14)$$

This determination is free of sound horizon information as BAO features are washed out when integrating over the projected kernels.¹⁰ The constraint comes instead from projecting the matter-radiation equality scale k_{eq} at

¹⁰See Appendix B for a detailed investigation into the (negligible) residual BAO information in the 5×2 pt combination.

TABLE V. Summary of cosmological constraints and model preferences. We report marginalized 68% confidence level (CL) constraints on H_0 , Ω_m , S_8 , and, where applicable, (w_0, w_a) for DDE and f_{EDE} for EDE. $\Delta\chi^2$ and n_σ quantify the improvement relative to the corresponding Λ CDM fit using Wilks' theorem. Three center dots indicate parameters not defined for a given model. CMB + BAO entries exclude CMB lensing; the 5×2 pt rows add $\text{LRG} \times \kappa_{\text{CMB}}$, $\kappa_{\text{CMB}}\kappa_{\text{CMB}}$, and ISW. We report both the 95% confidence intervals and the mean $\pm \sigma$ for the EDE constraints.

Model	Dataset	H_0 [km s ⁻¹ Mpc ⁻¹]	Ω_m	S_8	w_0	w_a	f_{EDE}	$\Delta\chi^2$	n_σ
Λ CDM	ACT DR6 + BAO	68.5 $\pm$ 0.3	0.300 $\pm$ 0.004	0.808 $\pm$ 0.008	...	...	...	...	...
	ACT DR6 + BAO + 5×2 pt	68.3 $\pm$ 0.3	0.303 $\pm$ 0.003	0.820 $\pm$ 0.007	...	...	...	...	...
	<i>Planck</i> PR4 + BAO	68.3 $\pm$ 0.3	0.300 $\pm$ 0.004	0.805 $\pm$ 0.009	...	...	...	...	...
	<i>Planck</i> PR4 + BAO + 5×2 pt	68.2 $\pm$ 0.3	0.303 $\pm$ 0.004	0.817 $\pm$ 0.007	...	...	...	...	...
DDE	ACT DR6 + BAO	63.9 $\pm$ 1.9	0.350 $\pm$ 0.021	0.849 $\pm$ 0.023	-0.44 $\pm$ 0.22	-1.70 $\pm$ 0.60	...	8.9	2.3
	ACT DR6 + BAO + 5×2 pt	63.6 $\pm$ 1.8	0.351 $\pm$ 0.021	0.854 $\pm$ 0.011	-0.40 $\pm$ 0.20	-1.84 $\pm$ 0.56	...	14.6	3.3
	<i>Planck</i> PR4 + BAO	64.0 $\pm$ 2.0	0.346 $\pm$ 0.022	0.840 $\pm$ 0.015	-0.49 $\pm$ 0.22	-1.50 $\pm$ 0.63	...	6.8	1.8
	<i>Planck</i> PR4 + BAO + 5×2 pt	63.4 $\pm$ 1.8	0.360 $\pm$ 0.021	0.851 $\pm$ 0.011	-0.40 $\pm$ 0.20	-1.80 $\pm$ 0.55	...	13.5	3.0
EDE	ACT DR6 + BAO	70.5 $\pm$ 1.2	0.299 $\pm$ 0.004	0.827 $\pm$ 0.013	...	...	<0.14 (95% CL) (0.069 $\pm$ 0.041)	8.7	1.8
	ACT DR6 + BAO + 5×2 pt	70.1 $\pm$ 1.0	0.300 $\pm$ 0.004	0.830 $\pm$ 0.010	...	...	<0.12 (95% CL) (0.057 $\pm$ 0.033)	11.4	2.3
	<i>Planck</i> PR4 + BAO	69.5 $\pm$ 0.8	0.299 $\pm$ 0.004	0.813 $\pm$ 0.011	...	...	<0.09 (95% CL) (0.037 $\pm$ 0.027)	4.1	0.7
	<i>Planck</i> PR4 + BAO + 5×2 pt	69.6 $\pm$ 0.8	0.300 $\pm$ 0.004	0.826 $\pm$ 0.009	...	...	<0.09 (95% CL) (0.041 $\pm$ 0.026)	6.7	1.4

different redshifts [84]. Consistent with this picture, we find our H_0 constraint to be insensitive to the prior placed on ω_b : fixing $\omega_b = 0.02236$ leaves the H_0 results unchanged. This indicates the information is coming from k_{eq} and distances and not r_s , which depends strongly on ω_b . We can further combine with Pantheon+ SNe data to break some of the $\Omega_m - h$ residual degeneracy, yielding

$$H_0 = 66.2 \pm 3.1 \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad (15)$$

These results serve as a cross-check of H_0 constraints from CMB and BAO data, which rely on the r_s ¹¹ calibration scale. This also has implications for models that aim to resolve the Hubble tension by reducing the sound horizon r_s as this constraint will be unaffected by such mechanisms. However, with our current data, the precision is not yet sufficient to make decisive claims, as our constraints are compatible with both the CMB-based determinations of H_0 and the SH0ES results within $\sim 2\sigma$. Forecasts and other contemporary measurements suggest that upcoming galaxy-survey and CMB-lensing analyses will substantially tighten such r_s -independent constraints and hence will be able to decisively weigh in on the Hubble tension [85–87].

B. Goodness of fit

We analyze the goodness of fit of the LSS dataset under the assumption of Λ CDM. We compute the Bayesian probability to exceed (PTE) in Λ CDM using the posterior

¹¹Throughout this discussion, we do not carefully distinguish between the sound-horizon scales used in BAO and CMB analyses, denoted r_d and r_s , respectively. Strictly speaking, r_s refers to the sound horizon at photon decoupling, while r_d is defined as the sound horizon at the end of the baryon drag epoch, which occurs slightly after photon decoupling.

predictive distribution. This quantifies how extreme the observed data are compared to synthetic datasets generated from the posterior [88,89], providing a test of how well the Λ CDM model fits our datasets. For Gaussian likelihoods, this is computed as [17]

$$\text{PTE} = \int d\theta \left[1 - \frac{\gamma(\frac{N_d}{2}, \frac{\chi^2(\theta)}{2})}{\Gamma(\frac{N_d}{2})} \right] P(\theta), \quad (16)$$

where N_d is the number of data points, $P(\theta)$ is the posterior, and γ and Γ are the incomplete and complete Gamma functions, respectively. This formula is only valid for Gaussian likelihoods so when assessing the goodness of fit of combinations with CMB data, we always remove the low- ℓ *Planck* based TT/EE likelihoods. We show the results for the 5×2 pt combination in Table IV, finding reasonable values for both the 5×2 pt analysis alone and with the addition of BAO data. When adding the ACT DR6 P-ACT likelihood, we do not find much change in the Bayesian PTE, suggesting that the combined data can be well fit in the Λ CDM model.¹²

C. Extensions meet LSS

The constraints for the two extended dark energy models are collected in Table V and displayed in Fig. 4. The novelty of our analysis lies in the inclusion of the 5×2 pt LSS data vector; relative to the already well-studied CMB + BAO baseline, this extra information strengthens the preference

¹²Note that we do not show the goodness of fit with *Planck* PR4 HiLLiPoP. This is very low when fit to the *Planck* PR4 HiLLiPoP likelihood alone, as described in detail in Refs. [7,32]. Hence, in combination with BAO and 5×2 pt, this remains very small, and as such it is difficult to interpret if combining the datasets leads to a significantly worse fit.

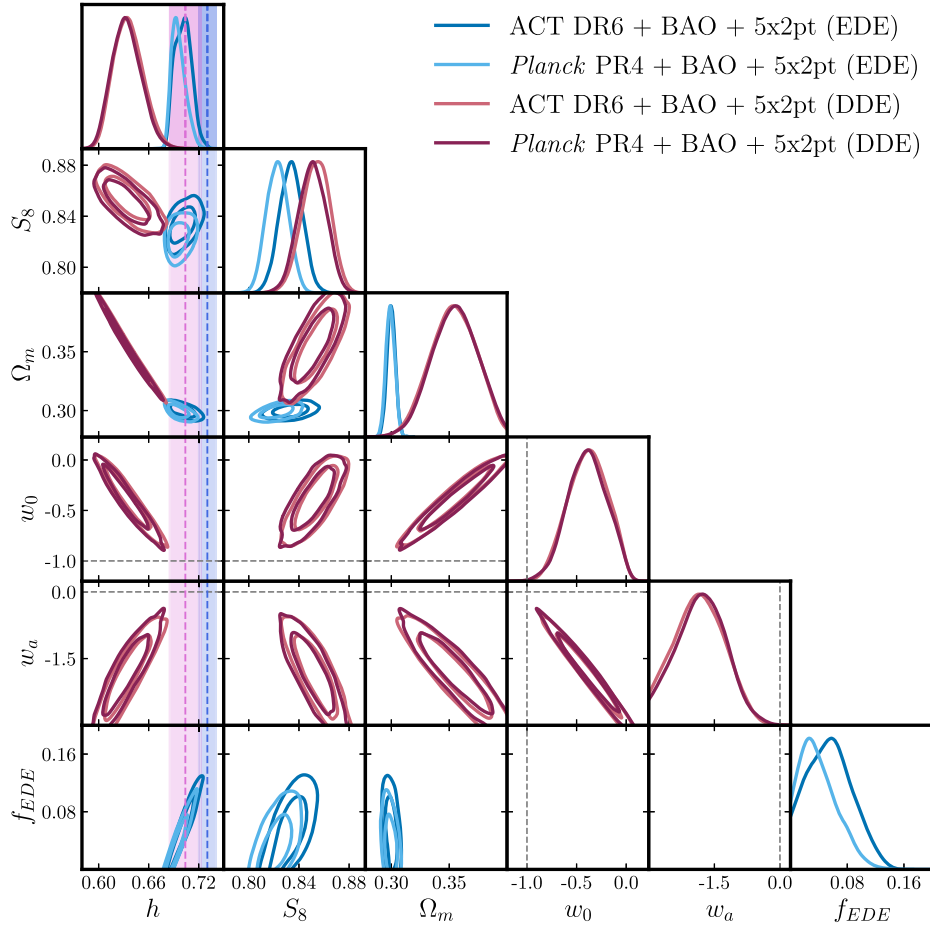


FIG. 4. Posterior constraints in extended dark-energy models. Shown are posteriors for DDE and EDE from CMB, BAO, and LSS combinations. Vertical shaded bands show local H_0 constraints, the latest from CCHP ($H_0 = 70.4 \pm 1.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$) [90], and SH0ES ($H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$) [22]. Dashed lines at $(w_0, w_a) = (-1, 0)$ indicate the Λ CDM cosmological constant limit.

for extensions beyond Λ CDM. For DDE, adding 5×2 pt to P-ACT + BAO raises the improvement in the global fit with respect to Λ CDM from $\Delta\chi^2 = 8.9$ ($n_\sigma = 2.3$) to $\Delta\chi^2 = 14.3$ ($n_\sigma = 3.2$), while for the equivalent combinations for HiLLiPoP the gain is from $\Delta\chi^2 = 6.8$ (1.8σ) to $\Delta\chi^2 = 13.47$ (3.0σ). For the combination with P-ACT, this represents the highest SNe-independent preference for DDE found to date, slightly higher than the 3.1σ found by Ref. [10] for the combination of *Planck* PR4 (CamSpec version) and DESI DR2 BAO. The inclusion of the 5×2 pt likelihood also *increases* the preference for EDE relative to CMB + BAO alone, albeit more modestly than for DDE. For P-ACT + BAO the EDE improvement rises from $\Delta\chi^2 = 8.7$ (1.8σ) to 11.4 (2.3σ) when 5×2 pt is added; for HiLLiPoP + BAO it grows from 4.1 (0.7σ) to 6.7 (1.4σ).

The mechanisms underlying these statistical improvements can be understood through examination of Fig. 5, which projects posteriors for various datasets onto the $\Omega_m - D_v/r_d$ plane at two redshifts where DESI makes BAO measurements ($z = 0.295$ and $z = 0.934$). Within the Λ CDM framework, the figure demonstrates an offset between CMB-derived constraints (*Planck* PR4, ACT

DR6) and BAO + LSS measurements, manifesting as a $\sim 2\sigma$ discrepancy in the inferred matter density and a smaller shift in the preferred value of $\frac{D_v}{r_s}$ ¹³ when combining SPT-3G, *Planck*, and ACT data [91]). The 5×2 pt LSS data vector (green contours in Fig. 5) functions as an independent probe that tightens constraints around the BAO-preferred region, thereby amplifying the statistical preference for extended models that can reconcile this discrepancy. The DDE model (middle panel) operates by freeing the dark energy equation of state, which primarily modifies D_v while leaving r_d unchanged, enabling the model to reconcile CMB and BAO constraints through altered expansion history. The colored points show samples from the posterior and demonstrate that models further from a cosmological constant (with $w_0 > -1$, $w_a < 0$) bring the CMB inference close to the preferred values from BAO + LSS data. The EDE model (right panel) can partially resolve this discrepancy through a geometric

¹³See also the recent South Pole Telescope (SPT)-3G D1 analysis, which finds a 2.8σ discrepancy in the $\Omega_m - hr_d$ plane.

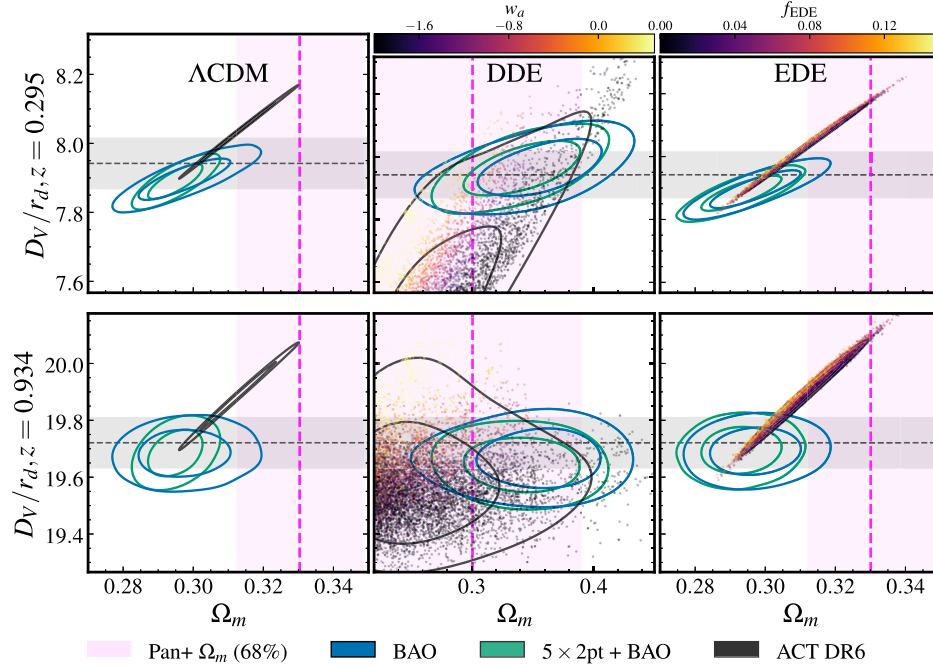


FIG. 5. Constraints in the $\Omega_m - \frac{D_V}{r_d}$ plane for different individual datasets in each of the three models analyzed in this work. The ACT DR6 constraints here are without lensing autocorrelation data which is instead included in the 5×2 data combination.

mechanism. EDE reduces the sound horizon scale r_s at recombination; to maintain a good fit to the observed CMB acoustic peaks necessitates an increase in the Hubble parameter H_0 . This elevated H_0 produces a fractional decrease in the angular diameter distance D_v to BAO positions that exceeds the fractional decrease in r_d itself. Consequently, models with higher EDE fractions (as shown in the brighter scatter points) systematically shift the CMB-preferred region in the $\Omega_m - D_v/r_d$ plane laterally toward the BAO measurements, as visible in the rightmost panel where EDE contours extend toward the BAO-preferred parameter space. Both extended models also modify the CMB-inferred Ω_m allowing for lower inferred values compared to Λ CDM which further lowers the discrepancy between BAO and CMB constraints. The purple shaded regions in Fig. 5 represent the Ω_m constraint from Pantheon+ SNe when fit in the respective models. In Λ CDM and EDE, these data tend to prefer a higher Ω_m than the 5×2 pt + BAO contours, while the constraint is significantly broadened and shifted to lower values in DDE. We revisit the implications of this for model preference in the next section.

Our constraint for the combination with ACT DR6 data of $f_{\text{EDE}} < 0.12$ exactly matches the corresponding constraint derived by the ACT Collaboration for the combination with DESI Y1 BAO and ACT DR6 lensing [41]. However, as in the DDE scenario, the inclusion of the 5×2 pt dataset strengthens the preference for the EDE extension over Λ CDM to a higher significance than previously found in analyses of combinations of data with

ACT DR6 primary data¹⁴ when not including additional SH0ES H_0 priors (which we explore later). Specifically, while previous combinations of ACT DR6 primary data with CMB lensing and BAO measurements found $\Delta\chi^2 \sim 6-7$ [13,41] in favor of EDE, our analysis incorporating the 5×2 pt LSS data yields $\Delta\chi^2 = 11.4$. We note that a recent SPT-3G analysis also found a mild preference for EDE when combining SPT-3G,¹⁵ *Planck*, and ACT-DR6 primary data with DESI BAO data [94], finding $\Delta\chi^2 = 10.8$ with respect to Λ CDM fit to the same combination of data, which is marginally lower than the $\Delta\chi^2 = 11.4$ we find for our baseline combination with P-ACT.

The EDE fits consistently push the Hubble constant to $H_0 \simeq 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, moving in the direction of the local distance ladder determination by SH0ES ($H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [22]) and thereby reducing the tension relative to Λ CDM to $\sim 2\sigma$, and the results are consistent with the Carnegie=Chicago Hubble Program (CCHP) value ($H_0 = 70.4 \pm 1.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$) [90] of the Hubble

¹⁴We note that our results display a lower preference for the EDE scenario compared to combinations of data with the older ACT DR4 likelihood. This can be traced to a fluctuation in the EE power spectrum of ACT DR4 around $\ell \sim 500$ and a broad feature in the TE spectrum of *Planck* and ACT DR4 both of which could be slightly better fit in the EDE scenario compared to Λ CDM [92].

¹⁵See also Ref. [93] who found a mild preference for EDE when not including the full *Planck* data in an earlier release of SPT data.

constant. By contrast, for DDE, we see a shift in the central value of H_0 to lower values, although the size of the contour is significantly broadened so the 1D Gaussian tension with SH0ES remains around the Λ CDM value of $\sim 4.5\sigma$. We revisit this point of difference in reconciling the late-time distance ladder H_0 measurements in the next section.

For the DDE model, the results are remarkably robust to the choice of CMB primary likelihood used with P-ACT preferring only a slightly larger deviation from Λ CDM when analyzed under Wilks' theorem, and the contours are almost indistinguishable in Fig. 4. However, the preference for EDE is clearly larger in the ACT DR6 combinations than in those based on *Planck* PR4, and this is also reflected in the contours, which display a larger preference for nonzero f_{EDE} . These results mirror those in Ref. [13], who analyzed the CMB + DESI DR2 combination and found that ACT DR6 allows a broader range of nonzero f_{EDE} than *Planck* PR4.¹⁶ At the level of this shift in model preference (1.4σ for HiLLiPoP combinations vs 2.3σ for P-ACT), this may be simply due to statistical fluctuations or a hint of a small systematic offset between the two CMB experiments; we do not further investigate this in this work. We also note that Ref. [96] showed that the updated *Planck* PR4 likelihoods place tighter limits on f_{EDE} compared to the older *Planck* PR3 likelihoods.

The results in this section demonstrate the impact of including our novel 5×2 pt LSS data vector when analyzing dark energy model extensions. As we have understood through examining Fig. 5, this generally bolsters the preference for models that can help to resolve CMB-BAO discrepancies present in Λ CDM. In the following sections, we further examine these extended models, first in the context of a free neutrino mass and then with several external datasets.

D. Neutrino masses

1. Neutrino masses in Λ CDM

Massive neutrinos free stream while relativistic and, upon becoming nonrelativistic, impede the growth of cosmic structure, imprinting a percent-level scale-dependent suppression in the matter power spectrum and a corresponding reduction in the CMB lensing amplitude [97–99]. Neutrinos also importantly affect the expansion rate at late times in a mass-dependent manner by contributing to the energy density during matter domination once they have become nonrelativistic. These physical effects allow low-redshift structure probes and CMB lensing to tighten bounds on M_ν beyond what primary CMB anisotropies alone can provide. In Fig. 6, we show constraints when allowing for a free neutrino mass in the Λ CDM

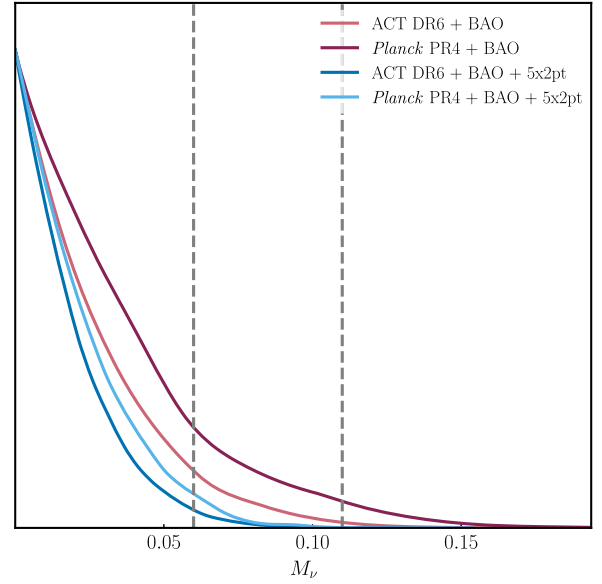


FIG. 6. Neutrino mass constraints in Λ CDM for CMB + BAO compared with CMB + BAO + 5×2 pt. The lower limits implied by the normal ordering (NO) and inverted ordering (IO) are shown in the gray vertical bands in order from left to right.

scenario. This plot demonstrates the significant additional constraining power on neutrino mass coming from the addition of our new 5×2 pt LSS data vector. We find an upper limit of $M_\nu < 0.050$ eV for the combination of CMB + BAO + 5×2 pt with P-ACT and $M_\nu < 0.056$ eV for the equivalent combination with HiLLiPoP instead. These results are markedly more stringent than the upper limit found by the ACT Collaboration of $M_\nu < 0.089$ eV found with the combination of P-ACT + CMB lensing + DESI Y1 BAO, and the baseline results from DESI, who find $M_\nu < 0.0774$ eV when combining DESI DR2 BAO with HiLLiPoP [10,41]. Our result is, however, slightly less stringent than the recent SPT-3G D1 $M_\nu < 0.048$ eV found when combining *Planck* PR4, ACT DR6 and SPT-3G data with DESI DR2 BAO.

There is ongoing debate in the literature regarding the compatibility of cosmological neutrino mass constraints with limits from neutrino oscillations, which require $M_\nu \geq 0.06$ eV under normal ordering (or $M_\nu \geq 0.11$ eV in the inverted ordering scenario). Under the baseline Λ CDM framework, several recent analyses combining CMB and BAO have found posteriors that peak at negative values of M_ν when analytically extending the neutrino mass range to allow for (unphysical) negative values [100–102]. Given the more stringent upper limits we find with our baseline combination of data under Λ CDM, this tension is increased relative to the CMB + BAO analyses; we find the normal and inverted ordering scenarios (NO and IO) are ruled out at and 97.64% and 99.99%, respectively, for the baseline combination with P-ACT and 96.07% and 99.93% for the combination with HiLLiPoP. These results, therefore,

¹⁶Note that this analysis used the CamSpec version of the *Planck* PR4 likelihood [95].

strongly motivate further exploring this apparent tension with neutrino oscillation measurements.

One possible origin is data/likelihood systematics that bias parameter estimates. For example, Refs. [103,104] showed that a systematically low reionization optical depth, τ , inference would bias neutrino masses to low values. Furthermore, using *Planck* PR3 and, to a lesser degree, the CamSpec implementation for *Planck* PR4, there is a preference for excess acoustic-peak smoothing, often captured by an effective $A_L > 1$, which can artificially strengthen neutrino-mass limits [16,105]. By contrast, the HiLLiPoP PR4 likelihood used here shows no such preference for $A_L > 1$ when analyzed alone,¹⁷ and in our P-ACT combination, the preference for $A_L > 1$ is mitigated by cutting the *Planck* PR3 temperature power spectrum at $\ell = 1000$. Furthermore, it was demonstrated in Ref. [16] that the consistent addition of multiprobe LSS data to CMB data enabled systematics-robust neutrino mass constraints even in the presence of a peak-smearing systematic effect. Therefore, we expect these results are not significantly impacted by anomalously high peak smearing. Alternatively, the issue may be model related. Several recent studies demonstrate that extending beyond Λ CDM, for example by allowing for a dynamical dark energy component, can relax neutrino-mass upper limits and help to reconcile the cosmological posteriors with oscillation priors [7,107–110]. We explore this possibility for the two extensions discussed in this work in the forthcoming section.

2. Extensions meet neutrino masses

In Fig. 7 and Table VI, we compare how extending the baseline $\nu\Lambda$ CDM model to either DDE or EDE modifies the posterior of the summed neutrino mass, M_ν , when fit to our full data combination. Allowing a dynamical dark energy sector relaxes the upper limit on M_ν and shifts the posterior peak to $M_\nu > 0$, yielding $M_\nu < 0.171$ eV for combinations with P-ACT and $M_\nu < 0.164$ eV for the corresponding constraints with HiLLiPoP. This result agrees well with previous studies of neutrino masses in this model; for example, DESI finds $M_\nu < 0.177$ eV when combining DR2 BAO with *Planck* PR4 (CamSpec) representing a significant broadening of the constraint in Λ CDM. By contrast, introducing EDE in our analysis produces only a small shift of the M_ν posterior toward larger values: the posterior still peaks at $M_\nu = 0$ eV, and the 95% upper limits are only marginally broader than the Λ CDM counterparts, ruling out NO/IO at 83.3%/98.4% for the baseline combination with P-ACT. This limited impact of EDE on M_ν is in line with the few studies that vary EDE and M_ν jointly: Ref. [111] finds an upper limit

¹⁷See, however, Ref. [106] which finds mild evidence of excess lensing when combining several datasets including HiLLiPoP.

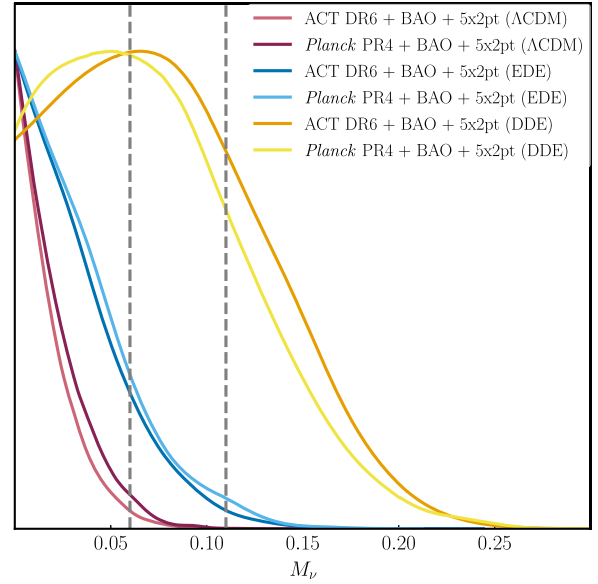


FIG. 7. Neutrino mass constraints for CMB + 5×2 pt + BAO for the three models explored in this work. The lower limits implied by the normal ordering (NO) and inverted ordering (IO) are shown in the gray vertical bands in order from left to right.

$M_\nu < 0.096$ eV (95% CL) when fitting EDE with Planck PR4 CMB, ACT DR6 and Planck PR4 CMB lensing, and DESI Y1 BAO, while Ref. [112] showed earlier that freeing M_ν does not appreciably increase the allowed EDE fraction once BAO distances are included.

The different behavior with respect to neutrino mass constraints can be traced to parameter degeneracies when fitting the extended models to the full combination of data. Increasing the EDE fraction (f_{EDE}) demands a compensating rise in the cold-dark-matter density (ω_{cdm}) to maintain the CMB fit [39]. As shown in Ref. [112], this strongly limits the extent to which the value of M_ν can be raised in models with $f_{\text{EDE}} > 0$, as the effect of the increased dark matter density on the BAO scale is similar to that of raising M_ν , which behaves like dark matter once it becomes non-relativistic, meaning there is not more room to raise M_ν .

TABLE VI. Constraints on M_ν for combinations of CMB, BAO and 5×2 pt. For most models, we quote the 95% CL upper limit (“<”). For the DDE, we report the posterior mean and 1σ error and also show the corresponding 95% upper limit in parentheses.

Dataset + model	M_ν [eV]
ACT DR6 + BAO + 5×2 pt (Λ CDM)	<0.050
<i>Planck</i> PR4 + BAO + 5×2 pt (Λ CDM)	<0.056
ACT DR6 + BAO + 5×2 pt (EDE)	<0.088
<i>Planck</i> PR4 + BAO + 5×2 pt (EDE)	<0.094
ACT DR6 + BAO + 5×2 pt (DDE)	0.081 ± 0.052 (95% CL: <0.171)
<i>Planck</i> PR4 + BAO + 5×2 pt (DDE)	0.074 ± 0.049 (95% CL: <0.164)

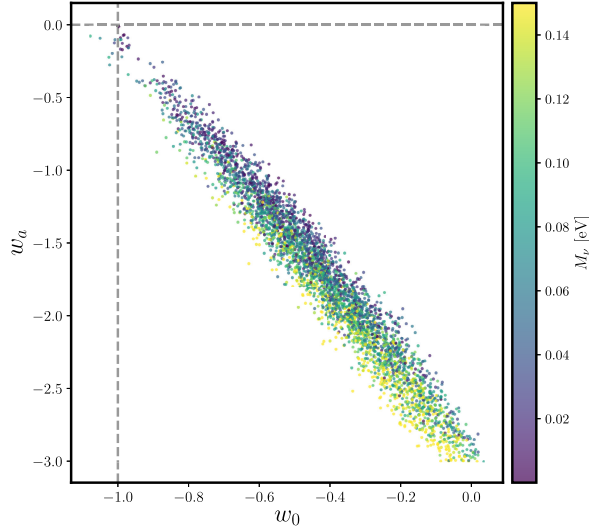


FIG. 8. Scatter plot of neutrino mass values in the $w_0 w_a$ plane for the P-ACT + 5×2 pt + BAO chain. The Λ CDM limit is denoted at the crossing of the two grey dashed lines.

while maintaining a good fit to BAO data. In the DDE case, however, departures from a cosmological-constant equation of state affect the BAO distances in a manner that is opposite in sign to raising M_ν , so the combined posterior allows for larger values of M_ν . This is demonstrated in Fig. 8, where for model parameters further from the Λ CDM limit, a higher inferred M_ν is preferred by the data to maintain a good fit to BAO distance ratios. Correspondingly, the constraints in the $w_0 w_a$ plane are degraded when allowing for a free neutrino mass.

These results suggest that even in light of the new 5×2 pt data vector, dynamical dark energy can offer a viable solution to resolve the apparent tension between oscillation measurements and cosmological neutrino mass constraints under Λ CDM, while EDE only marginally improves the situation. This is a clear point of difference between the models and adds some supporting evidence for DDE while at the same time not completely ruling out EDE. In the next section, we confront the extended models with several external data sets to assess their compatibility.

E. Adding external datasets

In this section, we explore the early and late-time dark energy modifications in the context of other external datasets. Here, we ask if the fit of these models to the CMB, BAO and 5×2 pt data is consistent with external data, namely, supernovae data from Pantheon+ and an external H_0 prior from SH0ES [22] (see Figs. 9 and 10).

F. Adding Pantheon+ SNe (uncalibrated)

Supernova distances tighten the late-time expansion constraint by providing a measure of the shape of $H(z)$

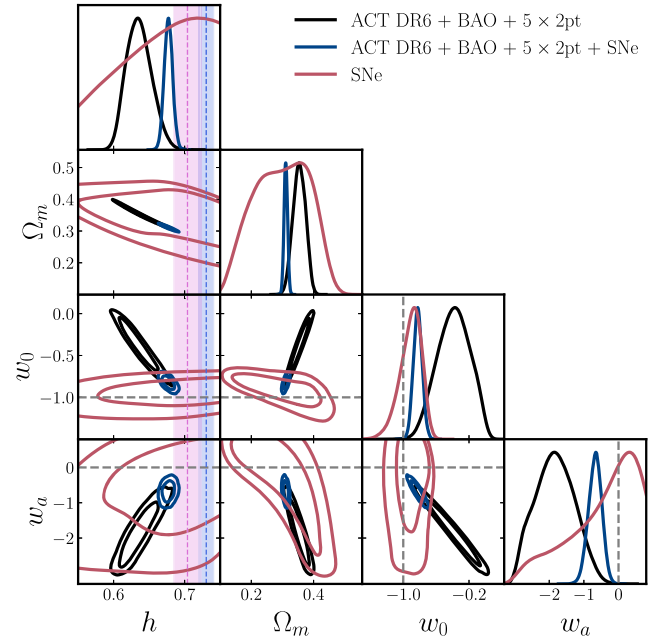


FIG. 9. Contours for the DDE model using the baseline and selected external data. Black: baseline; blue: baseline + Pantheon+ (uncalibrated SNe); red: Pantheon+ supernovae alone.

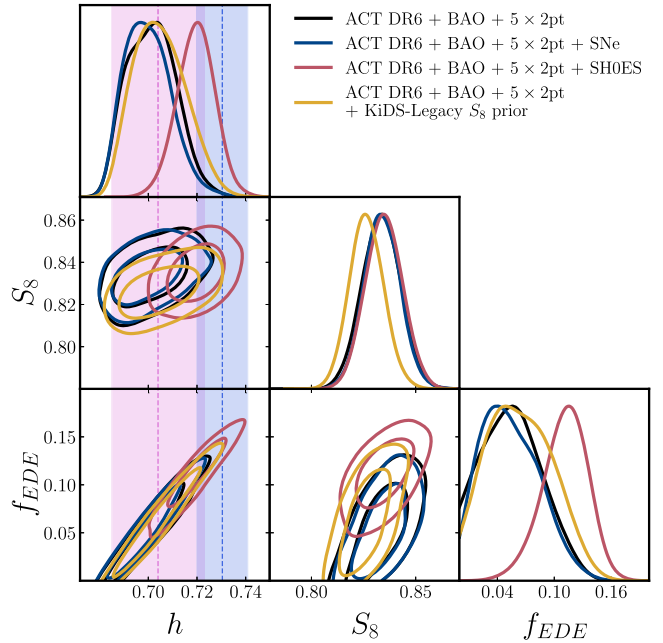


FIG. 10. Contours for the EDE model using the baseline and selected external data. Black: baseline; blue: baseline + Pantheon+ (uncalibrated SNe); red: baseline + SH0ES H_0 prior; yellow: baseline + KiDS-Legacy S_8 prior.

in the low-redshift Universe (until $z = 2.26$ for Pantheon+). This significantly improves the constraining power in the $w_0 w_a$ plane by adding additional expansion rate constraints at late times, essentially giving a relatively strong constraint

TABLE VII. Preferences for DDE and EDE with external datasets. Entries show best-fit $\Delta\chi^2 \equiv \chi^2_{\Lambda\text{CDM}} - \chi^2_{\text{model}}$ and the Gaussian-equivalent significance n_σ for the baseline CMB + BAO + 5×2 pt combination (first row in each block) and after additionally including each external dataset (subsequent rows).

Model	Dataset	Planck PR4		ACT DR6	
		$\Delta\chi^2$	n_σ	$\Delta\chi^2$	n_σ
DDE	Baseline	13.5	3.0	14.6	3.3
	+ SNe	8.3	2.2	9.5	2.5
EDE	Baseline	6.7	1.4	11.4	2.3
	+ SNe	6.6	1.4	10.3	2.1
	+ KiDS Legacy prior	6.3	1.3	10.0	2.0
	+ SH0ES prior	23.6	4.0	28.3	4.5

on w_0 while w_a is weakly constrained (see the red contour in Fig. 9). When adding these data to the baseline combination, the posterior becomes significantly tighter and is pulled toward $w_0 = -1$. We measure, via Wilks' theorem, a reduced preference over ΛCDM of 2.5σ for combinations with ACT DR6 and 2.1σ for HiLLiPOP (See Table VII). Inspecting Fig. 9, we can understand this as there is a mild ($\sim 1\sigma$) tension between the SNe alone constraints in the $w_0 w_a$ plane where the SNe data generally restrict the dark energy equation of state today to be closer to $w_0 = -1$ than the central value of the baseline constraint. We note that the DESI Collaboration also find a small reduction in the preference for DDE when analyzing the combination of CMB, BAO, and Pantheon+ data compared to the CMB + BAO preference.¹⁸ This also has implications for the neutrino mass constraint in DDE when adding SNe to the data combination; we find a tighter neutrino mass upper limit of $M_\nu < 0.11$ eV, and the posterior now peaks at $M_\nu = 0$ eV when allowing a free neutrino mass. This is due to the fact that the addition of SNe limits the departure from a cosmological constant in the $w_0 w_a$ plane, and as per Fig. 8, this means there is less scope for higher neutrino mass inferences. Nonetheless, this constraint still remains more compatible with oscillation measurements than the ΛCDM and EDE baseline constraints.

For the EDE model, adding Pantheon+ very slightly reduces the preference for the EDE scenario and tightens the upper limit to $f_{\text{EDE}} < 0.10$ (95% CL); this can be understood by the fact that Pantheon+ prefers a higher Ω_m compared to the 5×2 pt and BAO combination. Examining Fig. 5, we can see that the EDE model, when fit to CMB data alone, prefers a lower Ω_m as f_{EDE} is increased; hence, including data that prefer a larger Ω_m

¹⁸Note the DESI team explored two other supernovae datasets (Union3 [113] and DES Y5 SNe [114]), both of which show a slightly stronger preference for a DDE scenario in combination with CMB and BAO data; we expect to see a similar trend if we substituted the Pantheon+ dataset for either one of these.

TABLE VIII. EDE constraints from ACT DR6 with external datasets. Entries follow the rule: if the detection significance is below 2σ , report a one-tailed 95% upper limit; otherwise report the mean $\pm 1\sigma$. Baseline is ACT DR6 + BAO + 5×2 pt.

Dataset	f_{EDE}
Baseline (P-ACT + BAO + 5×2 pt)	$f_{\text{EDE}} < 0.12$ (95% CL)
+ SNe	$f_{\text{EDE}} < 0.10$ (95% CL)
+ KiDS-Legacy prior	$f_{\text{EDE}} < 0.12$ (95% CL)
+ SH0ES prior	$f_{\text{EDE}} = 0.11 \pm 0.02$

limits the extent to which f_{EDE} can be raised while maintaining a good global fit to the datasets. The EDE model does not affect late-time dynamics, and hence, the Ω_m constraint from Pantheon+ alone is essentially unchanged in the EDE model (the same is not true for DDE).

G. Compatibility with SH0ES

In this section, we discuss the compatibility of the two extended dark energy models with the SH0ES local distance ladder measurement ($H_0 = 73.04 \pm 1.04$ km s⁻¹ Mpc⁻¹ [22]). For DDE, our baseline constraints yield $H_0 = 63.6 \pm 1.8$ km s⁻¹ Mpc⁻¹ (P-ACT) and $H_0 = 63.4 \pm 1.8$ km s⁻¹ Mpc⁻¹ (HiLLiPOP), corresponding to 4.54σ and 4.64σ 1D Gaussian tensions. As seen in Fig. 9, the degeneracy directions imply that moving farther into the DESI BAO + CMB-preferred region with $w_0 > -1$ and $w_a < 0$ drives the inferred H_0 even lower, worsening the disagreement with SH0ES (see also Refs. [115,116]). It should be noted that the Gaussian tension in the baseline ΛCDM model is around the same level as seen for DDE, but this is because the error bar of the H_0 inference is greatly enlarged compared to ΛCDM which compensates for the lower central value. This model, hence, does not necessarily worsen this problem from a Bayesian constraint point of view, yet the best-fit model has a more discrepant value. Given the level of discrepancy, we do not additionally combine with a SH0ES prior on H_0 when fitting to the DDE model. Overall, the DDE model cannot effectively reconcile late-time local distance ladder measurements with the inferred H_0 from CMB, BAO, and LSS data.

The story is different for EDE, which was originally designed to help resolve this tension. Because EDE's fit to our *baseline* combination is only mildly inconsistent with SH0ES (Gaussian tensions of 2.0σ and 2.6σ for P-ACT and HiLLiPOP, respectively), we do analyze the situation when adding a SH0ES prior to our baseline dataset. Incorporating this prior shifts the posterior toward higher H_0 (closer to SH0ES) and yields a well-constrained $f_{\text{EDE}} = 0.11 \pm 0.02$. Relative to the corresponding ΛCDM fit, EDE is then favored at 4.5σ for the P-ACT combination and at 4.0σ for the HiLLiPOP combination. Thus, EDE can reconcile the local distance-ladder determination of H_0

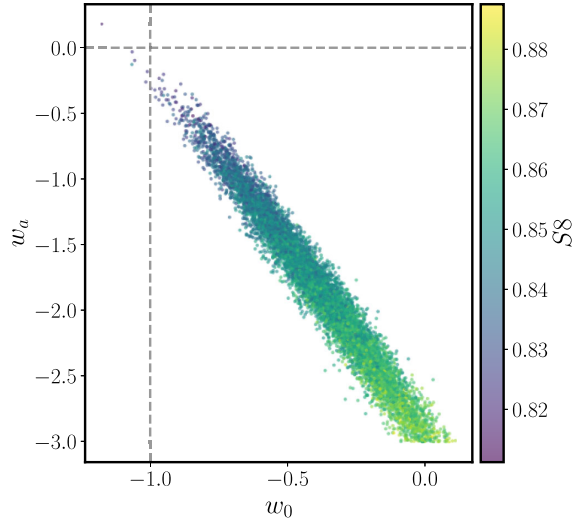


FIG. 11. Scatter plot of S_8 values in the $w_0 w_a$ plane for the P-ACT + 5×2 pt + BAO chain. Models far from a cosmological constant (crossing point of grey lines) prefer higher S_8 values.

with the global dataset without compromising the overall quality of fit; we find a Bayesian PTE = 0.472 when adding the SH0ES prior in the EDE scenario compared to 0.476 for the baseline combination.

H. Adding a KiDS-Legacy prior for EDE

To understand the effect of adding weak lensing data to the full data combination when analyzing the EDE model, we include a Gaussian $S_8 = 0.815 \pm 0.012$ prior based on the latest KiDS-Legacy results.¹⁹ As this updated likelihood was not made publicly available at the time of completing this work, this provides a useful estimate of the level of parameter shift expected when including this dataset. In EDE scenarios, increasing f_{EDE} generally raises the inferred S_8 when fitting CMB data [117,118]. Reference [117] showed that this exacerbates the “ S_8 tension,” disfavoring EDE when analyzing this model with a joint weak-lensing prior from KiDS-1000, DES-Y3, and HSC-Y1. Reexamining this with a prior based on the latest KiDS-Legacy result, we find that the EDE preference remains stable—ACT: $\Delta\chi^2 = 10.3$ ($n_\sigma = 2.5$), Planck: $\Delta\chi^2 = 6.9$ ($n_\sigma = 1.9$)—and the 95% CL upper limit on f_{EDE} is unchanged. This result would suggest that the latest weak lensing data, which show a significantly lower S_8 tension, do not provide a sufficiently strong limit on f_{EDE} to decisively rule out this model (see Table VIII).

For DDE, we cannot simply place a Gaussian prior on S_8 , as the S_8 constraint from the KiDS-Legacy data alone will be significantly changed in the DDE scenario.

¹⁹We note Ref. [117] validated that placing a Gaussian prior on S_8 is a very good approximation to including the full weak lensing dataset when analyzing EDE with CMB, BAO, and lensing data (see their Appendix B).

In future work, it would be interesting to consistently combine our analysis with weak lensing data, including all cross-correlations. It was demonstrated in Ref. [7] that the addition of KiDS-1000 data to the combination of CMB and BAO data reduced the preference for the dynamical dark energy scenario. This is because models far from a cosmological constant, when fit to CMB and BAO data, prefer a higher S_8 value than in Λ CDM (see Fig. 11) and hence tend to worsen the discrepancy with the lower $S_8 = 0.777 \pm 0.017$ value measured in KiDS-1000 [119]. We expect the most recent KiDS-Legacy data to be more compatible with the dynamical dark energy scenario, given its preference for an increased S_8 .

VI. DISCUSSION AND CONCLUSIONS

In this work, we analyzed a multiprobe 5×2 pt combination of ACT DR6 CMB lensing, LS LRGs, and Planck ISW for the first time. The 5×2 pt data vector is well described by a Λ CDM model with the computed Bayesian PTE = 0.36. In Λ CDM, we derived a constraint on the lensing amplitude of $S_8 = 0.819 \pm 0.016$. We also found a sound-horizon-free value of $H_0 = 70.0 \pm 4.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from the 5×2 pt data vector alone and $H_0 = 66.2 \pm 3.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ when additionally including Pantheon+SNe data. These values agree very well with CMB determinations of these parameters from Planck PR4 and ACT DR6. In particular, we do not observe the “lensing is low” trend for the combination of LSS data used here, suggesting that if the hints for low S_8 seen in some previous galaxy weak lensing analyses are confirmed to be physical in nature, the new physics required to explain these data resides in scales and redshifts not probed by our 5×2 pt combination.

Despite the fact that Λ CDM fits the 5×2 pt LSS, BAO, and CMB data individually very well (see, e.g., Refs. [10,27,32] and our PTE values in Table IV), when put together, we see a mild preference for extended models. This can be traced to a ($\sim 2\sigma$) discrepancy between the posteriors under Λ CDM for the CMB and 5×2 pt + BAO combination, which we exemplify in the $\Omega_m - \frac{D_v}{r_d}$ plane (Fig. 5). We investigated two dark energy extensions that can help reconcile this discrepancy: an early-Universe component prior to recombination (EDE) and a late-time dynamical equation of state (DDE). To assess the robustness of our results, we employed two complementary CMB primary likelihoods: Planck PR4 (HiLLiPoP) and ACT DR6 (P-ACT). In our baseline CMB + 5×2 pt + BAO combinations, the dynamical model is preferred over Λ CDM at 3.3σ (combination with P-ACT) and 3.0σ (combination with HiLLiPoP), whereas EDE yielded a milder preference of 2.3σ (combination with P-ACT) and 1.4σ (combination with HiLLiPoP). We demonstrated that adding our new 5×2 pt LSS data vector beyond CMB + BAO provides a stronger preference for extended dark energy in all cases; by $\simeq 1\sigma$ for DDE and by $\simeq 0.5\sigma$ for

EDE, which we traced back to an enhanced tension in the $\Omega_m - \frac{D_v}{r_d}$ plane.

To further investigate the dark energy extensions, we examined their impact on neutrino mass constraints, which exhibit tension with oscillation measurements within Λ CDM [100,101]. The inclusion of the 5×2 pt data vector to CMB + BAO tightened the upper limit on M_ν in Λ CDM, worsening the apparent tension with oscillation data. We found the normal (inverted) hierarchy scenario to be ruled out at 97.64% (99.99%) when combining with P-ACT with an upper limit of $M_\nu < 0.050$ eV (95% CL). The EDE scenario provides only marginal relief, with the 95% upper limit relaxed to $\lesssim 0.09$ eV and the posterior still peaking at $M_\nu = 0$ eV. By contrast, the DDE model significantly relaxes the neutrino mass bound to $M_\nu \lesssim 0.17$ eV, with the posterior peaking at $M_\nu > 0$ eV for both CMB likelihoods. This relaxation occurred due to a degeneracy between dynamical dark energy and neutrino mass effects on BAO distances at late times, as illustrated in Fig. 8, where models with $w_0 < -1, w_a < 0$ allow for higher neutrino masses. At face value, these findings strengthen the case for a DDE scenario over EDE and Λ CDM, as in this model we can effectively reconcile neutrino constraints with oscillation data. The degeneracy between dynamical dark energy and neutrino mass, however, remains a fundamental limitation of achieving precise neutrino mass measurements in the DDE scenario with current data.

We then considered adding several external datasets and priors to our baseline combination of data. First, we combined with SNe data from Pantheon+, finding that in both cases the preference for departures from Λ CDM is slightly decreased. In the case of EDE, this can be understood as the Pantheon+ supernovae prefer a relatively high value of $\Omega_m = 0.334 \pm 0.018$ [21], which is unchanged when analyzed under an EDE model, and this is incompatible with the high- f_{EDE} scenario, which prefers a slightly lower Ω_m when fit to CMB data alone. The shift is, however, not significant enough to rule out the EDE scenario; for the combination with ACT DR6 P-ACT, we find an upper limit of $f_{\text{EDE}} < 0.10$, compared to $f_{\text{EDE}} < 0.12$ for the baseline data combination. The addition of Pantheon+ has a relatively bigger impact on the DDE model, where the contours in the $w_0 w_a$ plane are significantly tightened compared to our baseline combination and the model preferences are decreased from 3.3σ (3.0σ) to 2.5σ (2.2σ) for the combination of data with ACT DR6 (*Planck* PR4). This is due to the relatively strong constraint on w_0 provided by the Pantheon+ SNe data, which prefers a value close to $w_0 = -1$ and hence limits the allowed departure from a cosmological constant in the combined constraints. This also has implications for the neutrino mass constraint in this model; this is tightened to $M_\nu < 0.11$ eV. While this remains more compatible with oscillation measurements than the baseline Λ CDM and EDE constraints, the posterior in this scenario peaks again at

$M_\nu = 0$ eV. It would be interesting, in future work, to compare these findings when including other supernova datasets such as Union3 [113] and DES-Y5 [114].

Next, we assessed the compatibility of the two extended dark energy models with the SH0ES local distance ladder ($H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [22]) measurement. Here, we see a more stark distinction between the models; when fit to the baseline combination of data, EDE brings the H_0 tension with SH0ES to $\lesssim 2.5\sigma$. Including the SH0ES measurement as a prior on H_0 when fitting to the baseline dataset, we find a constraint of $f_{\text{EDE}} = 0.11 \pm 0.02$ which peaks significantly away from $f_{\text{EDE}} = 0$. The EDE scenario is favored at $\sim 4\sigma$ over the Λ CDM fit to the same data (also including the SH0ES prior), and the Bayesian PTE of the fit including the SH0ES prior is not changed compared to the baseline. These results demonstrate that EDE can do what it was originally designed for: help to resolve the Hubble tension while maintaining a good global fit to data. We also showed that including an S_8 prior based on KiDS-Legacy measurements [79] does not alter the model preference for EDE, in contrast to previous studies using an S_8 prior based on the older KiDS-1000 dataset, DES-Y3, and HSC-Y1, which find this significantly reduces model preference (see, e.g., Ref. [117]). For DDE, our baseline Hubble constant constraints yield $H_0 = 63.6 \pm 1.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (P-ACT) and $H_0 = 63.4 \pm 1.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (HiLLIPOP), corresponding to 4.54σ and 4.64σ 1D Gaussian tensions. The degeneracy directions imply that moving farther into the DESI BAO + CMB-preferred region with $w_0 > -1$ and $w_a < 0$ drives the inferred H_0 even lower, worsening the disagreement with SH0ES. In short, the DDE model cannot effectively reconcile late-time local distance ladder measurements with the inferred H_0 from CMB, BAO and LSS data.

In summary, both the DDE and EDE extensions remain potentially viable explanations for the small discrepancies in current cosmological data, in the sense that neither model can be definitely ruled out with current data. However, neither model provides a compelling solution to all contemporary issues found when confronting Λ CDM with data. The DDE model generally yields an improved global fit to our baseline data and can reconcile the lower limit on M_ν from neutrino oscillation data, but it cannot address the high H_0 measurements from the late Universe. The EDE model offers a compelling (if partial) resolution to the Hubble tension, but its statistical preference over Λ CDM is not as strong, and neutrino mass constraints remain in some tension with oscillation data. A plethora of other model extensions exist that have the potential to resolve one or more of the mild discrepancies observed in the Λ CDM framework (see Ref. [120] for a recent review); it would be interesting to explore a subset of these in a future study. Another promising avenue is exploring model-independent reconstructions to elucidate where in redshift deviations from the expected evolution under Λ CDM may

occur and using this to inform model building (see, e.g., Refs. [121–125] for a nonexhaustive list of recent works employing this approach with DESI BAO data in combination with other datasets).

Looking ahead, upcoming observations will be pivotal in discriminating between Λ CDM and its contenders. On the CMB side, new high-resolution measurements from the next generation of experiments, such as the Simons Observatory, will provide independent cross-checks of the mild preference for EDE seen in ACT data. In parallel, forthcoming large-scale structure surveys (e.g., DESI Year 5, *Euclid* [126], and the Rubin Observatory’s LSST [127]) will dramatically sharpen measurements of the low- z expansion history and structure growth. In addition, improved supernova samples and gravitational lensing time-delay measurements will further pin down the late-Universe expansion rate. Together, these advances will either bolster the case for new physics—if the moderate hints reported here grow with more data—or else they will tighten the constraints enough to definitively reaffirm Λ CDM by ruling out its proposed alternatives. In either event, multiprobe techniques, capitalizing on the synergy of CMB, galaxy, and lensing surveys, will continue to be a powerful approach for testing the foundations of cosmology.

ACKNOWLEDGMENTS

This work was supported by an ETH Zurich Doc.Mobility Fellowship. A.R. thanks Martin White, Noah Sailer, Rongpu Zhou, and Gerrit Farren for useful correspondence regarding CMB lensing and DESI LS data. We also thank Colin Hill and Martin White for useful discussions related to early dark energy. We acknowledge the support of Euler Cluster by High Performance Computing Group from ETHZ Scientific IT Services that we used for most of our computations. A.R. thanks John Hennig for software expertise and support. S.F. is supported by Lawrence Berkeley National Laboratory and the Director, Office of Science, Office of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. A.N. acknowledges support from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program with Grant Agreement No. 101163128.

DATA AVAILABILITY

The data that support the findings of this article are openly available [26,128].

APPENDIX A: COMPRESSED HiLLiPoP LIKELIHOOD

To compress the HiLLiPoP likelihood, we bin the full high- ℓ likelihood (which has $N_d = 29,758$ data points corresponding to a concatenation of unbinned $TTTEEE$

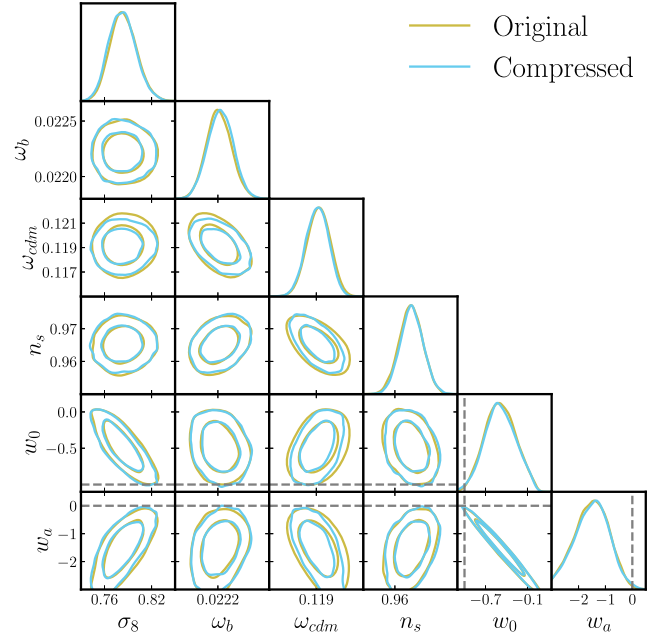


FIG. 12. Compressed HiLLiPoP vs original for combination of *Planck* PR4 + BAO data in the DDE model.

spectra for several frequency channels) into $N = 1573$ bandpowers. Specifically, we adopt a simple-minded binning scheme of

$$\Delta\ell = \begin{cases} 5, & 30 \leq \ell < 100, \\ 10, & 100 \leq \ell < 500, \\ 20, & 500 \leq \ell < 1000, \\ 50, & 1000 \leq \ell \leq 2500, \end{cases} \quad (\text{A1})$$

and we additionally weight each mode entering the bins with a cosmic variance weighting of $w_\ell = \ell(\ell + 1)$. This reduces the data-vector size by a factor of ~ 19 (from 29,758 to 1573 points), and we checked that the posteriors obtained in the Λ CDM, EDE, and DDE model are identical to the uncompressed posteriors (see Fig. 12 for the DDE comparison) as might be expected as cosmological parameters typically induce smooth changes to the associated CMB power spectra. This compression is useful as it speeds up the analysis by a factor of ~ 1.8 by reducing the memory overhead of evaluating one likelihood and thereby reducing memory latency when running inference on GPUs. We make the JAX version of the HiLLiPoP likelihood and the corresponding binning matrix for this compression publicly available at footnote³.

APPENDIX B: TO WHAT EXTENT ARE WE DOUBLE-COUNTING BAO INFORMATION?

We perform the same analysis presented in Appendix A of Ref. [7] using these updated data to assess the validity of the assumption that we can combine the LSS and BAO

information at the likelihood level while ignoring their cross-correlation. We begin by defining a wiggle–no-wiggle split of the linear matter power spectrum following Refs. [129–131], using an approximate analytic expression for the “wiggly” component,

$$P_w(P_{nw}, k, \alpha) \approx AP_{nw}(k) \sin\left(\frac{k\ell_{\text{BAO}}}{\alpha}\right) \times \exp[-k^2(\Sigma_{\text{NL}}^2 + \Sigma_{\text{Silk}}^2)], \quad (\text{B1})$$

where P_{nw} is the smooth (no-wiggle) power spectrum, $A \approx 0.05$ is an overall amplitude rescaling, $\ell_{\text{BAO}} \approx 105h^{-1}$ Mpc, $\Sigma_{\text{NL}} \approx 3h^{-1}$ Mpc, $\Sigma_{\text{Silk}} \approx 5h^{-1}$ Mpc, and α is the isotropic Alcock–Paczynski parameter. We obtain P_{nw} by performing a “wiggly–non-wiggly split” via the discrete spectral analysis method of Refs. [130,131]. This method identifies and removes BAO-induced features in the Fourier transform of $\ln(kP(k))$, replacing them with a smooth spline before inverse-transforming back to k space. This functional form accurately (to within 5%) reproduces the BAO residual in our fiducial (*Planck* 2018) cosmology, providing a suitable order-of-magnitude model of the BAO signal.

Next, to examine the sensitivity of our framework to the BAO scale, we construct a JAX-based theoretical calculation that combines the smooth component $P_{nw}(k, z)$ with its “wiggly” counterpart P_w in each DESI DR2 BAO redshift bin. Assuming linear theory (which is accurate for an order-of-magnitude assessment of the cross-covariance), we write

$$P_{\text{tot}}(k, z) = P_{nw}(k, 0)D^2(z) + P_w[P_{nw}(k, 0)D^2(z), k, \alpha(z)], \quad (\text{B2})$$

where $D(z)$ is the linear growth factor. We then project $P_{\text{tot}}(k, z)$ into angular power spectra C_ℓ via a Limber integral, using each probe’s window function. In this way, we can systematically vary $\alpha(z)$ and assess the extent to

which BAO wiggles affect our 5×2 pt observables. Since we vary $\alpha(z)$ uniformly across each DESI redshift bin without including detailed selection effects, our Fisher estimates should be regarded as an upper limit on the BAO information available to the 5×2 pt observables. In practice, survey window functions and nonuniform redshift weighting would further dilute this sensitivity.

We can derive the Fisher information matrix following:

$$\mathcal{F} = \left(\frac{\partial \vec{T}}{\partial \alpha_i}\right)^T C_{ij}^{-1} \left(\frac{\partial \vec{T}}{\partial \alpha_j}\right), \quad (\text{B3})$$

where $\vec{T}(\vec{\alpha})$ is the theory prediction for the 5×2 pt data vector, which depends on the α^{iso} parameters. We make use of JAX’s automatic differentiation feature to accurately compute these derivatives. The inverse of $\mathcal{F}$ (the precision matrix) provides an estimate of how sensitively our 5×2 pt data constrain each α parameter. We present the one-dimensional Gaussian distributions representing this constraining power in Fig. 13. Comparing these constraints with the DESI DR2 BAO uncertainties from Table IV of Ref. [10], we find that the 5×2 pt data vector is at least four times weaker (i.e., it yields parameter uncertainties about four times larger) than the DESI DR2 BAO results in constraining the α parameters. The BAO-scale parameter for the LRG1 sample is the most tightly constrained by the 5×2 pt data for the LRG3 + ELG1 DESI bin, which overlaps with the fourth and third tomographic bins of the LS LRGs. We do not display the other BAO bins, as the constraining power from the LSS data vector is found to be negligible due to the limited overlap in redshift with the LS LRGs.

Overall, this back-of-the-envelope calculation, which likely overestimates the sensitivity of projected LSS probes due to the simplification of uniformly varying $\alpha(z)$ across the redshift bins associated with the DR2 BAO data, demonstrates that the BAO information content in our

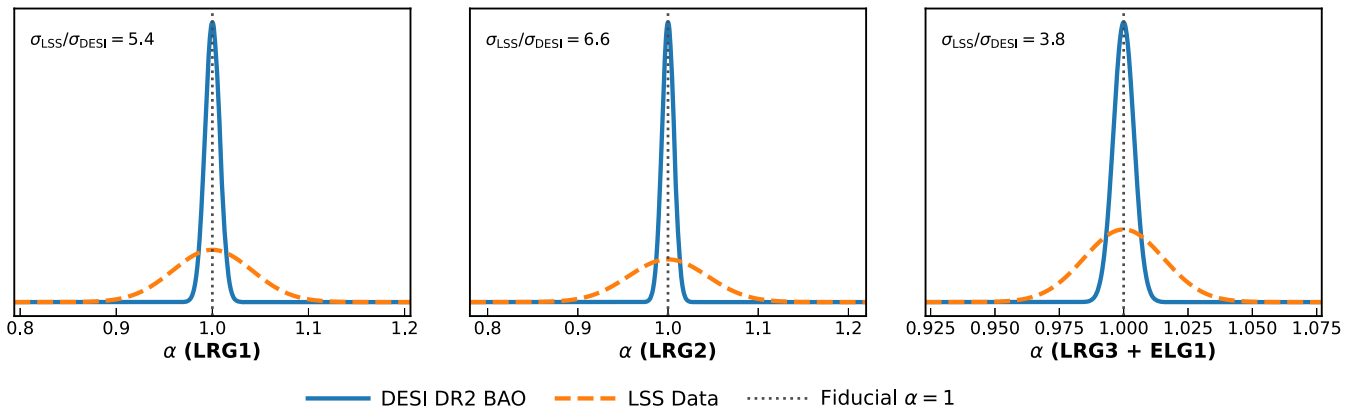


FIG. 13. Theoretical BAO information content in LSS data. The BAO information content is compared for the three redshift bins that are most tightly constrained by the LSS data. For all other DESI DR2 BAO redshift bins, the LSS data provide essentially no BAO information.

joint analysis comes almost exclusively from the DESI DR2 BAO sample. This justifies our assumption of ignoring the cross-covariance between the BAO and 5×2 pt data vectors.

APPENDIX C: COMPARISON WITH SAILER *ET AL.*

In Fig. 14, we compare our Λ CDM 2×2 pt (i.e. LS LRGs autocorrelation and the cross-correlation with ACT DR6 lensing) constraints to those of Sailer *et al.* in Ref. [17], where we adopt the same setup fixing $\omega_b = 0.02236$, $n_s = 0.9649$, $\Omega_m h^3 = 0.09633$ as Ref. [17] (this differs from the setup used in the main text and is employed here only for this test). The two analyses differ in several substantive ways. First, our covariance is simulation based, constructed from forward-modeled mock maps, whereas Ref. [17] uses an analytic approach to estimate the covariance. Second, we include the lowest-redshift LRG bin in our linear bias analysis, while Ref. [17] excludes it. Third, for theory modeling, we use linear galaxy bias and use HMCODE-2020 for the nonlinear matter power spectrum, whereas the fiducial constraints of Ref. [17] employ a hybrid effective field theory (HEFT) approach. Finally, our beyond-Limber modeling allows us to access larger angular scales (lower ℓ) with slightly different scale cuts, while Ref. [17] adopts more conservative large-scale cuts, though on the other hand in their HEFT setup they extend to smaller angular scales than we do. Despite these differences in approach, the posteriors closely agree across parameters comparing the fiducial setup of Ref. [17] and the constraints from this

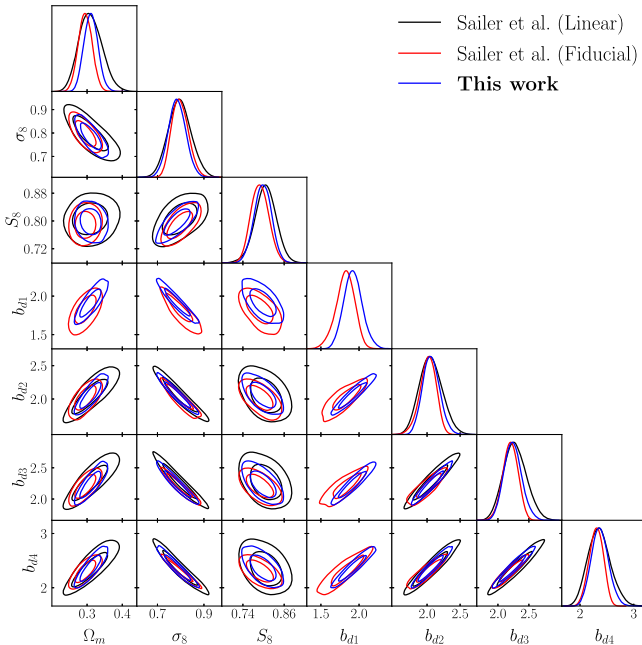


FIG. 14. Comparison of Λ CDM results to Ref. [17].

pipeline (Fig. 13), demonstrating that the $\text{LRG} \times \kappa_{\text{CMB}}$ Λ CDM constraints are robust to these analysis choices. The constraints are tighter than those for the linear theory case of Ref. [17], mostly due to our inclusion of the lowest redshift bin in the analysis.

APPENDIX D: COVARIANCE COMPARISON WITH NaMaster

To further validate our simulation-based covariance matrix, we compare the square root of the diagonal elements of our covariance matrix for our LSS dataset against an independent analytic calculation using NaMaster [49], which employs a Gaussian approximation to compute the covariance while accounting for the effects of mode-coupling due to the presence of a mask. We show the ratio of the diagonal elements in Fig. 15. We also run our LSS 5×2 pt analysis with this analytic covariance and compare the results to using our simulation based approach and find entirely consistent constraints (see Fig. 16).

APPENDIX E: EDE PARAMETER PRIORS

In this work, we adopted a Gaussian prior $\log_{10} a_c \sim \mathcal{N}(-3.531, 0.10)$ following Ref. [12] to reduce prior volume effects when $f_{\text{EDE}} \rightarrow 0$, where $\log_{10} a_c$ becomes effectively unconstrained (see, e.g., Refs. [132,133] for a discussion of prior volume effects in EDE model constraints). As a robustness check (Fig. 17), we repeat the analysis with a flat prior on $\log_{10} a_c$ and observe a mild shift of the marginalized contours toward $f_{\text{EDE}} = 0$, consistent with what was found for a similar test in Ref. [60]. The *upper limits* on f_{EDE} are essentially unchanged: for *Planck* PR4 + DESI/ACT BAO, we find $f_{\text{EDE}} < 0.089$

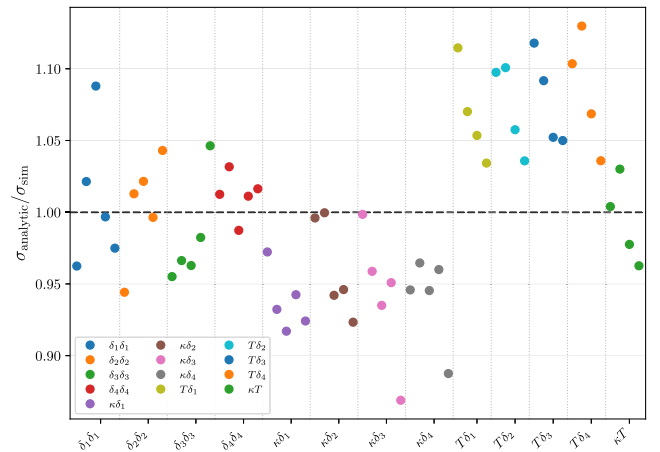


FIG. 15. Ratio of the marginal uncertainties ($\sigma_{\text{analytic}}/\sigma_{\text{sim}}$) comparing our NaMaster-based analytical LSS covariance to the simulation-derived version. The $\kappa\kappa$ block is omitted here, as we use the official covariance from ACT DR6 for this block as explained in the main text.

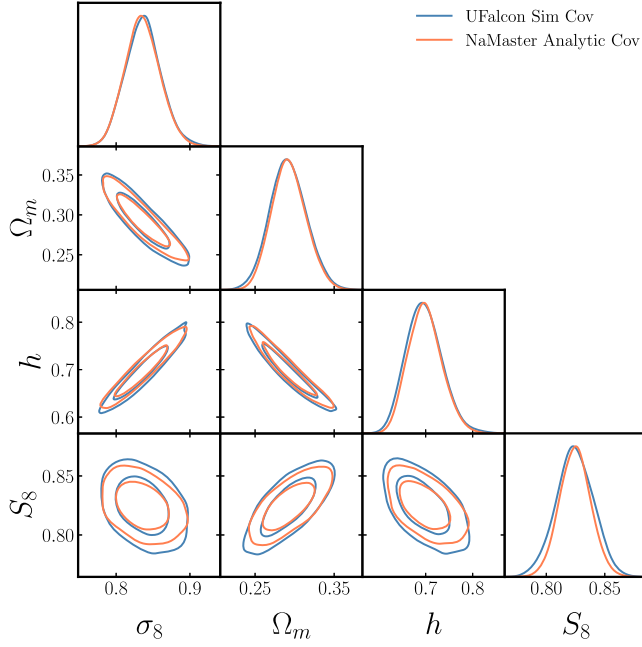


FIG. 16. Comparison of cosmological parameter posteriors from the 5×2 pt analysis using simulation-based (blue) versus analytical (orange) covariance matrices. The high degree of overlap between the contours demonstrates that the independent methods of deriving the covariances agree to the level that there is negligible difference in the resultant cosmological parameter contours.

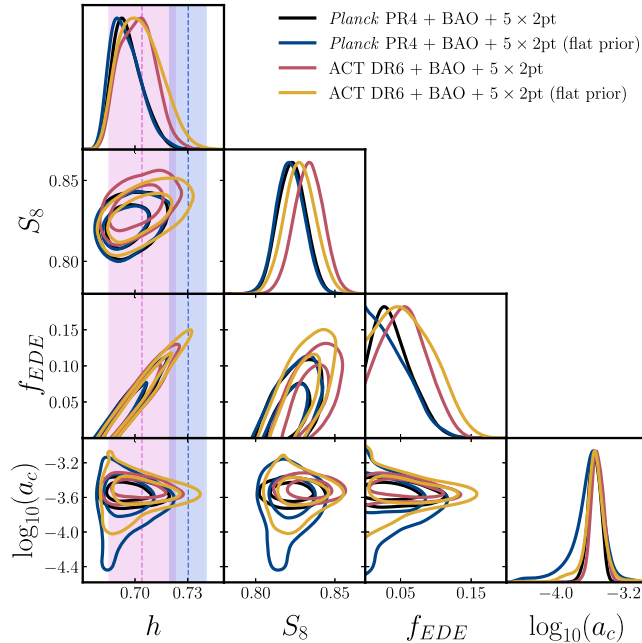


FIG. 17. Comparison of baseline constraints for the EDE model with a flat prior on $\log_{10} a_c$.

(95% CL), and with a flat prior $f_{\text{EDE}} < 0.090$; for ACT DR6 + DESI/ACT BAO, we obtain $f_{\text{EDE}} < 0.112$ (95% CL), and with a flat prior $f_{\text{EDE}} < 0.126$. The use of the Gaussian prior also does not affect our model comparison results, which are based on best-fit χ^2 values. We conclude that adopting this prior has a negligible impact on our results and leaves our overall conclusions regarding EDE unchanged.

APPENDIX F: CMB LENSING CROSS-CORRELATION NORMALIZATION CORRECTION

When CMB lensing maps are reconstructed from masked and anisotropically filtered CMB data, the resulting quadratic estimator acquires a spurious normalization that depends on the geometry of the mask. This effect is important for lensing cross-correlation analysis, where the normalization differs from that of the autospectrum and, if uncorrected, can bias cosmological parameter inference [134]. To correct for this, we follow Ref. [17] and compute a Monte Carlo (MC) normalization factor, defined as

$$(\text{MC})_L = \frac{\sum_{\ell, i, m} W_{L\ell} \{M^{\kappa_{\text{CMB}}} \widehat{\kappa_{\text{CMB}}}^i\}_{\ell m} \{M^g \kappa_{\text{CMB}}^i\}_{\ell m}^*}{\sum_{\ell, i, m} W_{L\ell} \{M^{\kappa_{\text{CMB}}} \kappa_{\text{CMB}}^i\}_{\ell m} \{M^g \kappa_{\text{CMB}}^i\}_{\ell m}^*}, \quad (\text{F1})$$

where $M^{\kappa_{\text{CMB}}}$ and M^g are the CMB lensing and galaxy masks, $\widehat{\kappa_{\text{CMB}}}^i$ is the reconstructed convergence from the i th simulation, κ_{CMB}^i is the corresponding input convergence, and $W_{L\ell}$ denotes the bandpower window function. The operator $\{AB\}_{\ell m} \equiv \int d^2 \hat{n} Y_{\ell m}^*(\hat{n}) A(\hat{n}) B(\hat{n})$ represents the masked spherical harmonic transform. In practice, we evaluate Eq. (F1) using the $N_{\text{sim}} = 480$ official ACT DR6 simulations, applying the same ACT lensing mask $M^{\kappa_{\text{CMB}}}$ and DESI LRG mask M^g as used in the data. Averaging across simulations yields a multiplicative correction factor that we apply to the DESI LRG–CMB lensing cross-spectra. We do not compute this correction for the $\kappa_{\text{CMB}} T$ ISW cross-correlation, since the sky overlap of the *Planck* PR3 and ACT DR6 lensing masks is nearly identical, and the resulting correction is expected to be negligible.

APPENDIX G: EMULATOR VALIDATION

In this appendix, we validate the accuracy of the neural network emulators for both the $w_0 w_a$ and early dark energy (EDE) models, including a free neutrino mass sum in both cases. We evaluate the emulators on an independent test set of $N = 10,000$ parameter points randomly drawn within the priors shown in Table III and compare their predictions to exact Boltzmann solver calculations.

To assess the impact on parameter inference, the absolute residuals are normalized by the 1σ error bars estimated from the square root of the diagonal elements of the covariances adopted in our likelihoods: ACT DR6

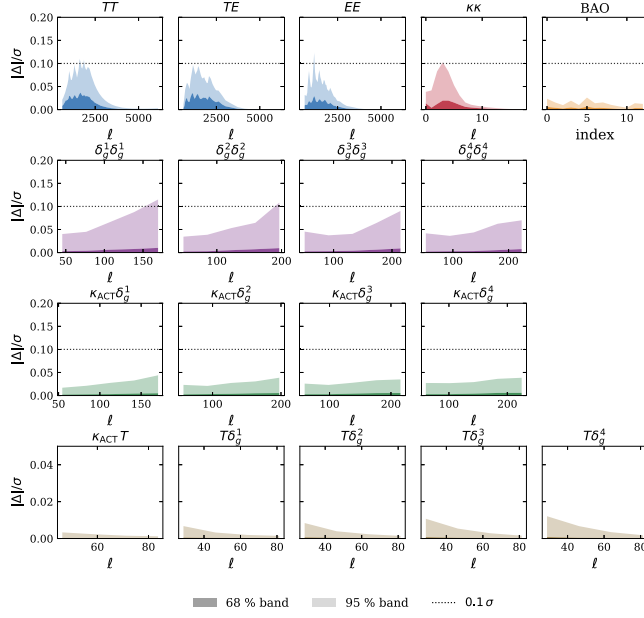


FIG. 18. Fractional emulator error for the EDE model emulators, normalized by the 1σ observational uncertainties. The shaded regions denote the 68% and 95% distribution bands evaluated on an independent test set. The horizontal dotted line indicates the 0.1σ threshold. For the BAO plot, we use “index” to represent the element in the DESI DR2 BAO datavector.

(P-ACT) for the CMB, our simulation-based covariance for LSS probes, and DESI DR2 for BAOs.

Figures 18 and 19 show the resulting fractional errors. For both models, the emulated theory falls within 0.1σ of

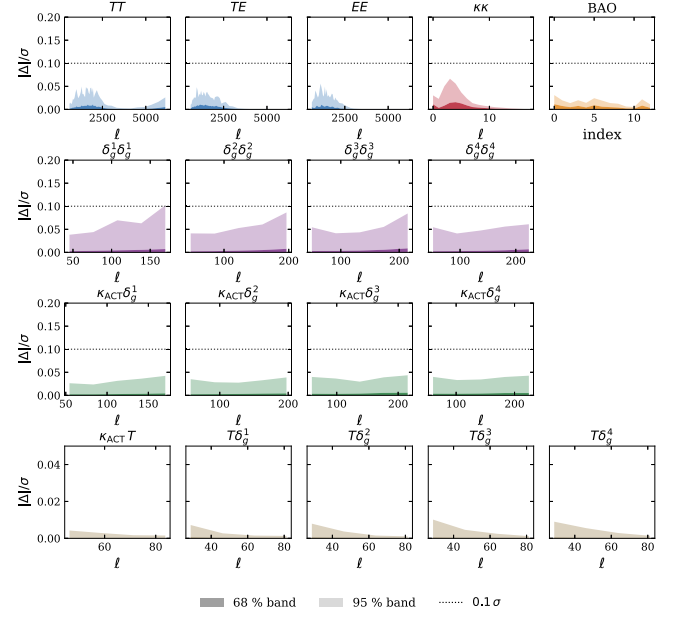


FIG. 19. Fractional emulator error for the w_0w_a model emulators, normalized by the 1σ observational uncertainties. The shaded regions denote the 68% and 95% distribution bands evaluated on an independent test set. The horizontal dotted line indicates the 0.1σ threshold. For the BAO plot, we use “index” to represent the element in the DESI DR2 BAO datavector.

the exact calculation for 95% of the test samples across all observables. This high level of precision guarantees that emulator errors are negligible and the resulting cosmological posterior contours remain unbiased.

- [1] T. M. C. Abbott *et al.* (DES Collaboration), Dark Energy Survey Year 3 results: Cosmological constraints from galaxy clustering and weak lensing, *Phys. Rev. D* **105**, 023520 (2022).
- [2] Catherine Heymans *et al.*, KiDS-1000 Cosmology: Multiprobe weak gravitational lensing and spectroscopic galaxy clustering constraints, *Astron. Astrophys.* **646**, A140 (2021).
- [3] Sunao Sugiyama *et al.*, Hyper Suprime-Cam Year 3 results: Cosmology from galaxy clustering and weak lensing with HSC and SDSS using the minimal bias model, *Phys. Rev. D* **108**, 123521 (2023).
- [4] Gerrit S. Farren *et al.*, Atacama Cosmology Telescope: Multiprobe cosmology with unWISE galaxies and ACT DR6 CMB lensing, *Phys. Rev. D* **111**, 083516 (2025).
- [5] Andrina Nicola, Alexandre Refregier, and Adam Amara, Integrated cosmological probes: Extended analysis, *Phys. Rev. D* **95**, 083523 (2017).
- [6] Andrina Nicola, Alexandre Refregier, and Adam Amara, Integrated approach to cosmology: Combining CMB,

large-scale structure and weak lensing, *Phys. Rev. D* **94**, 083517 (2016).

- [7] Alexander Reeves, Andrina Nicola, and Alexandre Refregier, Tuning the cosmic instrument: Robust cosmology through combined probes, *J. Cosmol. Astropart. Phys.* **06** (2025) 042.
- [8] T. M. C. Abbott *et al.* (DES and SPT Collaborations), Joint analysis of Dark Energy Survey Year 3 data and CMB lensing from SPT and Planck. III. Combined cosmological constraints, *Phys. Rev. D* **107**, 023531 (2023).
- [9] Jiachuan Xu, Tim Eifler, Vivian Miranda, Xiao Fang, Evan Saraivanov, Elisabeth Krause, Hung-Jin Huang, Karim Benabed, and Kunhao Zhong, Constraining baryonic physics with DES Y1 and Planck data: Combining galaxy clustering, weak lensing, and CMB lensing, *Phys. Rev. D* **110**, 063532 (2024).
- [10] DESI Collaboration, DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations, *Phys. Rev. D* **112**, 083515 (2025).

- [11] K. Lodha *et al.* (DESI Collaboration), Extended dark energy analysis using DESI DR2 BAO measurements, *Phys. Rev. D* **112**, 083511 (2025).
- [12] E. Chaussidon *et al.*, Early time solution as an alternative to the late time evolving dark energy with DESI DR2 BAO, *Phys. Rev. D* **112**, 063548 (2025).
- [13] Vivian Poulin, Tristan L. Smith, Rodrigo Calderón, and Théo Simon, Impact of ACT DR6 and DESI DR2 for early dark energy and the Hubble tension, *Phys. Rev. D* **113**, 063519 (2026).
- [14] Seyed Hamidreza Mirpoorian, Karsten Jedamzik, and Levon Pogorian, Is dynamical dark energy necessary? DESI BAO and modified recombination, *J. Cosmol. Astropart. Phys.* **12** (2025) 050.
- [15] Gabriel P. Lynch, Lloyd Knox, and Jens Chluba, DESI observations and the Hubble tension in light of modified recombination, *Phys. Rev. D* **110**, 083538 (2024).
- [16] Alexander Reeves, Andrina Nicola, Alexandre Refregier, Tomasz Kacprzak, and Luis Fernando Machado Poletti Valle, 12×2 pt combined probes: Pipeline, neutrino mass, and data compression, *J. Cosmol. Astropart. Phys.* **01** (2024) 042.
- [17] Noah Sailer *et al.*, Cosmological constraints from the cross-correlation of DESI Luminous Red Galaxies with CMB lensing from Planck PR4 and ACT DR6, *J. Cosmol. Astropart. Phys.* **06** (2025) 008.
- [18] Frank J. Qu *et al.*, Atacama Cosmology Telescope DR6 and DESI: Structure growth measurements from the cross-correlation of DESI legacy imaging galaxies and CMB lensing from ACT DR6 and Planck PR4, *Phys. Rev. D* **111**, 103503 (2025).
- [19] Joshua Kim *et al.*, The Atacama Cosmology Telescope DR6 and DESI: Structure formation over cosmic time with a measurement of the cross-correlation of CMB lensing and luminous red galaxies, *J. Cosmol. Astropart. Phys.* **12** (2024) 022.
- [20] Miguel A. Sabogal and Rafael C. Nunes, Robust evidence for dynamical dark energy from DESI Galaxy-CMB lensing cross-correlation and geometric probes, *J. Cosmol. Astropart. Phys.* **09** (2025) 084.
- [21] D. Brout and *et al.*, The Pantheon+ analysis: The full SN Ia data set and light-curve release, *Astrophys. J.* **938**, 113 (2022).
- [22] Adam G. Riess *et al.*, A comprehensive measurement of the local value of the Hubble constant with $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ Uncertainty from the Hubble space telescope and the SH0ES Team, *Astrophys. J. Lett.* **934**, L7 (2022).
- [23] R. Zhou *et al.*, DESI luminous red galaxy samples for cross-correlations, *J. Cosmol. Astropart. Phys.* **11** (2023) 097.
- [24] A. Dey *et al.*, Overview of the DESI legacy imaging surveys, *Astron. J.* **157**, 168 (2019).
- [25] A. G. Adame *et al.* (DESI Collaboration), Validation of the scientific program for the Dark Energy Spectroscopic Instrument, *Astron. J.* **167**, 62 (2024).
- [26] https://data.desi.lbl.gov/public/papers/c3/lrg_xcorr_2023/.
- [27] T. Louis *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: DR6 power spectra, likelihoods and Λ CDM parameters, *J. Cosmol. Astropart. Phys.* **11** (2025) 062.
- [28] L. Pagano, J.M. Delouis, S. Mottet, J.L. Puget, and L. Vibert, Reionization optical depth determination from Planck HFI data with ten percent accuracy, *Astron. Astrophys.* **635**, A99 (2020).
- [29] Heather Prince and Jo Dunkley, Compressed Python likelihood for large scale temperature and polarization from Planck, *Phys. Rev. D* **105**, 023518 (2022).
- [30] Frank J. Qu *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: A measurement of the DR6 CMB lensing power spectrum and its implications for structure growth, *Astrophys. J.* **962**, 112 (2024).
- [31] Y. Akrami *et al.* (Planck Collaboration), *Planck* intermediate results. LVII. Joint Planck LFI and HFI data processing, *Astron. Astrophys.* **643**, A42 (2020).
- [32] M. Tristram *et al.*, Cosmological parameters from the final Planck data release (PR4), *Astron. Astrophys.* **682**, A37 (2024).
- [33] DESI Collaboration, The DESI experiment part II: Instrument design, [arXiv:1611.00037](https://arxiv.org/abs/1611.00037).
- [34] Jesus Torrado and Antony Lewis, Cobaya: Code for Bayesian analysis of hierarchical physical models, *J. Cosmol. Astropart. Phys.* **05** (2021) 057.
- [35] Xiao Fang, Elisabeth Krause, Tim Eifler, and Niall MacCrann, Beyond Limber: Efficient computation of angular power spectra for galaxy clustering and weak lensing, *J. Cosmol. Astropart. Phys.* **05** (2020) 010.
- [36] Nora Elisa Chisari *et al.* (LSST Dark Energy Science Collaboration), Core cosmology library: Precision cosmological predictions for LSST, *Astrophys. J. Suppl. Ser.* **242**, 2 (2019).
- [37] Laura Reymond, Alexander Reeves, Pierre Zhang, and Alexandre Refregier, *SwiftC_ℓ*: Fast differentiable angular power spectra beyond Limber, *J. Cosmol. Astropart. Phys.* **01** (2026) 043.
- [38] D. Nelson Limber, The analysis of counts of the extragalactic nebulae in terms of a fluctuating density field, *Astrophys. J.* **117**, 134 (1953).
- [39] Vivian Poulin, Tristan L. Smith, Daniel Grin, Tanvi Karwal, and Marc Kamionkowski, Cosmological implications of ultralight axionlike fields, *Phys. Rev. D* **98**, 083525 (2018).
- [40] Diego Blas, Julien Lesgourgues, and Thomas Tram, The Cosmic Linear Anisotropy Solving System (CLASS) II: Approximation schemes, *J. Cosmol. Astropart. Phys.* **07** (2011) 034.
- [41] Erminia Calabrese *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: DR6 constraints on extended cosmological models, *J. Cosmol. Astropart. Phys.* **11** (2025) 063.
- [42] Nikhil Padmanabhan *et al.* (SDSS Collaboration), The clustering of luminous red galaxies in the Sloan Digital Sky Survey imaging data, *Mon. Not. R. Astron. Soc.* **378**, 852 (2007).
- [43] Mathew S. Madhavacheril *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: DR6 gravitational lensing map and cosmological parameters, *Astrophys. J.* **962**, 113 (2024).
- [44] Niall MacCrann *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: Mitigating the impact of extragalactic foregrounds for the DR6 cosmic microwave

- background lensing analysis, *Astrophys. J.* **966**, 138 (2024).
- [45] Alessio Spurio Mancini, Davide Piras, Justin Alsing, Benjamin Joachimi, and Michael P. Hobson, CosmoPower: Emulating cosmological power spectra for accelerated Bayesian inference from next-generation surveys, *Mon. Not. R. Astron. Soc.* **511**, 1771 (2022).
- [46] Martín Abadi *et al.*, TensorFlow: Large-scale machine learning on heterogeneous systems, software available from <https://www.tensorflow.org/> (2015).
- [47] Jonathan Heck, Anselm Levskaya, Avital Oliver, Marvin Ritter, Bertrand Rondepierre, Andreas Steiner, and Marc van Zee, Flax: A neural network library and ecosystem for JAX (2024).
- [48] E. Hivon, K. M. Gorski, C. B. Netterfield, B. P. Crill, S. Prunet, and F. Hansen, Master of the cosmic microwave background anisotropy power spectrum: A fast method for statistical analysis of large and complex cosmic microwave background data sets, *Astrophys. J.* **567**, 2 (2002).
- [49] David Alonso, Javier Sanchez, and Anže Slosar (LSST Dark Energy Science Collaboration), A unified pseudo- C_ℓ framework, *Mon. Not. R. Astron. Soc.* **484**, 4127 (2019).
- [50] Andrina Nicola, Carlos García-García, David Alonso, Jo Dunkley, Pedro G. Ferreira, Anže Slosar, and David N. Spergel, Cosmic shear power spectra in practice, *J. Cosmol. Astropart. Phys.* **03** (2021) 067.
- [51] Kevin Wolz, David Alonso, and Andrina Nicola, Catalog-based pseudo-CLs, *J. Cosmol. Astropart. Phys.* **01** (2025) 028.
- [52] Antón Baleato Lizancos and Martin White, Harmonic analysis of discrete tracers of large-scale structure, *J. Cosmol. Astropart. Phys.* **05** (2024) 010.
- [53] Douglas Potter, Joachim Stadel, and Romain Teyssier, PKDGRAV3: Beyond trillion particle cosmological simulations for the next era of galaxy surveys, *Comput. Astrophys. Cosmol.* **4**, 2 (2017).
- [54] Raphael Sgier, Janis Fluri, Jörg Herbel, Alexandre Réfrégier, Adam Amara, Tomasz Kacprzak, and Andrina Nicola, Fast lightcones for combined cosmological probes, *J. Cosmol. Astropart. Phys.* **02** (2021) 047.
- [55] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); **652**, C4(E) (2021).
- [56] J. Hartlap, Patrick Simon, and P. Schneider, Why your model parameter confidences might be too optimistic: Unbiased estimation of the inverse covariance matrix, *Astron. Astrophys.* **464**, 399 (2007).
- [57] Marcel M. Schmittfull, Anthony Challinor, Duncan Hanson, and Antony Lewis, Joint analysis of CMB temperature and lensing-reconstruction power spectra, *Phys. Rev. D* **88**, 063012 (2013).
- [58] Julien Peloton, Marcel Schmittfull, Antony Lewis, Julien Carron, and Oliver Zahn, Full covariance of CMB and lensing reconstruction power spectra, *Phys. Rev. D* **95**, 043508 (2017).
- [59] Raphaël Kou and Antony Lewis, Improving CMB constraints on early Universe physics with LSS: A multi-probe forecast including cross-covariance, *J. Cosmol. Astropart. Phys.* **08** (2025) 031.
- [60] Guido D’Amico, Leonardo Senatore, Pierre Zhang, and Henry Zheng, The Hubble tension in light of the full-shape analysis of large-scale structure data, *J. Cosmol. Astropart. Phys.* **05** (2021) 072.
- [61] Tristan L. Smith, Vivian Poulin, José Luis Bernal, Kimberly K. Boddy, Marc Kamionkowski, and Riccardo Murgia, Early dark energy is not excluded by current large-scale structure data, *Phys. Rev. D* **103**, 123542 (2021).
- [62] Daniel Foreman-Mackey, David W. Hogg, Dustin Lang, and Jonathan Goodman, EMCEE: The MCMC Hammer, *Publ. Astron. Soc. Pac.* **125**, 306 (2013).
- [63] Alexander Reeves, Pierre Zhang, and Henry Zheng, PyBird-JAX: Accelerated inference in large-scale structure with model-independent emulation of one-loop galaxy power spectra, *J. Cosmol. Astropart. Phys.* **02** (2026) 016.
- [64] Laura Herold, Elisa G. M. Ferreira, and Lukas Heinrich, Profile likelihoods in cosmology: When, why, and how illustrated with Λ CDM, massive neutrinos, and dark energy, *Phys. Rev. D* **111**, 083504 (2025).
- [65] Nils Schöneberg, Guillermo Franco Abellán, Andrea Pérez Sánchez, Samuel J. Witte, Vivian Poulin, and Julien Lesgourgues, The H_0 Olympics: A fair ranking of proposed models, *Phys. Rep.* **984**, 1 (2022).
- [66] Steen Hannestad, Stochastic optimization methods for extracting cosmological parameters from cosmic microwave background radiation power spectra, *Phys. Rev. D* **61**, 023002 (2000).
- [67] Diederik P. Kingma and Jimmy Ba, Adam: A method for stochastic optimization, [arXiv:1412.6980](https://arxiv.org/abs/1412.6980).
- [68] James Bradbury *et al.*, JAX: Composable transformations of Python+NumPy programs, version 0.3.13, 2018, <http://github.com/google/jax>.
- [69] S. S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses, *Ann. Math. Stat.* **9**, 60 (1938).
- [70] Evan McDonough, Meng-Xiang Lin, J. Colin Hill, Wayne Hu, and Shengjia Zhou, Early dark sector, the Hubble tension, and the swampland, *Phys. Rev. D* **106**, 043525 (2022).
- [71] Florian Niedermann and Martin S. Sloth, Hot new early dark energy: Towards a unified dark sector of neutrinos, dark energy and dark matter, *Phys. Lett. B* **835**, 137555 (2022).
- [72] Miguel Zumalacarregui, Gravity in the era of equality: Towards solutions to the Hubble problem without fine-tuned initial conditions, *Phys. Rev. D* **102**, 023523 (2020).
- [73] V. K. Oikonomou, Unifying inflation with early and late dark energy epochs in axion $F(R)$ gravity, *Phys. Rev. D* **103**, 044036 (2021).
- [74] Gen Ye, Jun Zhang, and Yun-Song Piao, Alleviating both H_0 and S_8 tensions: Early dark energy lifts the CMB-lockdown on ultralight axion, *Phys. Lett. B* **839**, 137770 (2023).
- [75] Santanu Das, Arad Nasiri, and Yasaman K. Yazdi, Aspects of everpresent Λ . Part II. Cosmological tests of current models, *J. Cosmol. Astropart. Phys.* **10** (2024) 076.
- [76] Tristan L. Smith, Vivian Poulin, and Mustafa A. Amin, Oscillating scalar fields and the Hubble tension: A resolution with novel signatures, *Phys. Rev. D* **101**, 063523 (2020).

- [77] Michel Chevallier and David Polarski, Accelerating universes with scaling dark matter, *Int. J. Mod. Phys. D* **10**, 213 (2001).
- [78] Eric V. Linder, Exploring the expansion history of the universe, *Phys. Rev. Lett.* **90**, 091301 (2003).
- [79] Angus H. Wright *et al.*, KiDS-Legacy: Cosmological constraints from cosmic shear with the complete Kilo-Degree Survey, *Astron. Astrophys.* **703**, A158 (2025).
- [80] M. Maus *et al.*, A joint analysis of 3D clustering and galaxy x CMB-lensing cross-correlations with DESI DR1 galaxies, *J. Cosmol. Astropart. Phys.* **11** (2025) 077.
- [81] Qianjun Hang, Shadab Alam, John A. Peacock, and Yan-Chuan Cai, Galaxy clustering in the DESI legacy survey and its imprint on the CMB, *Mon. Not. R. Astron. Soc.* **501**, 1481 (2021).
- [82] M. S. Madhavacheril *et al.*, The Atacama Cosmology telescope: DR6 gravitational lensing map, *Astrophys. J.* **945**, 123 (2023).
- [83] Alexie Leauthaud *et al.*, Lensing is low: Cosmology, galaxy formation, or new physics?, *Mon. Not. R. Astron. Soc.* **467**, 3024 (2017).
- [84] E. A. Zaborowski *et al.*, A sound horizon-free measurement of H_0 in DESI 2024, *J. Cosmol. Astropart. Phys.* **06** (2025) 020.
- [85] Gerrit S. Farren, Oliver H. E. Philcox, and Blake D. Sherwin, Determining the Hubble constant without the sound horizon: Perspectives with future galaxy surveys, *Phys. Rev. D* **105**, 063503 (2022).
- [86] Oliver H. E. Philcox, Gerrit S. Farren, Blake D. Sherwin, Eric J. Baxter, and Dillon J. Brout, Determining the Hubble constant without the sound horizon: A 3.6% constraint on H_0 from galaxy surveys, CMB lensing, and supernovae, *Phys. Rev. D* **106**, 063530 (2022).
- [87] Helena García Escudero, Seyed Hamidreza Mirpoorian, and Levon Pogorian, Sound-horizon-agnostic inference of the Hubble constant and neutrino mass from BAO, CMB lensing, and galaxy weak lensing and clustering, *arXiv:2509.16202*.
- [88] Andrew Gelman, Posterior predictive assessment of model fitness via realized discrepancies, *Stat. Sin.* **6**, 733 (1996).
- [89] Xiao-Li Meng, Posterior predictive p -values, *Ann. Stat.* **22**, 1142 (1994).
- [90] Wendy L. Freedman, Barry F. Madore, Taylor J. Hoyt, In Sung Jang, Abigail J. Lee, and Kayla A. Owens, Status report on the Chicago-Carnegie Hubble Program (CCHP): Measurement of the Hubble constant using the Hubble and James Webb Space Telescopes, *Astrophys. J.* **985**, 203 (2025).
- [91] E. Camphuis *et al.* (SPT-3G Collaboration), SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field, *Phys. Rev. D* **113**, 083504 (2026).
- [92] J. Colin Hill *et al.*, Atacama Cosmology Telescope: Constraints on prerecombination early dark energy, *Phys. Rev. D* **105**, 123536 (2022).
- [93] Adrien La Posta, Thibaut Louis, Xavier Garrido, and J. Colin Hill, Constraints on prerecombination early dark energy from SPT-3G public data, *Phys. Rev. D* **105**, 083519 (2022).
- [94] A. R. Khalife *et al.* (SPT-3G Collaboration), SPT-3G D1: Axion early dark energy with CMB experiments and DESI, *arXiv:2507.23355*.
- [95] Erik Rosenberg, Steven Gratton, and George Efstathiou, CMB power spectra and cosmological parameters from Planck PR4 with CamSpec, *Mon. Not. R. Astron. Soc.* **517**, 4620 (2022).
- [96] Evan McDonough, J. Colin Hill, Mikhail M. Ivanov, Adrien La Posta, and Michael W. Toomey, Observational constraints on early dark energy, *Int. J. Mod. Phys. D* **33**, 2430003 (2024).
- [97] Julien Lesgourgues and Sergio Pastor, Massive neutrinos and cosmology, *Phys. Rep.* **429**, 307 (2006).
- [98] Yvonne Y. Y. Wong, Neutrino mass in cosmology: Status and prospects, *Annu. Rev. Nucl. Part. Sci.* **61**, 69 (2011).
- [99] Cora Dvorkin *et al.*, Neutrino mass from cosmology: Probing physics beyond the standard model, *arXiv:1903.03689*.
- [100] Nathaniel Craig, Daniel Green, Joel Meyers, and Surjeet Rajendran, No νs is good news, *J. High Energy Phys.* **09** (2024) 097.
- [101] Daniel Green and Joel Meyers, The cosmological preference for negative neutrino mass, *Phys. Rev. D* **111**, 083507 (2025).
- [102] W. Elbers *et al.* (DESI Collaboration), Constraints on neutrino physics from DESI DR2 BAO and DR1 full shape, *Phys. Rev. D* **112**, 083513 (2025).
- [103] Noah Sailer, Gerrit S. Farren, Simone Ferraro, and Martin White, Dispurable: The high cost of a low optical depth, *Phys. Rev. Lett.* **136**, 081002 (2026).
- [104] Tanisha Jhaveri, Tanvi Karwal, and Wayne Hu, Turning a negative neutrino mass into a positive optical depth, *Phys. Rev. D* **112**, 043541 (2025).
- [105] Willem Elbers, Carlos S. Frenk, Adrian Jenkins, Baojiu Li, and Silvia Pascoli, Negative neutrino masses as a mirage of dark energy, *Phys. Rev. D* **111**, 063534 (2025).
- [106] Shouvik Roy Choudhury, Teppei Okumura, and Keiichi Umetsu, Cosmological constraints on non-phantom dynamical dark energy with DESI Data Release 2 Baryon Acoustic Oscillations: A $3\sigma+$ lensing anomaly, *Astrophys. J. Lett.* **994**, L26 (2025).
- [107] S. Ahlen *et al.* (DESI Collaboration), Positive neutrino masses with DESI DR2 via matter conversion to dark energy, *Phys. Rev. Lett.* **135**, 081003 (2025).
- [108] Helen Shao, Jahmour J. Givans, Jo Dunkley, Mathew Madhavacheril, Frank J. Qu, Gerrit Farren, and Blake Sherwin, Cosmological limits on the neutrino mass sum for beyond- Λ CDM models, *Phys. Rev. D* **111**, 083535 (2025).
- [109] Shouvik Roy Choudhury and Teppei Okumura, Updated cosmological constraints in extended parameter space with Planck PR4, DESI Baryon Acoustic Oscillations, and Supernovae: Dynamical dark energy, neutrino masses, lensing anomaly, and the Hubble tension, *Astrophys. J. Lett.* **976**, L11 (2024).
- [110] Shouvik Roy Choudhury, Cosmology in extended parameter space with DESI Data Release 2 Baryon Acoustic Oscillations: A $2\sigma+$ detection of nonzero neutrino masses with an update on dynamical dark energy and lensing anomaly, *Astrophys. J. Lett.* **986**, L31 (2025).

- [111] Frank J. Qu, Kristen M. Surrao, Boris Bolliet, J. Colin Hill, Blake D. Sherwin, Hidde T. Jense, and Adrien La Posta, Accelerated inference on accelerated cosmic expansion: New constraints on axionlike early dark energy with DESI BAO and ACT DR6 CMB lensing, *Phys. Rev. D* **111**, 123507 (2025).
- [112] Alexander Reeves, Laura Herold, Sunny Vagnozzi, Blake D. Sherwin, and Elisa G.M. Ferreira, Restoring cosmological concordance with early dark energy and massive neutrinos?, *Mon. Not. R. Astron. Soc.* **520**, 3688 (2023).
- [113] David Rubin *et al.*, Union through UNITY: Cosmology with 2,000 SNe using a unified Bayesian framework, *Astrophys. J.* **986**, 231 (2025).
- [114] T.M.C. Abbott *et al.* (DES Collaboration), The Dark Energy Survey: Cosmology results with ~ 1500 new high-redshift type Ia supernovae using the full 5 yr data set, *Astrophys. J. Lett.* **973**, L14 (2024).
- [115] Eoin Ó. Colgáin, Saeed Pourojaghi, M. M. Sheikh-Jabbari, and Lu Yin, How much has DESI dark energy evolved since DR1?, *Phys. Dark Universe* **52**, 102268 (2026).
- [116] Bum-Hoon Lee, Wonwoo Lee, Eoin Ó. Colgáin, M. M. Sheikh-Jabbari, and Somyadip Thakur, Is local H_0 at odds with dark energy EFT?, *J. Cosmol. Astropart. Phys.* **04** (2022) 004.
- [117] J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander, Early dark energy does not restore cosmological concordance, *Phys. Rev. D* **102**, 043507 (2020).
- [118] Sunny Vagnozzi, Seven Hints That early-time new physics alone is not sufficient to solve the Hubble tension, *Universe* **9**, 393 (2023).
- [119] Marika Asgari *et al.* (KiDS Collaboration), KiDS-1000 Cosmology: Cosmic shear constraints and comparison between two point statistics, *Astron. Astrophys.* **645**, A104 (2021).
- [120] Eleonora Di Valentino *et al.* (CosmoVerse Network Collaboration), The CosmoVerse white paper: Addressing observational tensions in cosmology with systematics and fundamental physics, *Phys. Dark Universe* **49**, 101965 (2025).
- [121] Purba Mukherjee and Anjan A. Sen, New expansion rate anomalies at characteristic redshifts geometrically determined using DESI-DR2 BAO and DES-SN5YR observations, *Rep. Prog. Phys.* **88**, 098401 (2025).
- [122] Yun Wang and Katherine Freese, Model-independent dark energy measurements from DESI DR2 and Planck 2015 data, *J. Cosmol. Astropart. Phys.* **02** (2026) 023.
- [123] Xue Zhang, Yin-Hao Xu, and Yu Sang, Reconstruction of dark energy using DESI DR2, *Commun. Theor. Phys.* **78**, 035404 (2026).
- [124] Maria Berti, Emilio Bellini, Camille Bonvin, Martin Kunz, Matteo Viel, and Miguel Zumalacarregui, Reconstructing the dark energy density in light of DESI BAO observations, *Phys. Rev. D* **112**, 023518 (2025).
- [125] Jun-Qian Jiang, Davide Pedrotti, Simony Santos da Costa, and Sunny Vagnozzi, Nonparametric late-time expansion history reconstruction and implications for the Hubble tension in light of recent DESI and type Ia supernovae data, *Phys. Rev. D* **110**, 123519 (2024).
- [126] R. Laureijs *et al.* (EUCLID Collaboration), Euclid definition study report, [arXiv:1110.3193](https://arxiv.org/abs/1110.3193).
- [127] Paul A. Abell *et al.* (LSST Science and LSST Project Collaborations), LSST science book, version 2.0, [arXiv:0912.0201](https://arxiv.org/abs/0912.0201).
- [128] https://lambda.gsfc.nasa.gov/product/act/actadv_dr6_lensing_maps_info.html.
- [129] Oliver H.E. Philcox, Mikhail M. Ivanov, Marko Simonović, and Matias Zaldarriaga, Combining full-shape and BAO analyses of galaxy power spectra: A 1.6% CMB-independent constraint on H_0 , *J. Cosmol. Astropart. Phys.* **05** (2020) 032.
- [130] Jan Hamann, Steen Hannestad, Julien Lesgourgues, Cornelius Rampf, and Yvonne Y.Y. Wong, Cosmological parameters from large scale structure—geometric versus shape information, *J. Cosmol. Astropart. Phys.* **07** (2010) 022.
- [131] Anton Chudaykin, Mikhail M. Ivanov, Oliver H.E. Philcox, and Marko Simonović, Nonlinear perturbation theory extension of the Boltzmann code CLASS, *Phys. Rev. D* **102**, 063533 (2020).
- [132] Laura Herold, Elisa G.M. Ferreira, and Eiichiro Komatsu, New constraint on early dark energy from Planck and BOSS data using the profile likelihood, *Astrophys. J. Lett.* **929**, L16 (2022).
- [133] Laura Herold and Elisa G.M. Ferreira, Resolving the Hubble tension with early dark energy, *Phys. Rev. D* **108**, 043513 (2023).
- [134] Gerrit S. Farren *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: Cosmology from cross-correlations of unWISE galaxies and ACT DR6 CMB lensing, *Astrophys. J.* **966**, 157 (2024).