SPT-3G lensing x DES Y3 shear

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The weak lensing of galaxies and of the cosmic microwave background (CMB) provide direct probes of the cosmic matter density field, but are sensitive to different redshift ranges and different survey systematics. Their cross-correlation is then able to provide consistency checks of the theoretical model and survey systematics. We present measurements of the CMB lensing - cosmic shear cross-correlation using new SPT-3G D1 lensing maps and the Y3 shear catalogs from the Dark Energy Survey (DES). For the first time, we detect this cross-correlation at high significance ($\sim 13\sigma$) when using a polarization-only CMB lensing reconstruction that is expected to be immune to extragalactic foregrounds. We also test a variety of other CMB lensing estimators that exhibit different tradeoffs between foreground biases and noise, as well as a pure blue shear sample that is expected to be less impacted by intrinsic alignments (IA). Assuming ΛCDM and marginalizing over IA, baryonic feedback, and various nuisance parameters, we obtain a constraint on the amplitude of matter clustering $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3} = 0.829^{+0.050}_{-0.064}$, consistent with both the primary CMB results from *Planck* and shear-only results from DES Y3. By combining our measurement with *Planck*, we show that it has some sensitivity to small-scale physics and obtain a constraint on the IA amplitude of the DES sample that is competitive with that from shear-only analyses as well as a lower limit on the strength of baryonic feedback.

I. INTRODUCTION

Gravitational lensing of distant light sources by the intervening large-scale structure (LSS) provides a wealth of information about the contents and evolution of the Universe since it is sensitive to both the cosmic expansion rate and the growth of structure [1, 2]. Additionally, one of the main strengths of weak lensing as a cosmological probe is that it provides an unbiased tracer of the matter density field, in contrast to galaxy clustering which has a very complicated connection to the underlying matter field.

The weak lensing signal has now been measured at high significance using both galaxies and the cosmic microwave background (CMB) as sources. On the galaxy lensing (also referred to as cosmic shear) side, Stage-III surveys, the Dark Energy Survey (DES), the Kilo-Degree Survey (KiDS), and the Hyper Suprime-Cam (HSC) survey, have been placing tight constraints on the amplitude of matter clustering at low redshift [3–6]. On the CMB lensing side, all major surveys, *Planck*, the Atacama Cosmology Telescope (ACT), and the South Pole Telescope (SPT), have achieved comparable constraints that are sensitive to significantly higher redshifts and larger physical scales [7–10].

With increasingly precise measurements of the amplitude of matter clustering across redshifts, a potential mild tension has emerged in the inferred value of the parameter $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$, where Ω_m is the fractional matter density and σ_8 parametrizes the amplitude of present-day density fluctuations. This so-called S_8-tension is typically presented as a consistent trend where cosmic shear surveys measure the value of S_8 to be ~ 2 to 3σ low relative to the ΛCDM prediction based on measurements of the primary CMB. This tension can be more precisely thought of as a mismatch between the amplitude of clustering on large and on small scales [11, 12]. While many recent studies have shown that the S_8 tension can be resolved by allowing very strong baryonic feedback effects that suppress the matter power spectrum on small scales [], other explanations such as ... have been proposed []. This provides motivation to measure S_8 using a variety of probes that are sensitive to different ranges of redshifts and scales.

Due to the fact that galaxy lensing and CMB lensing analyses use independent data sets with very different systematics, combined they provide very useful consistency checks of the standard ΛCDM model.

A major concern in CMB lensing measurements is contamination from extragalactic foregrounds that can mimic the lensing signal [13]. The main foregrounds include the Sunyaev-Zeldovich effects (both thermal, tSZ, and kinetic, kSZ), the cosmic infrared background (CIB), and radio sources. While a variety of techniques exist that aim to mitigate the impact of foregrounds on the reconstruction of CMB lensing maps, the foreground biases are expected to be worse when cross-correlating CMB lensing with low-redshift probes. This is due to the fact that the foregrounds are correlated with low-redshift LSS.

Previous analyses: [14–16], DESxACT [17], DESxSPT [18–20]

In this work, we measure the cross-correlation between CMB lensing and cosmic shear using new CMB lensing reconstructions based on data from SPT [21] and the DES Y3 shear catalog. We obtain the first high-significance measurement ($\sim 13\sigma$) of this cross-correlation using a CMB polarization-only lensing reconstruction, allowing us to effectively sidestep the issue of extragalactic foregrounds. We use this measurement as
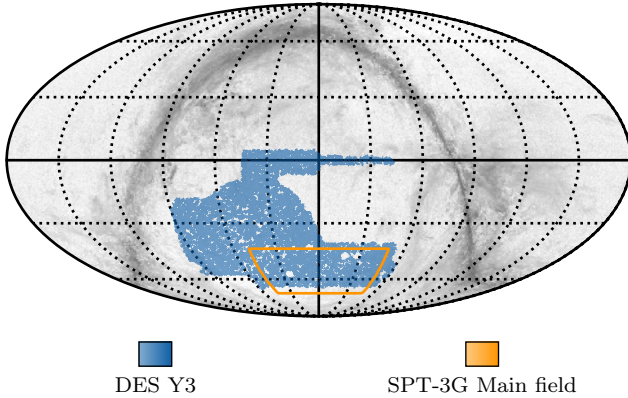
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FIG. 1. Survey footprints for DES Y3 and the SPT-3G Main field in equatorial coordinates. Galactic dust as measured by *Planck* is shown in the background. The overlapping region covers approximately 1,300 deg^2.

a baseline to then asses different foreground mitigation techniques when including CMB temperature data in the lensing reconstruction. We additionally use a high-purity sample of blue star-forming galaxies selected from the DES Y3 catalog [22] that is expected to have an IA amplitude consistent with zero as a consistency check on our modelling of IA.

This paper is structured as follows. We provide an overview of the data used in Section II. We describe the simulations used to validate our analysis in Section III. In Section IV we describe our measurement of the CMB lensing - cosmic shear cross-correlation. Section V provides details on the modelling and parameter inference. We present the results in Section VII and conclude in Section VIII.

Throughout, when assuming a fiducial cosmology, we use values consistent with the *Planck* 2018 flat ΛCDM results [23].

II.   DATA

A.   SPT-3G CMB lensing maps

The CMB lensing maps used in this work are presented in [21]. Here we provide a quick overview of the data used to construct the lensing maps and the different reconstruction techniques used to mitigate foreground biases.

SPT-3G [24] is the third generation camera installed on the South Pole Telescope [25] and has been in operation since 2018. The lensing maps used here are based on temperature and polarization observations made during the 2019 and 2020 winter seasons. The main SPT-3G survey field covers a 1500 deg^2 patch in the Southern sky as shown in Fig. 1 and achieves average coadded noise levels of 3.3 (5.1) μK-arcmin in temperature (polarization) [26].

CMB lensing maps are generally reconstructed from the primary CMB maps using some form of a quadratic estimator (QE). In this work, we consider five different variants that have different tradeoffs between foreground mitigation and noise.

1. Global minimum variance (GMV) map. This is an extension of the standard quadratic estimator (SQE) that was first introduced by [27]. The GMV estimator was derived by [28] and incorporates correlations between the CMB temperature and polarization fields that are neglected in the traditional SQE.

2. Polarization-only SQE map. This reconstruction only uses polarization information and is expected to be immune to extragalactic foreground biases due to the fact that they are essentially unpolarized. [refs on limits of foreground polarization: [29–31]]

3. Profile hardened GMV map. Profile-hardening (or bias-hardening) [13, 32] modifies the QE to make it insensitive to contributions from the trispectra of some assumed source profiles such as galaxy clusters and radio sources.

4. Gradient-cleaned GMV [33] and

5. Cross-ILC GMV map. This estimator uses the internal linear combinations (ILC) algorithm to construct tSZ-nulled and CIB-nulled CMB maps which are then used as input in the QE [34].

The gradient-cleaned and cross-ILC estimators are implemented on top of the GMV (rather than SQE) estimator using the formalism of [35].

We refer to these five lensing reconstruction variants as 'GMV', 'Pol', 'Prof', 'MH', and 'xILC', respectively. Of these variants, the GMV reconstruction is expected to have the lowest noise, especially on small scales, but be the most impacted by foregrounds. The Pol reconstruction is expected to be the most robust to foregrounds while having significantly higher noise on small scales. The other variants all include temperature information and employ some foreground mitigation technique in order to attempt to extract more lensing signal while remaining unaffected by foreground biases.

B.   DES Y3 shear catalog

The Dark Energy Survey (DES) has observed about 5,000 deg^2 of the Southern sky in five photometric bands ($grizY$) [36–38]. The observations were taken using the DECam [39] camera on the Blanco telescope at the Cerro Tololo Inter-American Observatory in Chile.
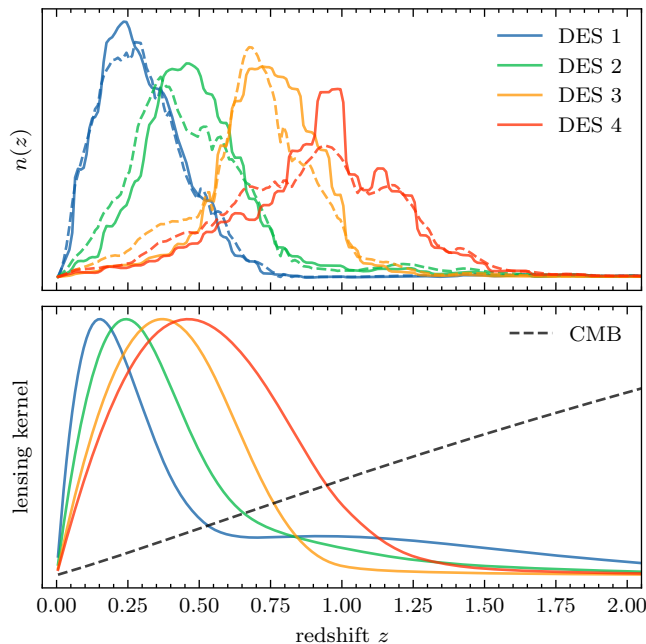
FIG. 2. Top panel: Redshift distributions of the four DES Y3 tomographic bins. Solid lines represent the full sample while dashed lines represent the blue subsample. Bottom panel: The corresponding lensing kernels for the full DES Y3 sample compared to the lensing kernel of the CMB (black dashed line). The kernels for the blue subsample are qualitatively very similar to those of the full sample. All kernels have been normalized to unit height.

In this work we use the publicly released catalogs[1] based on data from the first three years of observations (Y3). This is a subset of the Gold catalog [40] and consists of 100 million galaxies with shape measurements [41] and divided into 4 tomographic bins using photometric redshifts [42]. The redshift distributions of the DES Y3 tomographic bins are shown in the top panel of Fig. 2.

Additionally, we use the blue subsample of the DES Y3 data derived and analyzed by [22]. This subsample was developed with the goal of obtaining a pure sample of blue star-forming galaxies that are expected to be less impacted by intrinsic alignments than a mixed sample. We use the publicly released sample selection[2] to generate the blue catalogs and use the updated redshift distributions and calibrations that are presented in [22] when analyzing this sample.

We calibrate each of the shear catalogs using the METACALIBRATION algorithm [43, 44]. For each tomographic bin, we subtract the mean ellipticity and correct by the multiplicative shear bias to obtain calibrated

galaxy shear estimates $\boldsymbol{\gamma}_i$ from the galaxy shape measurements $\boldsymbol{e}_i$:

$$\hat{\boldsymbol{\gamma}}_i = \frac{1}{\langle R \rangle}(\boldsymbol{e}_i - \langle \boldsymbol{e} \rangle), \qquad (1)$$

where $R = R_\gamma + R_s$ is the combination of the shear response and selection response. This calibration is calculated from the catalogs as detailed in [41].

In Table I we provide an overview of the properties and calibration values of the four tomographic bins for both the full DES Y3 shear sample and the blue subsample.

III. SIMULATIONS

To validate our measurement and analysis pipelines, we use the AGORA[3] simulations [45] which are based on the MULTIDARK-PLANCK2 (MDPL2) [46] N-body simulation. AGORA uses the halos and particles from MDPL2 to generate lightcones, full-sky fields, and mock observations for a variety of observables. AGORA consists of a single full-sky realization which we split into 10 independent patches that each cover the same sky area as the SPT-3G main field.

A. Mock DES Y3 shear catalogs

The AGORA full-sky galaxy weak lensing signal maps [45] were generated to match the actual DES Y3 redshift distributions and include a level of intrinsic alignments that is consistent with the results of [47]. We generate simulated shear catalogs from the full-sky maps by sampling the signal at the locations of galaxies in the DES Y3 catalog. These noiseless catalogs are used to test for potential bias in the measured cross-correlation. We additionally incorporate realistic shape noise by randomly rotating the shear measurements of the DES Y3 catalog and adding the resulting noise to the noiseless catalogs. These realistic catalogs allow us to test the estimated covariance matrix of the measured cross-correlations.

B. Mock SPT-3G lensing maps

Since foreground contamination is expected to be a problem when cross-correlating temperature-based lensing maps with low-redshift tracers such as cosmic shear, it is important to use realistic simulations that include this effect in order to quantify the potential impact on cosmological parameter inference. AGORA includes full non-Gaussian realizations of the tSZ, kSZ, and CIB fields that are included when generating mock observations of the CMB field. Full details on the construction of these mock lensing maps can be found in [21, 45].

[1] https://des.ncsa.illinois.edu/releases/y3a2/Y3key-catalogs. Note that we use the updated SOMPZ v0.50 photometric catalog which corrects the tomographic bin placement for some galaxies. See also footnote 5 in [22].
[2] https://jamiemccullough.github.io/data/blueshear/
[3] https://yomori.github.io/agora/index.html

Bin	$N_{\rm gal}$	R_γ	R_s	$\langle z \rangle$	$\sigma_{\Delta z}$	$\langle m \rangle$	σ_m
Full 1	24,882,718	0.763	0.005	0.33	0.018	-0.0063	0.0091
Full 2	25,224,643	0.719	0.008	0.52	0.015	-0.0198	0.0078
Full 3	24,831,367	0.693	0.012	0.74	0.011	-0.0241	0.0076
Full 4	25,265,298	0.609	0.015	0.93	0.017	-0.0369	0.0076
Blue 1	18,031,829	0.760	0.007	0.36	0.018	-0.0129	0.0091
Blue 2	16,670,470	0.713	0.012	0.52	0.015	-0.0180	0.0078
Blue 3	12,233,530	0.696	0.018	0.70	0.011	-0.0203	0.0076
Blue 4	18,130,765	0.618	0.015	0.90	0.017	-0.0356	0.0076

TABLE I. Properties and calibration parameters for the full DES Y3 shear sample and the blue subsample. For each tomographic bin we list the number of galaxies ($N_{\rm gal}$), the average shear and selection responses (R_γ, R_s), the average redshift ($\langle z \rangle$), the uncertainty on the shift in the mean redshift ($\sigma_{\Delta z}$), the residual shear calibration ($\langle m \rangle$), and the uncertainty on the shear calibration (σ_m).

IV. MEASUREMENT

A. Shear map making

We generate shear maps and associated masks from the calibrated DES Y3 catalogs following [48, 49]. Throughout, we use the HEALPix pixelization scheme as implemented in HEALPY [50, 51] with a resolution parameter of $N_{\rm side} = 2048$.

The average shear $\boldsymbol{\gamma}$ at pixel p is given by

$$\boldsymbol{\gamma}_p = \sum_{i \in p} v_i \boldsymbol{\gamma}_i \bigg/ \sum_{i \in p} v_i \, , \qquad (2)$$

where $\boldsymbol{\gamma}_i$ and v_i are the shear and measurement weight (which is assumed to be approximately an inverse variance weight) respectively of the i-th galaxy.

The mask associated with the shear maps is simply given by the sum of weights map

$$w_p = \sum_{i \in p} v_i. \qquad (3)$$

B. Power spectra

Cosmic shear $\boldsymbol{\gamma}$ is a spin-2 field and can be decomposed into E- and B-modes [52]. The harmonic-space cross-correlation of cosmic shear with the scalar CMB lensing field κ then has two components: $C_\ell^{\kappa \gamma_E}$ and $C_\ell^{\kappa \gamma_B}$. At linear order, weak lensing by LSS does not generate B-modes, so our measurement mainly concerns $C_\ell^{\kappa \gamma_E}$, while $C_\ell^{\kappa \gamma_B}$ is expected to be consistent with zero. For simplicity, we will generally refer to $C_\ell^{\kappa \gamma}$ which is assumed to be the E-mode cross-spectrum unless otherwise noted.

We use NaMASTER[4] [53], which implements the pseudo-C_ℓ or MASTER algorithm [54] for arbitrary spin

fields, to measure the mask-deconvolved cross-spectra $C_\ell^{\kappa \gamma}$ from the masked shear γ and CMB lensing κ maps. The mask applied to the CMB lensing maps is effectively three powers of an apodized border mask resulting from the quadratic estimator reconstruction process and an additional point source mask that is constructed from a list of detected point sources and galaxy clusters as described in [21]. The mask applied to the shear field is the map of inverse-variance weights as given by Eq. (3).

The full details of the pseudo-C_ℓ method for general fields are given in [53] and its specific application to cosmic shear is described in [48]. Here we provide a brief description. For masked observed fields $\tilde{\gamma}$ and $\tilde{\kappa}$, the E-mode pseudo-cross-spectrum is defined as

$$\tilde{C}_\ell^{\kappa \gamma} = \frac{1}{2\ell + 1} \sum_m \tilde{\gamma}_{\ell m}^E \tilde{\kappa}_{\ell m}^*. \qquad (4)$$

The pseudo-cross-spectrum is related to the underlying true cross-spectrum through a mode-coupling matrix $M_{\ell \ell'}$:

$$\langle \tilde{C}_\ell^{\kappa \gamma} \rangle = \sum_{\ell'} M_{\ell \ell'} C_\ell^{\kappa \gamma}. \qquad (5)$$

The coupling matrix depends only on the masks applied to the two fields and the field spin values (see [53] for the full expressions). We additionally correct the pseudo-cross-spectra by one power of the HEALPIX pixel window function to account for the pixelization of the shear maps.

In order to invert the mode-coupling matrix, NaMASTER bins the cross-spectra into bandpowers. We choose to use the following binning scheme: 6 linear bins over the range $30 \leq \ell \leq 246$ and 18 logarithmic bins over the range $246 \leq \ell \leq 3500$. The minimum and maximum values of ℓ are given by the range of angular multipoles included in the lensing reconstruction. CC: justification of these scales AO: sufficient justification? scale cuts are covered later The mix of linear and logarithmic binning allows us to have somewhat finer bins on large scales where the signal is the largest and wider bins on small

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[4] https://namaster.readthedocs.io/en/latest/

scales where the noise in the CMB lensing maps increases substantially.

We calculate the Gaussian part of the bandpower covariances using the improved narrow kernel approximation (iNKA) as described in [48, 55] and implemented in NaMASTER. The covariances are calculated directly from the mode-coupled pseudo-C_ℓs and do not rely on a theory prediction for the cross-spectra in order to avoid any mis-modeling of signal and noise on small scales.

We show the resulting cross-correlation bandpowers involving the full DES Y3 shear sample in Fig. 3 and involving the blue subsample in Fig. 4. We find no evidence for non-zero cross-spectra with the shear B-modes. The full shear B-mode cross-spectra are shown in Appendix A.

V. ANALYSIS

A. Modelling

In the Limber approximation [56, 57] (valid on scales $\ell \gtrsim 20$) lensing cross-correlations are given by

$$C_\ell^{ij} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_m \left[k_\ell(\chi), z(\chi) \right], \quad (6)$$

where $k_\ell(\chi) \equiv (\ell + 1/2)/\chi$, χ is the comoving radial distance, and $P_m(k, z)$ is the 3D matter power spectrum. The indices i, j refer to the different tracers or tomographic bins that are being cross-correlated and W_i is the corresponding lensing kernel.

For a sample of galaxies with redshift distribution $n(z)$, the lensing convergence (κ) kernel is

$$W_\kappa^i(\chi) = \frac{3}{2} \Omega_m H_0^2 \frac{\chi}{a(\chi)} \int_\chi^\infty d\chi' n_i(\chi') \frac{\chi - \chi'}{\chi'}. \quad (7)$$

For galaxy lensing, the direct observable is the reduced shear $\boldsymbol{g} = \boldsymbol{\gamma}/(1 - \kappa)$, rather than the lensing convergence κ. But, in the weak lensing regime ($\kappa \ll 1$) and at the current levels of sensitivity, the difference between reduced shear and shear can be neglected [49]. Additionally, the difference between the E-mode shear power spectrum and the convergence power spectrum is only an ℓ dependent prefactor that is ~ 1 on scales $\ell \gtrsim 20$ and can also be neglected in this analysis. Finally, as in most analyses, we do not model the shear B-mode power spectrum since it is below the current detection threshold.

The CMB is very well approximated by a single source at $\chi = \chi_\star$, where $\chi_\star$ is the distance to the surface of last scattering, so the CMB lensing kernel becomes

$$W_\kappa^{\mathrm{CMB}}(\chi) = \frac{3}{2} \Omega_m H_0^2 \frac{\chi}{a(\chi)} \frac{\chi - \chi_\star}{\chi_\star}. \quad (8)$$

We use CAMB [58, 59] and HMCODE [60] to calculate the non-linear matter power spectrum.

1. Intrinsic alignments

Due to tidal forces, galaxies are not randomly oriented, but tend to align with the large-scale tidal field, leading to an additional contribution to the shear power spectrum. Intrinsic alignments are one of the main sources of systematic uncertainty in the modelling of shear data and many methods have been developed to model their contribution (see [61, 62] for reviews).

The DES Y3 analysis used the tidal alignment and tidal torquing (TATT) model [63], which includes second-order effects, as their fiducial analysis choice, but showed that the simpler nonlinear linear alignment (NLA) model [64, 65] was sufficient to model the DES Y3 data [66]. Since the cross-correlations with CMB lensing are less constraining than the shear auto-spectra, we use the simpler NLA model in this analysis.

The NLA model assumes that the IA power spectrum is linearly proportional to the matter power spectrum. In this model, we simply add an extra term to the galaxy lensing kernel:

$$W_\kappa^i(\chi) \to W_\kappa^i(\chi) + W_{\mathrm{IA}}^i(\chi). \quad (9)$$

$$W_{\mathrm{IA}}^i(\chi) = -A_1 C_1 \rho_{\mathrm{crit}} \frac{\Omega_m}{D(z)} n_i(\chi) \left(\frac{1 + z}{1 + z_0} \right)^{\alpha_1}, \quad (10)$$

where $D(z)$ is the linear growth factor, $C_1 = 5 \times 10^{-14} h^{-2} M_\odot^{-1} \mathrm{Mpc}^3$ is a normalization constant, $z_0 = 0.62$, and A_1 and α_1 are free parameters that determine the IA amplitude and redshift evolution respectively.

When modelling cross-correlations with the Blue shear sample, we assume zero IA amplitude as done in [22].

2. Baryonic feedback

Baryonic feedback is a major source of theoretical uncertainty in the small scales ($k \gtrsim 1h \ \mathrm{Mpc}^{-1}$) of the nonlinear matter power spectrum [67]. Instead of applying scale cuts to the data that remove sensitivity to these scales, we account for this uncertainty by marginalizing over the $\log T_{\mathrm{AGN}}$ parameter in HMCODE. This parameterization was calibrated to reproduce the matter power spectrum observed in the BAHAMAS hydrodynamical simulations [68].

3. Shear measurement uncertainties

As in the official DES Y3 analysis [49], we marginalize over uncertainties inn the shear calibration and the redshift distributions of the source galaxies.

Uncertainties in the redshift distributions are parameterized through a shift Δz_i of their means:

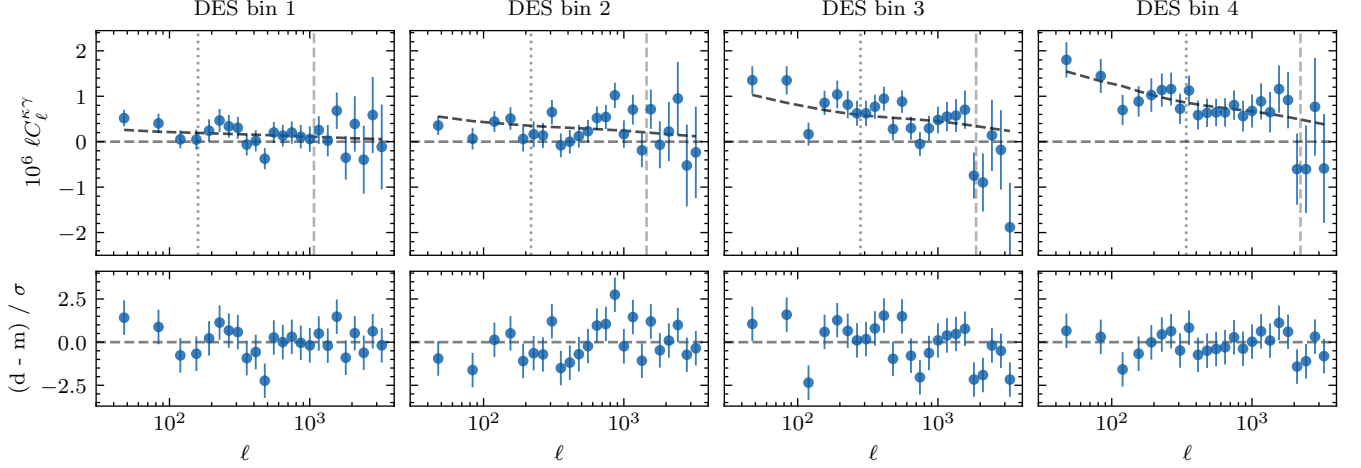$$n_i(z) \to n_i(z + \Delta z_i). \quad (11)$$

FIG. 3. Measured $C_\ell^{\kappa\gamma}$ cross-correlation bandpowers using the SPT-3G polarization-only lensing reconstruction and the full DES Y3 shear sample. The black dashed lines show the best fit model using all scales and the bottom panels show the residuals relative to this model. The grey vertical lines indicate the ℓ values corresponding to scale cuts of $k_{max} = 5h$ Mpc^{-1} (dashed) and $1h$ Mpc^{-1} (dotted) (see Section V B 3).
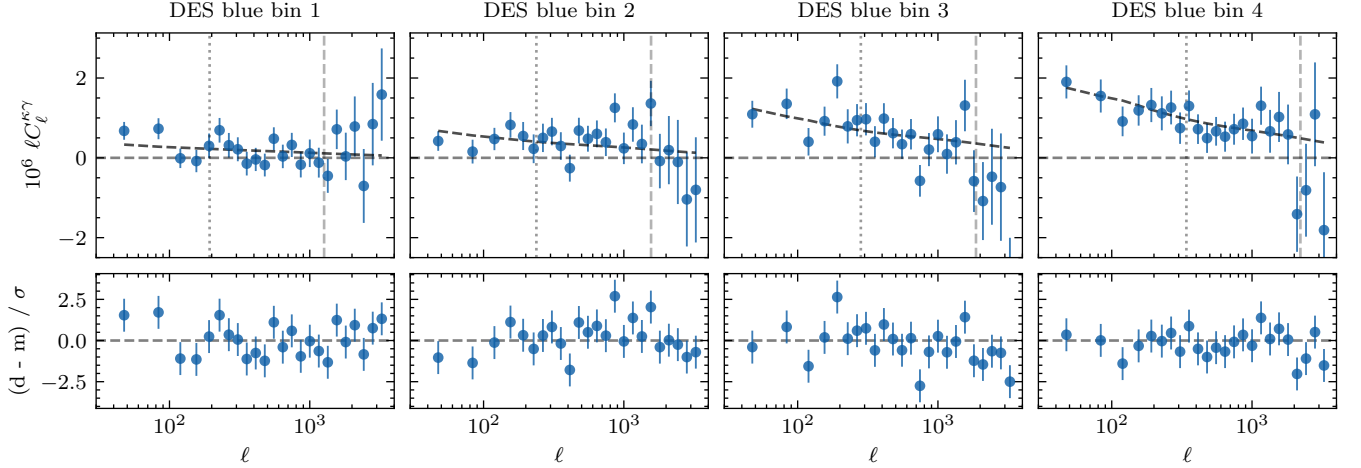

FIG. 4. Same as Fig. 3, but using the DES blue subsample.

Residual uncertainties in the shear calibration are parameterized using a constant amplitude m_i for each bin:

$$C_\ell^{\kappa\gamma_i} \rightarrow (1+m_i)C_\ell^{\kappa\gamma_i}. \qquad (12)$$

All of the redshift shift parameters Δz_i and shear calibration parameters m_i have tight Gaussian priors from detailed simulations of the DES data. Extensive testing in the official DES Y3 analyses has shown that these parameterizations of the measurement uncertainties are sufficiently accurate [69].

Since the shear calibration parameters m_i enter only as linear amplitudes on the cross-spectra, we choose to analytically marginalize over them in a similar manner to what is done in [70, 71]. This is accomplished by fixing m_i to the means of their priors and adding an additional term to the data covariance:

$$\text{Cov}_m(C_\ell^{\kappa\gamma_i}, C_{\ell'}^{\kappa\gamma_j}) = \sigma_i^2 \delta_{ij} C_\ell^{\kappa\gamma_i} C_{\ell'}^{\kappa\gamma_j}, \qquad (13)$$

where σ_i is the Gaussian prior on m_i and the cross-spectra are computed at the fiducial model. This expression can be straightforwardly derived from the expressions in [70, 71] with slight modifications to account for the DES assumption of uncorrelated calibrations per tomographic bin and the fact that $m = 0$ for the κ field. We have verified that we get essentially identical results whether we use this analytic marginalization method or sample the m_i parameters.

4. Non-Gaussian covariance terms

We model the total covariance of the cross-spectra as the sum of the Gaussian covariance computed using NA-MASTER (C$_G$, Section IV B), the shear calibration term (C$_m$, Section V A 3), and two additional terms that ac-
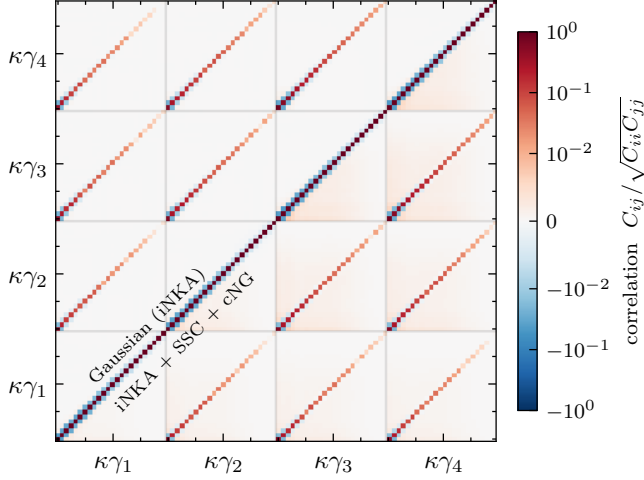
FIG. 5. Normalized data covariance matrix for the Full x Pol cross-correlation. The upper half of the matrix shows only the Gaussian part computed using NaMASTER, while the bottom half shows the full covariance, including the non-Gaussian components. The sub-blocks correspond to the cross-correlations between the CMB lensing (κ) and the individual DES tomographic bins (γ_i).

count for mode coupling from the non-Gaussianity of the lensing field:

$$C = C_G + C_m + C_{SSC} + C_{cNG}. \qquad (14)$$

C_{SSC} is the super-sample covariance term [72] that arises from modes larger than the survey mask. C_{cNG} is the connected non-Gaussian term [73] that arises from the non-Gaussian matter trispectrum.

The SSC and cNG terms are calculated through a halo model approximation implemented using the Core Cosmology Library (CCL) [74]. To construct the halo model, we assume a NFW profile [75] for dark matter halos, use the halo mass function and halo bias parameterizations from [76], and the halo concentration relation from [77].

In theory, there should be another contribution to the total covariance due to the uncertainty in the fiducial cosmology used in the CMB lensing reconstruction. We neglect this contribution as it is expected to be negligibly small. AO: need additional details about lensing response function

The full data covariance matrix is shown in Fig. 5. Both the SSC and cNG terms are sub-dominant to the Gaussian term, but the SSC term adds small off-diagonal correlations on large scales. The cNG term is mostly negligible, but is still included for completeness.

Parameter	Fiducial value	Prior
Cosmology		
Ω_m	0.311	$\mathcal{U}(0.1, 0.9)$
Ω_b	0.049	$\mathcal{U}(0.03, 0.07)$
h	0.677	$\mathcal{U}(0.55, 0.91)$
$10^9 A_s$	2.105	$\mathcal{U}(0.5, 5)$
n_s	0.967	$\mathcal{U}(0.87, 1.07)$
m_ν	0.06 eV (fixed)	
Intrinsic alignments		
A_1	0.44	$\mathcal{U}(-5, 5)$
α_1	0.0	$\mathcal{N}(0, 2)$
Baryonic feedback		
$\log T_{AGN}$	7.8	$\mathcal{U}(7.3, 8.3)$
Shear calibration		
m_1		
m_2	fixed to mean values in	
m_3	Table I and marginalized	
m_4	over analytically	
Redshift uncertainties		
Δz_1	0.0	$\mathcal{N}(0, 0.018)$
Δz_2	0.0	$\mathcal{N}(0, 0.015)$
Δz_3	0.0	$\mathcal{N}(0, 0.011)$
Δz_4	0.0	$\mathcal{N}(0, 0.017)$

TABLE II. Summary of parameters and priors used in the analysis. $\mathcal{U}(a, b)$ indicates a uniform prior, while $\mathcal{N}(\mu, \sigma)$ indicates a Gaussian prior. When doing a joint analysis with the *Planck* likelihood, we additionally vary the optical depth τ using a prior $\mathcal{U}(0.01, 0.8)$.

B. Parameter inference

1. Priors

We sample all parameters over the same ranges used in the DES Y3 analysis with a few small changes. We assume a single massive neutrino species with a fixed mass of $m_\nu = 0.06$ eV. For intrinsic alignments, we uniformly sample the amplitude A_1 over the range (-5, 5) and sample the power law exponent using a Gaussian prior centered at zero with width $\sigma = 2$. We choose to use a Gaussian prior for α_1 since this parameter is unconstrained by the data and very steep power laws are not expected to be physically plausible. For the shear nuisance parameters m_i and Δz_i, we use the same Gaussian priors used in the official DES Y3 analyses. We sample the baryonic feedback parameter $\log T_{AGN}$ uniformly over the range (7.3, 8.3). While HMCode was calibrated to match hydrodynamical simulations over the range (7.6, 8.3), we extend the range, following [4], in order to include low feedback models that are roughly consistent with a gravity-only model. We provide a summary of all the priors and fiducial parameter values used in our parameter inference in

k_{max} cut	ℓ_{max} cut (Full / Blue)				N_d
$[h$ Mpc$^{-1}]$	bin 1	bin 2	bin 3	bin 4	
0.5	82	115	150	182	10
	99	126	151	183	12
1	160	218	281	340	24
	193	238	282	341	26
2	342	462	593	709	43
	409	501	593	710	45
5	1071	1451	1871	2216	75
	1266	1563	1867	2213	77

TABLE III. Conversion of k_{max} cuts to ℓ_{max} cuts, assuming the fiducial model listed in Table II. Due to the slightly different redshift distributions of the Full and Blue shear samples, a given k cut translates into slightly different ℓ cuts, especially for the first two tomographic bins. The last column lists the number of remaining data points N_d (out of the total of 96) after applying the scale cuts.

Table II.

2. Likelihood

We assume a Gaussian likelihood $\mathcal{L}$ for the joint distribution of the cross-spectra bandpowers:

$$-2\ln\mathcal{L} + K \equiv$$
$$\chi^2 = (\boldsymbol{d} - \boldsymbol{m}(\boldsymbol{\theta}))^T \mathrm{C}^{-1}(\boldsymbol{d} - \boldsymbol{m}(\boldsymbol{\theta})), \quad (15)$$

where K is an arbitrary constant, $\boldsymbol{d}$ is the data vector consisting of the measured cross-spectra, $\boldsymbol{m}$ is the model computed at given values of the parameters $\boldsymbol{\theta}$, and C is the covariance matrix of the data. The posterior is then proportional to the product of the likelihood and the prior:

$$P(\boldsymbol{\theta}|\boldsymbol{d}) \propto \mathcal{L}(\boldsymbol{d}|\boldsymbol{\theta})P(\boldsymbol{\theta}). \quad (16)$$

The likelihood is implemented using the COSMOSIS[5] framework [78] and we sample the posterior using the nested sampler NAUTILUS[6] [79]. Starting from the highest posterior sample in each NAUTILUS chain, we find the maximum a posteriori (MAP) point using the Nelder-Mead optimization algorithm as implemented in SCIPY [80]. For each fit, we estimate the effective number of parameters N_{eff} that are constrained relative to the prior using the Gaussian approximation implemented in TENSIOMETER[7] [81]. This is then used to estimate the goodness-of-fit by comparing the χ^2 value of the MAP point to the estimated degrees of freedom $N_{dof} = N_d - N_{eff}$, where N_d is the size of the data vector.

---

3. Scale cuts

For our fiducial analysis, we attempt to fit all scales present in the measured data vectors ($30 \leq \ell \leq 3500$). To test the robustness of our results, we also test the effect of scale cuts designed to remove sensitivity to all scales in k space $k > k_{max}$. To convert a k_{max} cut to a corresponding ℓ_{max} cut, we use a method similar to that developed by [70]. Specifically, for a given cross-spectrum we calculate the C_ℓ using the full nonlinear $P(k)$ and using a $P(k)$ that has been exponentially suppressed for $k > k_{max}$. We then define ℓ_{max} as the maximum value of ℓ for which the two C_ℓs agree within a given threshold (here we choose 5%). The resulting scale cut ensures that no more than 5% of the signal in the data vectors depends on k modes beyond k_{max}. Table III lists the specific ℓ_{max} cuts that correspond to $k_{max} \in \{0.5, 1, 2, 5\}$ h Mpc^{-1} for each of the tomographic bins of the $\kappa\gamma$ cross-correlation for both the Full and Blue samples.

There are two main components of the theory model that are expected to be mis-modeled at some level in this analysis: the matter power spectrum and galaxy IA. Since HMCODE has been calibrated against simulations to roughly the per-cent level at $k < 20h$ Mpc^{-1} and $z < 1$ [60], systematic uncertainty in the matter power spectrum is not expected to be significant compared to the statistical uncertainty of our measurement. On the other hand, it is reasonable to expect more significant problems on the IA modeling side, since IA models are generally not tested on nonlinear scales. While the model that we use (NLA) is particularly simplistic, there is evidence from simulations that it is roughly valid out to $k \sim 1h$ Mpc^{-1} [82].

We find that for all of the $\kappa\gamma$ data vectors, the total bandpower SNR fully saturates by the scale cuts corresponding to $k_{max} = 5h$ Mpc^{-1} and approximately 50% of the total SNR comes from multipoles that are insensitive to $k > 0.5h$ Mpc^{-1}. It is important to note that, due to the very wide lensing kernels, a given range in ℓ receives contributions from a wide range in k. This means that applying a k_{max} scale cut as described above removes some sensitivity in the data to modes $k < k_{max}$ in addition to removing the sensitivity to all modes $k > k_{max}$. Based on these considerations, we do not expect our fiducial choice of including all multipoles to significantly bias our results.

VI. VALIDATION

Using the AGORA simulated CMB lensing reconstructions and simulated shear catalogs, we conduct three tests to validate our measurement and analysis. First, using the simulated shear catalogs without shape noise, we test for biases in the cross-correlation bandpowers. We then include a realistic level of shape noise to test our analytic estimate of the covariance matrix and to test the analysis pipeline for correct parameter recovery.
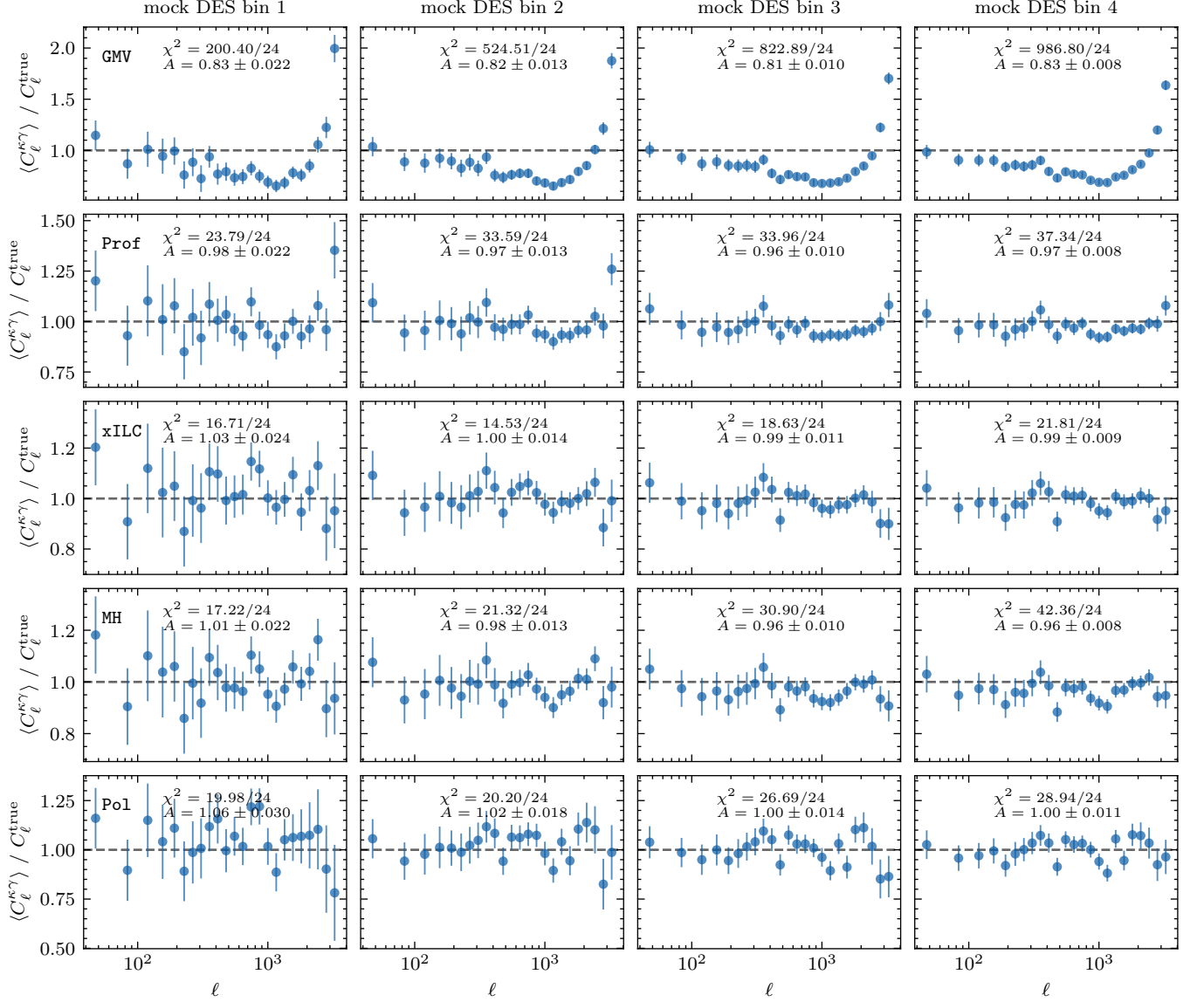
FIG. 6. Measurement validation on AGORA simulated data. Each panel compares the mean measured $\kappa\gamma$ cross-correlation to the truth (measured over the full sky with no noise). Each column corresponds to a different tomographic bin, while each row corresponds to a different CMB lensing reconstruction. The simulated shear catalogs in this test do not include shape noise to increase statistical power. In each panel we list the χ^2 of the ratio relative to one and the best fit amplitude. The errorbars represent the standard deviation of the mean of the 10 AGORA patches.

A. Cross-correlation bandpower recovery

In Fig. 6, for each of the AGORA simulated CMB lensing reconstructions, we plot the ratio of the average recovered $C_\ell^{\kappa\gamma}$ cross-spectra over the "true" cross-spectra. Here the recovered cross-spectra are measured from all 10 of the AGORA realizations of simulated CMB lensing reconstructions and simulated DES shear catalogs (without shape noise, to increase sensitivity to potential biases). The "true" cross-spectra are calculated from the noiseless full-sky AGORA lensing maps.

We find that using the Pol lensing maps (bottom row of Fig. 6) we are able to recover the cross-correlation bandpowers without bias, confirming that they are immune to foreground contamination and that our measurement pipeline correctly recovers the input power spectra. On the other hand, we find significant evidence for foreground biases in the GMV maps (top row of Fig. 6). On large to intermediate angular scales, this manifests as a negative ~ 20 - 40% bias, while on small angular scales ($\ell > 2000$) it becomes a large positive $\sim 50\%$ bias. The shape of this bias is qualitatively consistent with what is expected from tSZ contamination [45, 83].

For the Prof and MH lensing maps, which mainly attempt to remove tSZ contamination, we find hints of

FIG. 7. Distributions of χ^2 values for each of the simulated SPT-3G x DES Y3 data vectors. For each variant we list the p-value corresponding to the null hypothesis that the values follow the expected distribution computed using a two-sided Kolmogorov-Smirnov test.
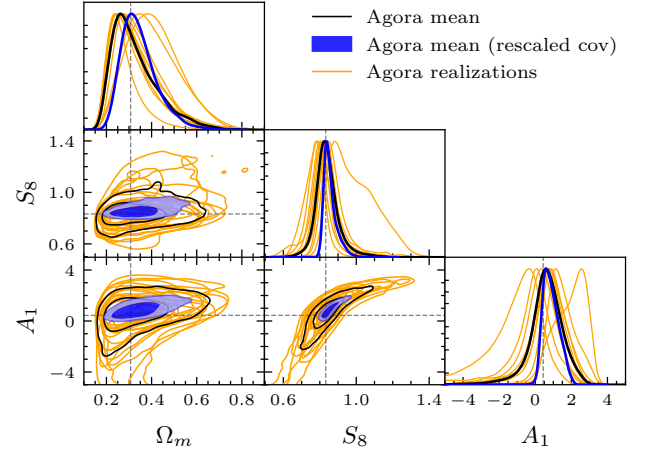

FIG. 8. AGORA parameter recovery test for the Pol $\kappa\gamma$ data vectors. We plot the marginal posterior distributions corresponding to the mean AGORA datavector with the data covariance in black and with the data covariance scaled by a factor of $1/10$ in blue. The posteriors for each of the individual realizations are shown in orange.

small (no more than a few percent) biases, potentially indicating either imperfect removal or potential CIB contamination. The xILC maps, which attempt to remove both tSZ and CIB contamination, are fairly consistent with no bias. AO: speculate about amounts of bias in different reconstructions: Prof and MH variants mainly remove tSZ, xILC might be better at removing both tSZ and CIB? AO: also comment on why we don't need to correct for a different QE response in the xcorr compared to the lensing auto

B. χ^2 test

In addition to confirming that the cross-correlation bandpowers are unbiased, we test our estimate of the covariance matrix by computing the distribution of $\chi^2 = \boldsymbol{d}^T \mathrm{C}^{-1} \boldsymbol{d}$ values for each set of simulated bandpowers. Under the assumption that the bandpowers are drawn from a multivariate Gaussian distribution, the χ^2 values are expected to follow a χ^2-distribution with number of degrees of freedom equal to the length of the data vector. If our analytic estimate of the covariance matrix is incorrect, then we would expect deviations from the expected distribution.

The results of this test are shown in Fig. 7 where we also list the p-values corresponding to the null hypothesis that the values follow the expected distribution computed using a two-sided Kolmogorov-Smirnov (KS) test. While this test is not particularly powerful due to the limited number of AGORA realizations, we do not find any evidence that the observed distributions deviate from the expected one for any of the non-GMV cross-correlations. Since the GMV data vectors are clearly biased due to foregrounds, we do not include their χ^2 values (which

FIG. 9. AGORA S_8 recovery test for each of the five lensing map variants. The thick errorbars represent the marginalized errorbar on S_8 from the combination of all 10 realizations, while the thin errorbars are scaled by a factor of $\sqrt{10}$ to represent the mean errorbar of a single realization. We also list the resulting biases relative to the input value for the combined and (single realization) cases.

are generally biased $\sim 20\%$ high relative to the other variants) in Fig. 7.

C. Parameter recovery

When inferring cosmological parameters from the simulated bandpowers, we use a slightly modified COSMOSIS pipeline compared to what is used on the data. 1. To

be consistent with the MDPL2 cosmology, neutrinos are assumed to be massless. 2. The nonlinear matter power spectrum is computed using HMCODE without baryonic feedback, since AGORA is based on a gravity-only N-body simulation.

We run the inference pipeline on all 10 AGORA realizations for each of the 5 lensing map variants. We also run the pipeline on the mean data vector for each lensing map variant with a covariance corresponding to a single realization and with a covariance that has been scaled by a factor of 1/10, representing the variance of the mean.

We show the results of this test on the Pol $\kappa\gamma$ data vectors in Fig. 8, where we plot the marginalized posteriors in the Ω_m-S_8-A_1 parameter space. We find that the contours for individual realizations scatter around the true input values and the contours corresponding to the mean data vectors are correctly centered on the input values.

In Fig. 9 we summarize the marginalized constraints on S_8 obtained from each of the lensing map variants. Specifically, the thick errorbars represent the combined constraint obtained from all 10 realizations, while the thin errorbars are scaled by a factor of $\sqrt{10}$ to represent the mean errorbar of a single realization. When using the GMV reconstruction, we find a -6.8σ bias on S_8 when combining all 10 AGORA realizations, translating to roughly an average of a -2.1σ bias for a single realization. All of the other estimators result in constraints that are consistent with the input. Only the Prof/MH estimators can be considered to result in a slight tension with the input at roughly 1.8/2.0 σ respectively when combining all 10 AGORA realizations.

VII. RESULTS

A. Detection significance

In Table IV we list the estimated signal-to-noise ratio for each set of cross-correlation bandpowers which we define as

$$\mathrm{SNR} = \sqrt{\boldsymbol{d}^T \mathrm{C}^{-1} \boldsymbol{d} - N_d}, \qquad (17)$$

where N_d is the length of the data vector. We also list the amplitude of the measured cross-correlations relative to the prediction assuming a *Planck* 2018 cosmology. This amplitude is calculated as

$$A_{\mathrm{Planck}} = \frac{\boldsymbol{t}^T \mathrm{C}^{-1} \boldsymbol{d}}{\boldsymbol{t}^T \mathrm{C}^{-1} \boldsymbol{t}}, \qquad (18)$$

where $\boldsymbol{t}$ is the theory vector calculated using the fiducial model listed in Table II.

For all data combinations, we get high significance ($> 12\sigma$) detections of the $\kappa\gamma$ cross-correlation. The highest significance detection (15.5σ) is obtained when using the full shear sample and the profile-hardened lensing estimator. It is notable that when using the polarization-only estimator, we only lose ~ 2 points of SNR, indica-

Data vector	SNR	A_{Planck}
Full x GMV	13.9	0.86 ± 0.060
Full x Prof	15.5	0.98 ± 0.062
Full x MH	15.2	0.98 ± 0.063
Full x xILC	14.9	0.99 ± 0.065
Full x Pol	13.4	0.99 ± 0.075
Blue x Pol	12.8	1.08 ± 0.086

TABLE IV. Singal-to-noise ratios (SNR) and amplitudes relative to the Planck prediction (A_{Planck}) for each of the cross-correlation variants.

tive of the very low polarization noise levels in the SPT-3G maps. Right away, we can also see evidence of foreground biases in the GMV reconstruction. While the GMV reconstruction is expected to produce the highest SNR measurement, it is in fact 1.6 SNR points lower than the profile-hardened reconstruction due to the foreground bias that is expected to be negative across almost all scales. Additionally, the cross-correlation with the GMV reconstruction is the only one that is biased by more than 1σ relative to the *Planck* prediction. For all other variants we obtain values of A_{Planck} that are fully consistent with 1.

B. Cosmological constraints

Our main results are shown in Fig. 10 where we show the marginalized posteriors in the Ω_m-σ_8-S_8 parameter space obtained from the Full x Pol and Blue x Pol data vectors. We also compare our results with those from three external data sets: DES Y3 + KiDS-1000 cosmic shear [4], DES Y3 blue shear [22], and measurements of the primary CMB from *Planck* (TTTEEE+lowE) [23]. While they are significantly less constraining, we find that our constraints using both the Full x Pol and the Blue x Pol data vectors are fully consistent with both shear-only and primary CMB results.

Using the Full x Pol data vector and assuming the NLA model for galaxy IA, we obtain:

$$\Omega_m = 0.288^{+0.034}_{-0.094},$$
$$S_8 = 0.829^{+0.050}_{-0.064}.$$

Using the Blue x Pol data vector and assuming no IA, we obtain:

$$\Omega_m = 0.312^{+0.039}_{-0.10},$$
$$S_8 = 0.853 \pm 0.032.$$

We summarize the the main cosmological constraints from all considered data combinations in Table V. For the parameters Ω_m and S_8, we list the marginalized 68% confidence intervals and the estimated MAP points. We also list the χ^2 value of the estimated MAP point.

We summarize the results from several analysis variations in the following subsections and in Fig. 11.
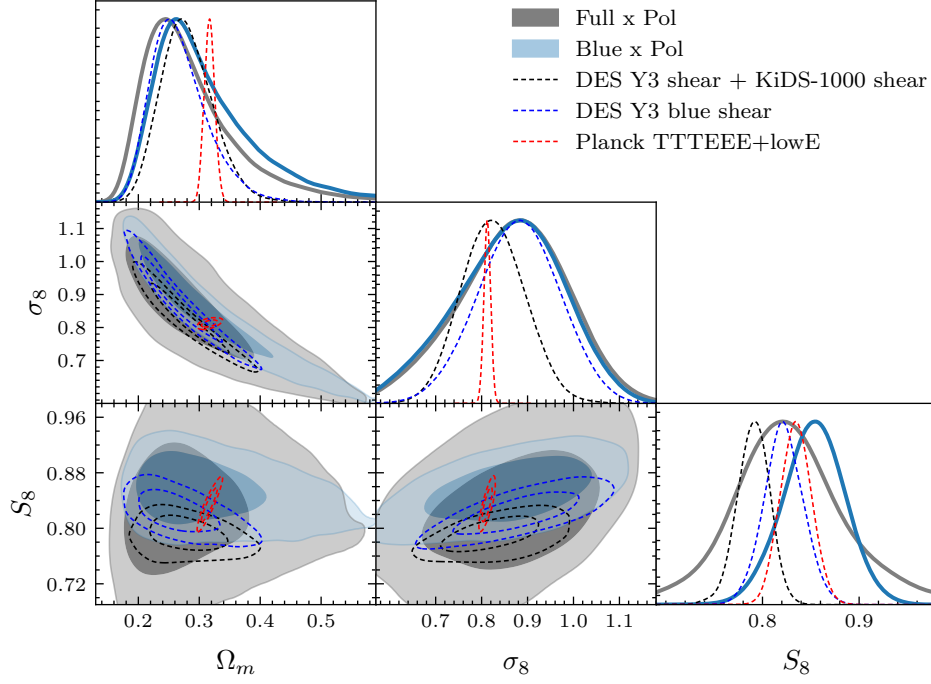
FIG. 10. Marginalized posteriors in the Ω_m-σ_8-S_8 parameter space for our Full x Pol and Blue x Pol data vectors. We also compare our results with published cosmic shear constraints (DES Y3 + KiDS-1000 [4] and DES Y3 blue shear [22]) and the primary CMB (*Planck* TTTEEE+lowE [23]).
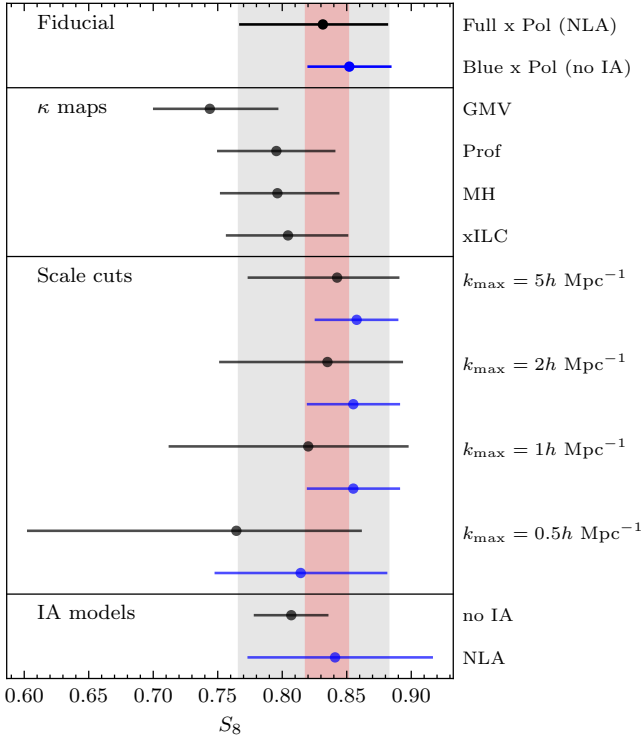

FIG. 11. Effect of different analysis choices on the resulting S_8 constraint. The vertical red band corresponds to the constraint from *Planck* TTTEEE+lowE.

Data vector	S_8	χ^2_{MAP} / PTE
Full x GMV	$0.744^{+0.053}_{-0.044}$ (0.79)	84.9 / 0.71
Full x Prof	0.795 ± 0.052 (0.82)	87.0 / 0.65
Full x MH	0.796 ± 0.052 (0.83)	83.1 / 0.75
Full x xILC	0.804 ± 0.054 (0.84)	83.8 / 0.74
Full x Pol	$0.831^{+0.051}_{-0.065}$ (0.85)	98.3 / 0.33
Blue x Pol	0.852 ± 0.033 (0.88)	101.2 / 0.29

TABLE V. Summary of S_8 constraints for all data combinations considered. For each combination we list the marginalized 68% confidence limits as well as the maximum a posteriori (MAP) values in parentheses. We also list the χ^2 value at the estimated MAP point and the estimated probability-to-exceed (PTE) value calculated using the number of degrees of freedom as described in Section V B 2. The effective number of constrained parameters for each data combination is 3.2, 3.2, 3.3, 3.2, 3.1, and 2.0 respectively.

1. CMB lensing foregrounds

In the second section of Fig. 11 we compare the constraints obtained when cross-correlating all five variants of the CMB lensing maps with the full DES Y3 sample. Generally, we see very good agreement between all of the data combinations, except for the one that uses the GMV map which is clearly biased towards lower S_8 values, consistent with the lower amplitude found relative to *Planck*

(Table IV) compared to the other data combinations.

We find that the signs of foregrounds in the data are fairly consistent with the AGORA foreground models. Using TENSIOMETER to calculate the Gaussian tension between marginalized S_8 posteriors, we find differences of 1.7σ, 0.7σ, 0.7σ, 0.5σ, and 0.1σ between Planck TT-TEEE+lowE and the GMV, Prof, MH, xILC, and Pol $\kappa\gamma$ cross-correlations respectively. These differences are very similar to the average AGORA single-realization biases (Fig. 9).

Notably, while the Full x Pol data vector has about 16% less total SNR compared to the Full x Prof data vector, the constraint on S_8 is only 12% wider.

2. Scale cuts

A potential concern about this analysis is that we attempt to use all scales to extract cosmological constraints while using relatively simplistic models for IA and baryonic feedback. Since the measured $\kappa\gamma$ cross-correlation on its own is unable to constrain the parameters related to these effects, we conclude that there is not enough sensitivity in the data on small scales to warrant more complicated models. For completeness, in the third section of Fig. 11 we show the marginalized constraints on S_8 obtained when applying scale cuts of $k_{\max} = 5$, 2, 1, and $0.5h$ Mpc^{-1} as described in Section V B 3. As expected, applying more conservative scale cuts significantly loosens the S_8 constraint, but we do not see any significant shifts in the mean values that might indicate biases due to mis-modelling of small scales.

3. Intrinsic alignments

By comparing our results obtained using the Full x Pol combination and the Blue x Pol combination, we find that they are robust against unmodelled IA systematics. Even though the Blue x Pol combination has the lowest SNR, we are able to obtain the tightest S_8 constraint from this combination. This is simply due to the fact that we assume zero IA amplitude for the blue sample, breaking the degeneracy between S_8 and IA. Together with [22], this highlights the usefulness of mitigating IA at the sample selection level.

C. Combining with Planck

We run a joint analysis of our measured $\kappa\gamma$ cross-correlation with the Planck 2018 TTTEEE+lowE likelihood. This has the effect of putting a tight prior on the cosmological parameters, allowing us to put constraints on astrophysical parameters (IA and baryonic feedback). Fig. 12 shows the marginalized posteriors resulting from the combination of the Pol and Prof cross-correlations with Planck. By combining with Planck, we are able to significantly tighten the constraints on the IA amplitude of the DES Y3 sample. From the Pol cross-correlation alone, we find $A_1 = 0.32^{+1.0}_{-0.76}$, while in combination with Planck we find $A_1 = 0.48 \pm 0.45$. We get a very similar constraint using the Prof cross-correlation combined with Planck: $A_1 = 0.39 \pm 0.41$. In all cases, we see no evidence for any redshift evolution of the IA amplitude. It is noteworthy that these constraints on the IA amplitude are fully consistent with (and in some cases tighter than) the constraints found in shear auto-correlation analyses [4, 49, 66].

By combining with Planck, we can also test our assumption of no IA in the DES blue sample. When analyzing Blue x Pol + Planck assuming NLA, we find an IA amplitude of $A_1 = -0.23^{+0.55}_{-0.47}$, consistent with zero and the constraint found by [22].

Finally, we find that our data have some mild sensitivity to the strength of baryonic feedback as parameterized by $\log T_{\mathrm{AGN}}$. The Pol lensing maps are too noisy on small scales to provide constraining power on the strength of baryonic feedback, even when mitigating IA using the blue sample selection. By combining the Full x Prof cross-correlation with Planck, we begin to see evidence for small-scale suppression of the matter power spectrum from baryonic feedback. We get a 68% credible lower limit of $\log T_{\mathrm{AGN}} > 7.70$ which is consistent with the amount of suppression generally found in shear auto-correlation analyses [11]

VIII. CONCLUSIONS

The cross-correlation between CMB lensing (κ) and cosmic shear (γ) provides a useful consistency test that is less sensitive to the measurement systematics of each survey. We have measured the cross-correlation between CMB lensing from SPT-3G and DES Y3 cosmic shear over an overlapping sky area of approximately 1,300 deg^2. The main findings of this analysis are as follows.

- We detect the $\kappa\gamma$ cross-correlation at a significance of 13σ when only using CMB polarization data in the lensing reconstruction. The significance increases to $\sim 15 - 16\sigma$ when including temperature data and using some foreground mitigation technique.

- We fit a model to the data, marginalizing over galaxy intrinsic alignments, baryonic feedback, and cosmic shear nuisance parameters, and find a 7% constraint on the amplitude of matter clustering S_8 that is consistent with both results from Planck and from cosmic shear surveys.

- Using a high-purity sub-selection of blue star-forming galaxies from the full DES Y3 catalog that is expected to be less impacted by IA than the full sample [22, 84], we show that reducing the uncertainty on the IA amplitude, significantly improves
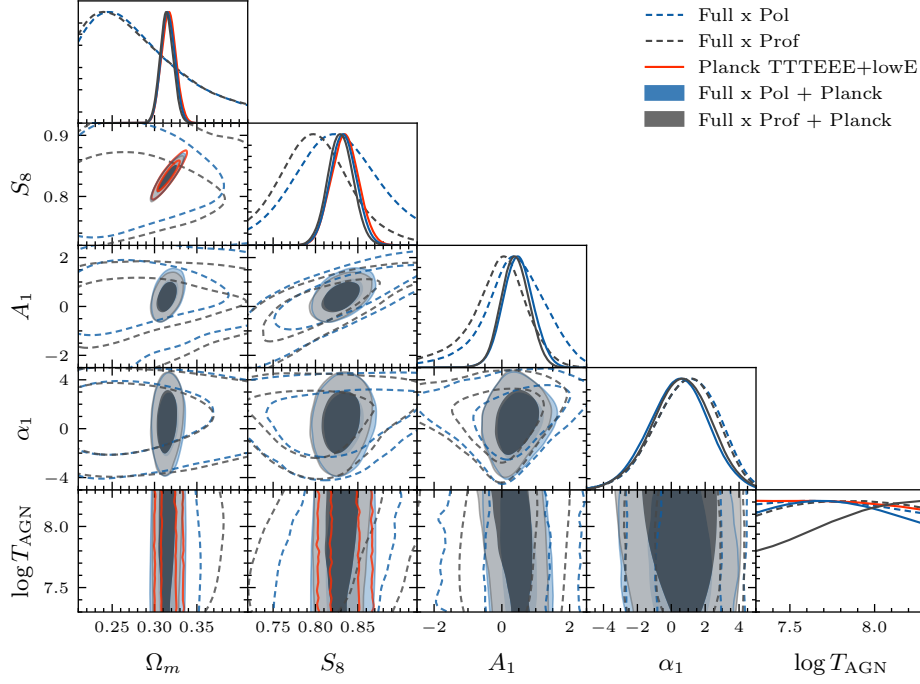
FIG. 12. Cosmological and astrophysical constraints from the combination of *Planck* with the Pol and Prof $\kappa\gamma$ cross-correlations.

the constraining power on S_8. When modeling the $\kappa\gamma$ cross-correlation with the blue sample under the assumption of no IA, we obtain a 4% constraint on S_8 that is still consistent with both the primary CMB and cosmic shear surveys.

- We use the *Planck* 2018 results to put a tight prior on cosmological parameters and show that the measured $\kappa\gamma$ cross-correlation has some sensitivity to small-scale physics. Using the Pol x Full data vector, we find a 1.1σ constraint on the IA amplitude that is comparable to what is found in the full DES Y3 cosmic shear analysis. We find no evidence for significant redshift evolution of this amplitude. Using the Prof x Full data vector, we additionally find hints of a small-scale suppression of power due to baryonic feedback.

These results represent the first high-significance detection of the $\kappa\gamma$ cross-correlation using a polarization-only lensing reconstruction and are a significant improvement over the first such measurement with POLAR-BEAR and HSC [14]. This highlights the power of polarization-only CMB lensing reconstructions to mitigate extragalactic foregrounds when very low noise CMB polarization observations are available.

Future work: include shear autos to measure the small scale matter power spectrum, work towards 6x2-pt analysis

With data from future surveys, more work will need to be done to ensure accurate modelling on small scales. In particular, IA modeling will need significant attention. [perturbative and non-perturbative techniques]

tional Center for Supercomputing Applications (NCSA), University of Illinois Urbana-Champaign. This work made use of the following computing resources: the Illinois Campus Cluster, a computing resource that is operated by the Illinois Campus Cluster Program (ICCP) in conjunction with the National Center for Supercomputing Applications (NCSA) and which is supported by funds from the University of Illinois Urbana-Champaign; and Crossover, a high-performance computing cluster operated by the Laboratory Computing Resource Center at Argonne National Laboratory. This work relied on NumPy [85] and SciPy [86] for numerical calculations, Matplotlib [87] for plotting, and GetDist [88] for plotting and analyzing posterior distributions.

Appendix A: Additional validation test plots

In Fig. 13 we show the measured B-mode cross-correlations when using the Pol lensing reconstruction

and both of the DES shear samples. We find no significant evidence for non-zero B-modes. Out of all of the data vectors (including the GMV, Prof, MH, and xILC lensing reconstructions), the worst χ^2 value is 37.6 with 24 degrees of freedom for bin 2 of the full shear sample. While this is somewhat high, it is within the expected distribution when considering four independent shear bins.

Appendix B: Full posteriors

For completeness, we show the full posteriors for the Full x Pol, Full x Prof, and Blue x Pol data combinations in Fig. 14.

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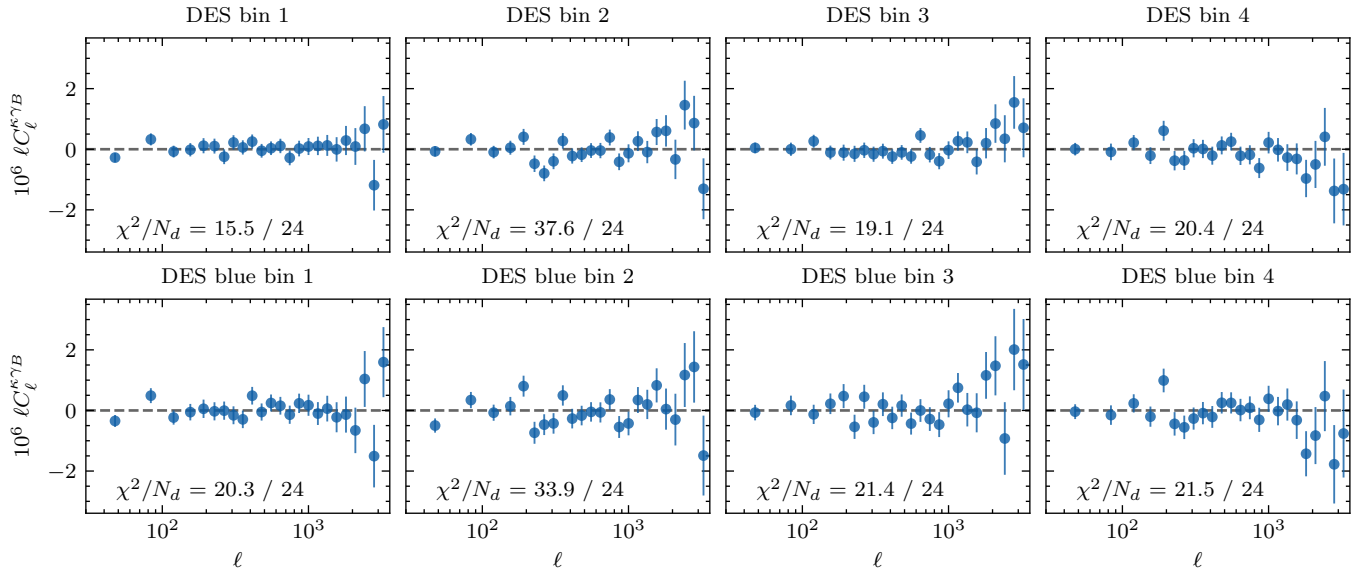
FIG. 13. Top row: B-mode $\kappa\gamma$ cross-correlations for the full shear sample and the Pol lensing reconstruction. Bottom row: same as top row, but for the blue shear subsample. We list the χ^2 values for each data vector relative to zero.

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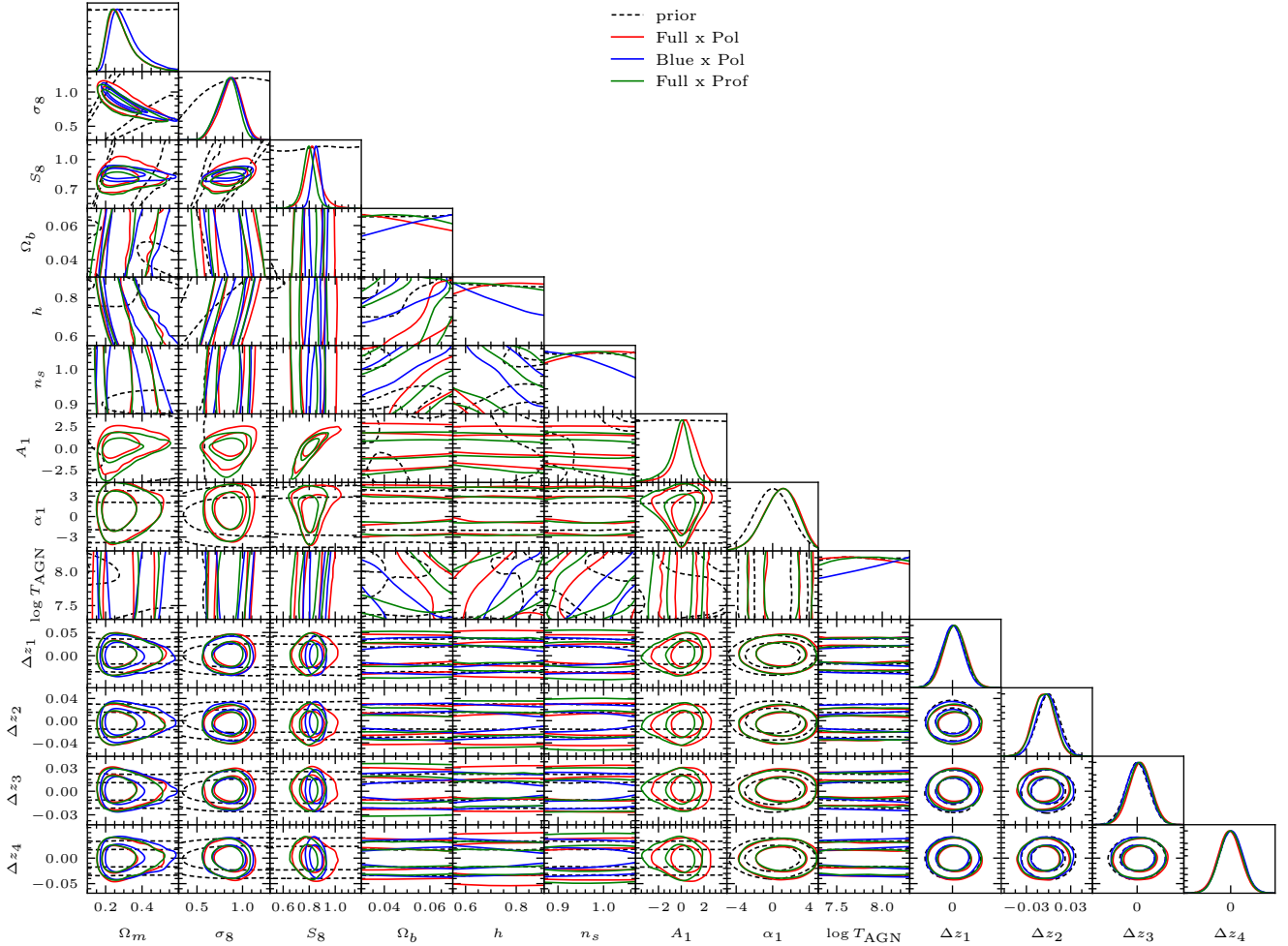
FIG. 14. Full posteriors for the Full x Pol, Blue x Pol, and Full x Prof $\kappa\gamma$ cross-correlations. The black dashed contours show the result of sampling the prior as specified in Table II.

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