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Y. Omori *et al.* (DES and SPT Collaborations)

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Dark Energy Survey Year 1 Results: tomographic cross-correlations between DES galaxies and CMB lensing from SPT+Planck

Y. Omori,^{1,2,3} T. Giannantonio,^{4,5,6} A. Porredon,^{7,8} E. J. Baxter,⁹ C. Chang,¹⁰ M. Crocce,^{7,8} P. Fosalba,^{7,8} A. Alarcon,^{7,8} N. Banik,¹¹ J. Blazek,^{12,13} L. E. Bleem,^{10,14} S. L. Bridle,¹⁵ R. Cawthon,¹⁰ A. Choi,¹² R. Chown,^{16,3} T. Crawford,^{17,10} S. Dodelson,¹⁸ A. Drlica-Wagner,¹¹ T. F. Eifler,^{19,20} J. Elvin-Poole,¹⁵ O. Friedrich,^{21,6} D. Gruen,^{2,22} G. P. Holder,^{3,23,24,25} D. Huterer,²⁶ B. Jain,⁹ M. Jarvis,⁹ D. Kirk,²⁷ N. Kokron,^{1,2} E. Krause,¹⁹ N. MacCrann,^{12,28} J. Muir,² J. Prat,²⁹ C. L. Reichardt,³⁰ A. J. Ross,¹² E. Rozo,³¹ E. S. Rykoff,^{2,22} C. Sánchez,^{9,29} L. F. Secco,⁹ G. Simard,³ R. H. Wechsler,^{1,2,22} J. Zuntz,³² T. M. C. Abbott,³³ F. B. Abdalla,^{27,34} S. Allam,¹¹ S. Avila,³⁵ K. Aylor,³⁶ B. A. Benson,^{10,11,17} G. M. Bernstein,⁹ E. Bertin,^{37,38} F. Bianchini,³⁰ D. Brooks,²⁷ E. Buckley-Geer,¹¹ D. L. Burke,^{2,22} J. E. Carlstrom,^{10,17,14,39,40} A. Carnero Rosell,^{41,42} M. Carrasco Kind,^{24,43} J. Carretero,²⁹ F. J. Castander,^{7,8} C. L. Chang,^{10,17,14} H-M. Cho,²² A. T. Crites,⁴⁴ C. E. Cunha,² L. N. da Costa,⁴² T. de Haan,^{45,46} C. Davis,² J. De Vicente,⁴⁷ S. Desai,⁴⁸ H. T. Diehl,¹¹ J. P. Dietrich,^{49,50} M. A. Dobbs,^{3,51} W. B. Everett,⁵² P. Doel,²⁷ J. Estrada,¹¹ B. Flaugher,¹¹ J. Frieman,^{10,11} J. García-Bellido,⁵³ E. Gaztanaga,^{7,8} D. W. Gerdes,^{26,54} E. M. George,^{45,55} R. A. Gruendl,^{24,43} J. Gschwend,^{41,42} G. Gutierrez,¹¹ N. W. Halverson,^{52,56} N. L. Harrington,⁴⁵ W. G. Hartley,^{27,57} D. L. Hollowood,⁵⁸ W. L. Holzappel,⁴⁵ K. Honscheid,^{12,28} Z. Hou,^{10,17} B. Hoyle,^{21,6} J. D. Hrubes,⁵⁹ D. J. James,⁶⁰ T. Jeltema,⁵⁸ K. Kuehn,⁶¹ N. Kuropatkin,¹¹ A. T. Lee,^{45,46} E. M. Leitch,^{10,17} M. Lima,^{62,41} D. Luong-Van,⁵⁹ A. Manzotti,^{63,10,17} D. P. Marrone,⁶⁴ J. L. Marshall,⁶⁵ J. J. McMahon,²⁶ P. Melchior,⁶⁶ F. Menanteau,^{24,43} S. S. Meyer,^{10,17,40,67} C. J. Miller,^{26,54} R. Miquel,^{29,68} L. M. Mocanu,^{10,17} J. J. Mohr,^{21,49,50} T. Natoli,^{10,39,69} S. Padin,^{10,17} A. A. Plazas,²⁰ C. Pryke,⁷⁰ A. K. Romer,⁷¹ A. Roodman,^{2,22} J. E. Ruhl,⁷² E. Sanchez,⁴⁷ V. Scarpine,¹¹ K. K. Schaffer,^{10,40,73} M. Schubnell,²⁶ S. Serrano,^{7,8} I. Sevilla-Noarbe,⁴⁷ E. Shirokoff,^{10,17,45} M. Smith,⁷⁴ M. Soares-Santos,⁷⁵ F. Sobreira,^{41,76} Z. Staniszewski,^{72,20} A. A. Stark,⁶⁰ K. T. Story,^{2,77} E. Suchyta,⁷⁸ M. E. C. Swanson,⁴³ G. Tarle,²⁶ D. Thomas,³⁵ M. A. Troxel,^{12,28} K. Vanderlinde,^{69,79} J. D. Vieira,^{24,25} A. R. Walker,³³ W. L. K. Wu,¹⁰ and O. Zahn⁸⁰

(DES & SPT Collaborations)

¹Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305, USA

²Kavli Institute for Particle Astrophysics & Cosmology,

P. O. Box 2450, Stanford University, Stanford, CA 94305, USA

³Department of Physics and McGill Space Institute, McGill University, Montreal, Quebec H3A 2T8, Canada

⁴Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

⁵Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

⁶Universitäts-Sternwarte, Fakultät für Physik, Ludwig-Maximilians Universität München, Scheinerstr. 1, 81679 München, Germany

⁷Institut d'Estudis Espacials de Catalunya (IEEC), 08193 Barcelona, Spain

⁸Institute of Space Sciences (ICE, CSIC), Campus UAB,

Carrer de Can Magrans, s/n, 08193 Barcelona, Spain

⁹Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA

¹⁰Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA

¹¹Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510, USA

¹²Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA

¹³Institute of Physics, Laboratory of Astrophysics, École Polytechnique Fédérale

de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland

¹⁴High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA 60439

¹⁵Jodrell Bank Center for Astrophysics, School of Physics and Astronomy,

University of Manchester, Oxford Road, Manchester, M13 9PL, UK

¹⁶Department of Physics and Astronomy, McMaster University, 1280 Main St. W., Hamilton, ON L8S 4L8, Canada

¹⁷Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA

¹⁸Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15312, USA

¹⁹Department of Astronomy/Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721-0065, USA

²⁰Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA

²¹Max Planck Institute for Extraterrestrial Physics, Giessenbachstrasse, 85748 Garching, Germany

²²SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

²³Canadian Institute for Advanced Research, CIFAR Program in Cosmology and Gravity, Toronto, ON, M5G 1Z8, Canada

²⁴Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL 61801, USA

²⁵Department of Physics, University of Illinois Urbana-Champaign, 1110 W. Green Street, Urbana, IL 61801, USA

²⁶Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

²⁷Department of Physics & Astronomy, University College London, Gower Street, London, WC1E 6BT, UK

²⁸Department of Physics, The Ohio State University, Columbus, OH 43210, USA

²⁹Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of

Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona) Spain

³⁰School of Physics, University of Melbourne, Parkville, VIC 3010, Australia

³¹Department of Physics, University of Arizona, Tucson, AZ 85721, USA

- ³²*Institute for Astronomy, University of Edinburgh, Edinburgh EH9 3HJ, UK*
- ³³*Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile*
- ³⁴*Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown, 6140, South Africa*
- ³⁵*Institute of Cosmology & Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK*
- ³⁶*Department of Physics, University of California, Davis, CA, USA 95616*
- ³⁷*CNRS, UMR 7095, Institut d'Astrophysique de Paris, F-75014, Paris, France*
- ³⁸*Sorbonne Universités, UPMC Univ Paris 06, UMR 7095, Institut d'Astrophysique de Paris, F-75014, Paris, France*
- ³⁹*Department of Physics, University of Chicago, Chicago, IL 60637, USA*
- ⁴⁰*Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
- ⁴¹*Laboratório Interinstitucional de e-Astronomia - LIneA, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil*
- ⁴²*Observatório Nacional, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil*
- ⁴³*National Center for Supercomputing Applications, 1205 West Clark St., Urbana, IL 61801, USA*
- ⁴⁴*California Institute of Technology, Pasadena, CA, USA 91125*
- ⁴⁵*Department of Physics, University of California, Berkeley, CA, USA 94720*
- ⁴⁶*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA 94720*
- ⁴⁷*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ⁴⁸*Department of Physics, IIT Hyderabad, Kandi, Telangana 502285, India*
- ⁴⁹*Excellence Cluster Universe, Boltzmannstr. 2, 85748 Garching, Germany*
- ⁵⁰*Faculty of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, 81679 Munich, Germany*
- ⁵¹*Canadian Institute for Advanced Research, CIFAR Program in Gravity and the Extreme Universe, Toronto, ON, M5G 1Z8, Canada*
- ⁵²*Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO, 80309*
- ⁵³*Instituto de Física Teórica UAM/CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain*
- ⁵⁴*Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA*
- ⁵⁵*European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany*
- ⁵⁶*Department of Physics, University of Colorado, Boulder, CO, 80309*
- ⁵⁷*Department of Physics, ETH Zurich, Wolfgang-Pauli-Strasse 16, CH-8093 Zurich, Switzerland*
- ⁵⁸*Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA*
- ⁵⁹*University of Chicago, Chicago, IL 60637, USA*
- ⁶⁰*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
- ⁶¹*Australian Astronomical Observatory, North Ryde, NSW 2113, Australia*
- ⁶²*Departamento de Física Matemática, Instituto de Física, Universidade de São Paulo, CP 66318, São Paulo, SP, 05314-970, Brazil*
- ⁶³*Institut d'Astrophysique de Paris, F-75014, Paris, France*
- ⁶⁴*Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721*
- ⁶⁵*George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA*
- ⁶⁶*Department of Astrophysical Sciences, Princeton University, Peyton Hall, Princeton, NJ 08544, USA*
- ⁶⁷*Department of Physics, University of Chicago, Chicago, IL, USA 6063*
- ⁶⁸*Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain*
- ⁶⁹*Dunlap Institute for Astronomy & Astrophysics, University of Toronto, 50 St George St, Toronto, ON, M5S 3H4, Canada*
- ⁷⁰*Department of Physics, University of Minnesota, Minneapolis, MN, USA 55455*
- ⁷¹*Department of Physics and Astronomy, Pevensey Building, University of Sussex, Brighton, BN1 9QH, UK*
- ⁷²*Physics Department, Center for Education and Research in Cosmology and Astrophysics, Case Western Reserve University, Cleveland, OH, USA 44106*
- ⁷³*Liberal Arts Department, School of the Art Institute of Chicago, Chicago, IL, USA 60603*
- ⁷⁴*School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK*
- ⁷⁵*Brandeis University, Physics Department, 415 South Street, Waltham MA 02453*
- ⁷⁶*Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, 13083-859, Campinas, SP, Brazil*
- ⁷⁷*Dept. of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305*
- ⁷⁸*Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831*
- ⁷⁹*Department of Astronomy & Astrophysics, University of Toronto, 50 St George St, Toronto, ON, M5S 3H4, Canada*
- ⁸⁰*Berkeley Center for Cosmological Physics, Department of Physics, University of California, and Lawrence Berkeley National Labs, Berkeley, CA, USA 94720*

We measure the cross-correlation between `redMAGiC` galaxies selected from the Dark Energy Survey (DES) Year-1 data and gravitational lensing of the cosmic microwave background (CMB) reconstructed from South Pole Telescope (SPT) and *Planck* data over 1289 deg^2 . When combining measurements across multiple galaxy redshift bins spanning the redshift range of $0.15 < z < 0.90$, we reject the hypothesis of no correlation at 19.9σ significance. When removing small-scale data points where thermal Sunyaev-Zel'dovich signal and nonlinear galaxy bias could potentially bias our results, the detection significance is reduced to 9.9σ . We perform a joint analysis of galaxy-CMB lensing cross-correlations and galaxy clustering to constrain cosmology, finding $\Omega_m =$

$0.276_{-0.030}^{+0.029}$ and $S_8 = \sigma_8 \sqrt{\Omega_m/0.3} = 0.800_{-0.094}^{+0.090}$. We also perform two alternate analyses aimed at constraining only the growth rate of cosmic structure as a function of redshift, finding consistency with predictions from the concordance Λ CDM model. The measurements presented here are part of a joint cosmological analysis that combines galaxy clustering, galaxy lensing and CMB lensing using data from DES, SPT and *Planck*.

I. INTRODUCTION

The cosmic microwave background (CMB) is one of the fundamental cosmological observables. Measurements of primary anisotropies in the CMB, sourced by fluctuations in the photon-baryon fluid at the time of recombination, have been used to place tight constraints on the physical properties of the Universe, most recently by the *Planck* satellite mission [1].

In addition to the information contained in the primary CMB anisotropy, there is also a wealth of information in secondary anisotropies resulting from perturbations to CMB light after the time of recombination [2]. A particularly interesting source of secondary anisotropy is gravitational lensing, which causes the paths of photons from the last-scattering surface to be perturbed by the matter in the Universe (see the review by [3]). These deflections, on the order of a few arcminutes [4], alter the CMB primary anisotropies by redistributing power across different angular scales and producing a non-Gaussian component to the primordial distribution of temperature anisotropies. Measurement of this non-Gaussian structure can be used to infer the total amount of deflection that has occurred in a given direction [5, 6]. High signal-to-noise measurements of CMB lensing have been obtained by several collaborations, including the Atacama Cosmology Telescope [ACT, 7, 8], *Planck* [9–11], POLARBEAR [12], and the South Pole Telescope [SPT, 13–15].

The reconstructed CMB lensing signal is an integral of all deflections sourced by the large-scale structure between the last-scattering surface and us. Due to this projection, we cannot directly measure the evolution of structure along the line of sight by analyzing the lensing signal alone. However, the signal from CMB lensing can be *cross-correlated* with tracers of the matter distribution, such as galaxy catalogues with known redshifts. This allows us to measure the growth of structure in the Universe across cosmic time.

Galaxy density-CMB lensing cross-correlations have been detected by several groups, using a variety of data sets. The first significant detection was reported by [16] correlating WMAP data with radio galaxies from NVSS [17], which was later combined with other galaxy catalogues by [18]. Other recent galaxy-CMB lensing cross-correlation measurements include the cross-correlation with quasars [19–22], with optical, IR and radio galaxies [23–32], the cosmic infrared background [33–36], galaxy clusters [37, 38], and many others. The first *tomographic* cross-correlation analysis using multiple redshift bins from a single galaxy survey was carried out by ([39], hereafter G16) using CMB lensing data from SPT and *Planck* and the Dark Energy Survey (DES) Science Verification (SV) galaxies.

In this work, we update the results of G16 by measuring the cross-correlations between galaxy density from the DES Year-1 (Y1) data and a CMB lensing reconstruction using a

combination of SPT and *Planck* data in the SPT-SZ survey area.¹ The total area used in this work is nearly a factor of 10 larger than in G16. We find a highly significant detection of the correlation between galaxy density and CMB lensing. We subject the correlation function measurements and corresponding covariance estimates to several tests for systematic effects, finding that biases due to these systematic effects are negligible over the range of angular scales used for the main analysis.

We use the measured galaxy-CMB lensing cross-correlations to extract cosmological information in several ways. First, assuming a fiducial cosmological model based on the results of [41], we measure the amplitude of our measurement relative to this model. The amplitude we obtain from this procedure can be directly compared with similar constraints obtained in previous studies. Second, we infer the linear growth function over the redshift ranges that DES is sensitive to, and compare that with the baseline Λ CDM model predictions derived from CMB observations. Two different approaches are used: (i) the D_G estimator introduced in G16, and (ii) a method that allows us to marginalize over galaxy bias parameters and parameters associated with systematic measurement errors. Finally, we fix the lensing amplitude and growth-rate parameters to their Λ CDM values and simultaneously estimate cosmological and systematics parameters.

In some of these analyses, we perform joint fits to both the galaxy-CMB lensing cross-correlations and galaxy clustering measurements in order to break degeneracies with galaxy bias.

The measurements presented in this study are part of the joint analysis which also involves galaxy clustering, galaxy-galaxy lensing and cosmic shear measurements presented in [42] and also galaxy weak lensing-CMB weak lensing correlation presented in [43]. The methods that will be used to combine these data sets are described in [44], and the results are presented in [45].

This paper is structured as follows. We first review in Sec. II the theoretical foundations of CMB lensing and galaxy clustering; we then describe the DES, SPT and *Planck* data we use in Sec. III, and the analysis methods we follow in Sec. IV. The tests for possible systematics are described in Sec. V and the main results of this paper, together with their cosmological implications, are presented in Sec. VI. We finally conclude in Sec. VII.

¹ G16 cross-correlated galaxies with CMB lensing maps from SPT and *Planck* separately, whereas in this study, a lensing map derived from a combined temperature map presented in [40] is used.

II. THEORY

From the CMB lensing convergence κ_{CMB} and galaxy overdensity δ_g fields, one can construct the auto- and cross-angular power spectra, which can be written as a function of multipole ℓ using the Limber approximation² as:

$$C^{\delta_g^i \delta_g^i}(\ell) = \int d\chi \frac{q_{\delta_g^i}\left(\frac{\ell+\frac{1}{2}}{\chi}, \chi\right) q_{\delta_g^i}\left(\frac{\ell+\frac{1}{2}}{\chi}, \chi\right)}{\chi^2} P_{\text{NL}}\left(\frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\right) \quad (1)$$

$$C^{\delta_g^i \kappa_{\text{CMB}}}(\ell) = \int d\chi \frac{q_{\delta_g^i}\left(\frac{\ell+\frac{1}{2}}{\chi}, \chi\right) q_{\kappa_{\text{CMB}}}(\chi)}{\chi^2} P_{\text{NL}}\left(\frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\right), \quad (2)$$

where χ is the comoving distance to redshift z , $P_{\text{NL}}(k, z)$ is the non-linear matter power spectrum, and the galaxy and CMB lensing kernels are:

$$q_{\delta_g^i}(k, \chi) = b_g^i(k, z(\chi)) \frac{n_g^i(z(\chi))}{\bar{n}_g^i} \frac{dz}{d\chi}, \quad (3)$$

$$q_{\kappa_{\text{CMB}}}(\chi) = \frac{3H_0^2 \Omega_m}{2c^2} \frac{\chi}{a(\chi)} \frac{\chi^* - \chi}{\chi^*}. \quad (4)$$

Here $b_g^i(k, z)$ is the galaxy bias, $n_g^i(z)$ is the redshift distribution of the i -th galaxy sample with total density \bar{n}_g^i , a is the cosmological scale factor, and χ^* is the comoving distance to the horizon. We adopt a linear galaxy bias model (i.e. constant value for all values of k) with a single galaxy bias b^i parameter for each galaxy redshift bin. Following [46] and [44], we restrict the analysis to angular scales over which the linear bias approximation is accurate.

In order to be consistent with the filtering that has been applied to the CMB lensing maps (see §III B), we multiply $C^{\delta_g^i \kappa_{\text{CMB}}}(\ell)$ by the filter function, $F(\ell)$, given by

$$F(\ell) = \begin{cases} \exp(-\ell(\ell+1)/\ell_{\text{beam}}^2), & \text{for } 30 < \ell < 3000 \\ 0, & \text{otherwise,} \end{cases} \quad (5)$$

where $\ell_{\text{beam}} \equiv \sqrt{16 \ln 2} / \theta_{\text{FWHM}}$, and $\theta_{\text{FWHM}} = 5.4'$. The Gaussian filtering is equivalent to convolving the CMB lensing maps with a Gaussian beam of full width at half maximum θ_{FWHM} .

The harmonic-space expression above can be rewritten in position space by applying a Legendre transformation, yielding the two-point correlation functions between two fields a, b :

$$w^{ab}(\theta) = \sum_{\ell=0}^{\infty} \left(\frac{2\ell+1}{4\pi} \right) P_{\ell}(\cos \theta) C^{ab}(\ell) F(\ell), \quad (6)$$

² See [46] for a discussion regarding the validity of the Limber approximation in the DES multi-probe framework.

where $a, b \in \{\delta_g^i, \kappa_{\text{CMB}}\}$, P_{ℓ} are the Legendre polynomials, and the summation can be truncated to $\ell_{\text{max}} \sim 10^4$ for the angular scales of interest.

Following [46] and [44], we model potential biases in the estimation of the galaxy redshift distributions using a single additive bias parameter for each galaxy redshift bin. The galaxy $n(z)$ is modified via

$$n_{\text{g,unbiased}}^i(z) = n_g^i(z - \Delta_{z,g}^i), \quad (7)$$

where $\Delta_{z,g}^i$ is the bias parameter. The biased $n_g^i(z)$ is then propagated to the $C^{\delta_g^i \kappa_{\text{CMB}}}(\ell)$ as described above.

We calculate the power spectrum using the Boltzmann code CAMB³ [47, 48] with the Halofit extension to nonlinear scales [49, 50] and the [51] neutrino extension.

III. DATA

A. Galaxy Samples

Our analysis relies on data from first-year DES observations, which were taken between August 2013 and February 2014. The photometry and production of the science-grade ‘Gold’ catalog are described in [52]. The total footprint of Y1 observations with an exposure time > 90 seconds per filter and a valid photometric calibration covers more than 1800 deg², which is reduced to ~ 1500 deg² after masking for bright stars and other poor-quality regions, including the Large Magellanic Cloud.

For the galaxy sample in this work, we use the lens galaxy catalog from [42]. The large-scale clustering properties of these galaxies are described in detail in [53]. This galaxy catalog was generated using the REDMAGiC algorithm [54], which is designed to find red-sequence galaxies in photometric data. The resulting galaxy sample has a photometric redshift uncertainty of $\sigma_z/(1+z) \leq 2\%$, over the entire redshift range $0.15 < z < 0.90$ used in this analysis. We split this into 5 tomographic bins of width $\Delta z = 0.15$, as shown in Table I.

REDMAGiC produces luminosity-thresholded samples of constant comoving densities to avoid density variations that may lead to biases in clustering analyses. Therefore, setting the luminosity threshold high leads to a sample with lower overall output number density. Following [53], we use three different luminosity cuts ($L > 0.5L_*$, $L > 1.0L_*$, and $L > 1.5L_*$); using a lower luminosity threshold for the three low redshift bins allows for a higher number density in these redshift bins while the two higher redshift bins require a higher luminosity cut to produce a sample with uniform density across the footprint.

We estimate the redshift distributions of our galaxy samples by assuming a Gaussian redshift probability distribution function (PDF) for each object given the best-fit values for the

³ See `camb.info`.

LUMINOSITY	REDSHIFT RANGE	\bar{n}_g^i
$L > 0.5L_*$	0.15 – 0.30	61,913
	0.30 – 0.45	158,616
	0.45 – 0.60	234,204
$L > 1.0L_*$	0.60 – 0.75	139,707
$L > 1.5L_*$	0.75 – 0.90	41,270
TOTAL	0.15 – 0.90	635,710

TABLE I. Summary statistics of the DES red-sequence galaxy samples (REDMAGiC) used throughout this paper. The effective sky area covered by these samples is 1289 deg².

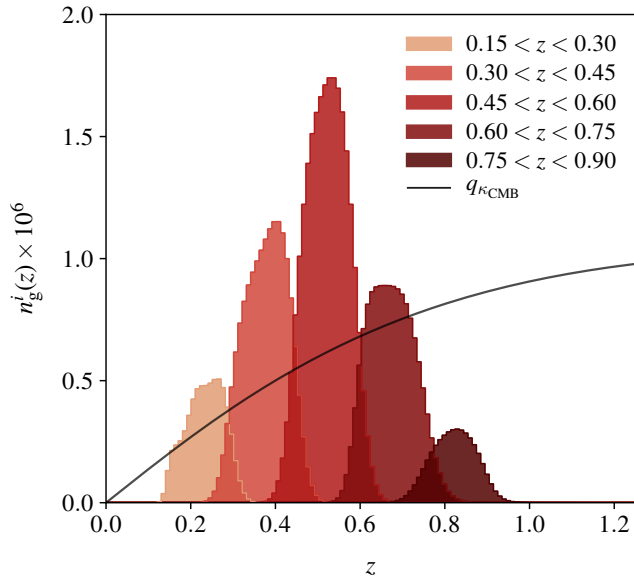


FIG. 1. Estimated redshift distribution of the REDMAGiC sample for the 5 tomographic bins used in this analysis. These are obtained by stacking Gaussian PDFs with mean equal to the REDMAGiC redshift prediction and standard deviation equal to the resulting redshift error. Each distribution is normalized to give the total number of galaxies in each bin. The CMB lensing efficiency $q_{\kappa_{\text{CMB}}}$ is shown in black for comparison.

redshift and associated error produced by the REDMAGiC algorithm. We then obtain an overall estimate of the $n_g^i(z)$ of the samples by stacking these Gaussian probability distribution functions. We show the derived redshift distributions in Fig. 1, from which it can be seen that the number of galaxies increases with redshift at low redshift because of the increasing volume, and decreases thereafter due to the brighter luminosity cuts imposed.

As done in [53], the galaxy mask is constructed from the REDMAGiC galaxy catalog over the SPT contiguous region by excluding areas outside the survey footprint, bad quality regions, and pixels with an observed coverage fraction smaller than 80%. For the pixels with coverage fraction above this threshold, we assign to each mask pixel i its coverage fraction f_i , and use this value as a weight in the clustering measurements that follow. In order to ensure the uniformity of the galaxy samples, we only use the fraction of the sky where

the $L = 0.5 (1.0, 1.5) L_*$ galaxy sample is complete up to $z = 0.6 (0.75, 0.90)$. We multiply this mask with the κ_{CMB} mask, which results in a combined mask with an effective area of 1289 deg².

B. CMB lensing maps

The CMB weak lensing map used in this analysis is described by [15], and we give a brief description here. The lensing map is derived from an inverse variance weighted combination of SPT 150 GHz and Planck 143 GHz temperature data over the SPT-SZ survey region (20^h to 7^h in right ascension and from -65° to -40° in declination, see, e.g. [55]).

Modes in this combined temperature map with $\ell < 100$ and $\ell > 3000$ are removed to avoid foreground contamination. Point sources in the flux density range $50 < F_{150} < 500$ mJy ($F_{150} > 500$ mJy) in the 150 GHz band are masked with an aperture of radius $6'$ ($9'$), while sources in the flux density range $6.4 < F_{150} < 50$ mJy are inpainted – the objects are masked and filled in with fluctuations similar to the CMB plus noise. Clusters from the SPT-detected sample of [56] with detection significance $S/N > 6$ are also masked with an aperture of $r = 5'$. The quadratic estimator technique [5] is then applied to the combined temperature map to reconstruct a filtered lensing map. Simulations are then used to debias and renormalise the amplitude of the lensing map. In constructing the lensing map, we use the lensing multipole range of $30 < \ell < 3000$ and apply a Gaussian smoothing of $\theta_{\text{FWHM}} = 5.4'$ to the map. The low-pass filter is applied to suppress foreground contamination, while the high-pass filter is applied to remove modes we measure poorly in the data. When calculating the correlation functions, we apply an additional stricter mask that removes all the clusters with detection significance > 5 listed in [56] and DES REDMAPPER clusters with richness $\lambda > 80$ as well as point sources with flux density range $6.4 < F_{150} < 50$ mJy (which were inpainted prior to the reconstruction), in addition to that mask that was applied prior to the lensing reconstruction step.

By masking massive clusters in the CMB lensing map, we remove regions of high contamination by the tSZ effect [57]. However, we also induce a secondary bias due to masking regions of high lensing convergence. It was shown in [44] that this secondary bias is small compared to other systematic effects such as tSZ.

IV. METHODS

We measure the clustering of the galaxies and their correlations with the CMB lensing maps in position-space. Note that we take an approach slightly different from G16 here, and no smoothing is applied to the galaxy density maps. This smoothing only needs to be applied to the CMB lensing map in order to cut off the high level of noise that would otherwise leak from the high multipoles down to larger scales when transforming from harmonic to position-space. The same smoothing was applied also to the galaxy overdensity

maps in G16 for consistency, but this had the unwanted consequence of then spreading the shot-noise contribution (which in position-space is normally confined to the zero-separation bin) out to larger angular separations, thus requiring a more complex modelling (see Appendix B of G16).

A. Correlation function

We measure both the auto-correlation of the galaxy density field and the cross-correlation between galaxies and κ_{CMB} . The former is calculated using the Landy-Szalay estimator [58]:

$$w^{\delta_g \delta_g}(\theta_\alpha) = \frac{DD(\theta_\alpha) - 2DR(\theta_\alpha) + RR(\theta_\alpha)}{RR(\theta_\alpha)}, \quad (8)$$

with

$$DD(\theta_\alpha) = \frac{1}{N_{\theta_\alpha}^{DD}} \sum_{i=1}^{N_{\text{gal}}} \sum_{j=1}^{N_{\text{gal}}} \eta_i^D \eta_j^D \Theta_\alpha(\hat{\theta}^i - \hat{\theta}^j), \quad (9)$$

$$DR(\theta_\alpha) = \frac{1}{N_{\theta_\alpha}^{DR}} \sum_{i=1}^{N_{\text{gal}}} \sum_{j=1}^{N_{\text{rand}}} \eta_i^D \eta_j^R \Theta_\alpha(\hat{\theta}^i - \hat{\theta}^j), \quad (10)$$

$$RR(\theta_\alpha) = \frac{1}{N_{\theta_\alpha}^{RR}} \sum_{i=1}^{N_{\text{rand}}} \sum_{j=1}^{N_{\text{rand}}} \eta_i^R \eta_j^R \Theta_\alpha(\hat{\theta}^i - \hat{\theta}^j), \quad (11)$$

where η^D are the weights for the individual galaxies determined from cross-correlation with systematic maps (for randoms $\eta^R = 1$, see [53] for further details), N_θ are the total number of pairs of a given type [data-data (DD), data-random (DR), random-random (RR)] in a given angular bin θ_α , and $\Theta_\alpha(\hat{\theta}^i - \hat{\theta}^j)$ is 1 if a pair lies at an angular distance θ within the angular bin α and 0 otherwise. Random galaxies are generated uniformly over the union of the galaxy and κ_{CMB} masks, and are included in the random catalog with probabilities matching the weight f_i at the pixel which the random galaxies fall onto.⁴

For the correlation function between a galaxy catalog and a pixellated map such as the CMB lensing convergence map, the correlation function is calculated using:

$$w^{\delta_g \kappa_{\text{CMB}}}(\theta_\alpha) = D\kappa_{\text{CMB}}(\theta_\alpha) - R\kappa_{\text{CMB}}(\theta_\alpha), \quad (12)$$

with

$$D\kappa_{\text{CMB}}(\theta_\alpha) = \frac{1}{N_{\theta_\alpha}^{D\kappa_{\text{CMB}}}} \sum_{i=1}^{N_{\text{gal}}} \sum_{j=1}^{N_{\text{pix}}} \eta_i^D \eta_j^{\kappa_{\text{CMB}}} \kappa_{\text{CMB},j} \Theta_\alpha(\hat{\theta}^i - \hat{\theta}^j), \quad (13)$$

$$R\kappa_{\text{CMB}}(\theta_\alpha) = \frac{1}{N_{\theta_\alpha}^{R\kappa_{\text{CMB}}}} \sum_{i=1}^{N_{\text{rand}}} \sum_{j=1}^{N_{\text{pix}}} \eta_i^R \eta_j^{\kappa_{\text{CMB}}} \kappa_{\text{CMB},j} \Theta_\alpha(\hat{\theta}^i - \hat{\theta}^j), \quad (14)$$

where $\eta_j^{\kappa_{\text{CMB}}}$ is the value of the mask, and $\kappa_{\text{CMB},j}$ is the value of convergence at the j -th pixel.⁵ In measuring the auto-correlation of galaxy density, we use 20 bins equally spaced in logarithm between $2.5' < \theta < 250'$; these angular bins are consistent with those of [53]. For $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$, we use 10 equally log-spaced angular bins over the same angular range due to the higher noise levels of this measurement. The measurements in both cases are carried out using the TREECORR package.⁶

Unlike G16, we do not perform a harmonic analysis in this paper since the other DES-Y1 two-point analyses are all conducted in position-space, and our goal is to combine our measurements with those. We note that $C(\ell)$ estimators allow one to get a complementary understanding of systematics to those affecting the position-space estimators and are expected to yield consistent results in terms of significance of the cross-correlation signal and corresponding cosmological implications (as discussed in detail in G16).

B. Angular scale cuts

Our model for the correlation functions ignores several potential complications, such as the effects of tSZ bias in the CMB lensing map, the effects of non-linear galaxy bias, and the effects of baryons on the matter power spectrum. In order to minimize biases to the inferred cosmological parameters in our analysis, we remove measurements at angular scales that we expect to be significantly impacted by these effects.

The choices of these angular scale cuts employed here were motivated for the analyses of $w^{\delta_g \delta_g}(\theta)$ and $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ in [46] and [44]. The scale cuts were determined by introducing unmodeled effects into simulated data vectors and performing simulated likelihood analyses to infer parameter biases. The scale cuts ultimately chosen in [46] and [44] were determined based on the joint analysis of two-point functions between the galaxy density, galaxy lensing and CMB lensing. Since the analysis of a single correlation function — such as $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ — will necessarily be less constraining, by adopting these scale cuts in this analysis we are being conservative. It was shown in [44] that with these scale cuts, the bias on the cosmological parameter constraints will be less than 0.4σ , where σ represents the statistical uncertainty on the parameters.

The scale cut choices motivated by [46] and [44] result in removing from the galaxy-CMB lensing cross-correlations angular scales that are smaller than

$$\theta_{\text{min}}^{\delta_g \kappa_{\text{CMB}}} = [15', 25', 25', 15', 15'] \quad (15)$$

for the five redshift bins. The corresponding scale cuts for the galaxy auto-correlations are [53]

$$\theta_{\text{min}}^{\delta_g \delta_g} = [45', 25', 25', 15', 15']. \quad (16)$$

⁴ Here, we only consider the weights coming from the *galaxy* mask, although both the galaxy and κ_{CMB} masks are used to determine the valid pixels.

⁵ Here, we only consider the weights coming from the κ_{CMB} mask, although both the galaxy and κ_{CMB} masks are used to determine the valid pixels.

⁶ <https://github.com/rmjarvis/TreeCorr>

C. Covariance matrix

It was shown by G16 that several covariance matrix estimators (including a Gaussian analytic covariance in harmonic-space) yield consistent results for the galaxy-CMB lensing correlation. Based on this comparison and the analysis of [46], we decided to use an analytic covariance estimate described in [46], but extended to include CMB lensing cross-correlations as described by [44]. Briefly, this estimator is a sum of Gaussian covariance and non-Gaussian terms based on a halo-model approach (which includes the trispectrum term and the super-sample covariance). We additionally modify the term of this covariance that involves correlations between κ_{CMB} noise and δ_{g} noise, to take into account the survey geometry. This is done by replacing the analytic noise-noise covariance (which is calculated based on the galaxy number density and survey area only) with the covariance calculated from correlating Gaussian realizations of the κ_{CMB} map and the galaxy random catalog using the survey mask. This correction increases the diagonal elements of the analytic covariance by $\sim 10\%$ for $w^{\delta_{\text{g}}\kappa_{\text{CMB}}}(\theta)$. We compare this theoretical covariance estimate to a data-based jackknife estimate of the covariance in Appendix A.

D. Parameter constraints

The cross-correlation between galaxy density and the CMB convergence map contains cosmological information. To extract this information, we assume that the likelihood of the measured data vector \vec{d} given a model \vec{m} , is Gaussian:

$$\ln \mathcal{L}(\vec{d}|\vec{m}(\vec{p})) = -\frac{1}{2} \sum_{ij}^N (d_i - m_i(\vec{p})) \mathbf{C}_{ij}^{-1} (d_j - m_j(\vec{p})), \quad (17)$$

where N is the number of points in the data and model vectors. The posteriors on the model parameters are given by:

$$P(\vec{m}(\vec{p})|\vec{d}) \propto \mathcal{L}(\vec{d}|\vec{m}(\vec{p})) P_{\text{prior}}(\vec{p}), \quad (18)$$

where $P_{\text{prior}}(\vec{p})$ is the prior on the model parameters.

1. Galaxy bias and lensing amplitude constraints

Assuming the cosmological model is tightly constrained, joint measurement of $w^{\delta_{\text{g}}\kappa_{\text{CMB}}}(\theta)$ and $w^{\delta_{\text{g}}\delta_{\text{g}}}(\theta)$ allows us to simultaneously constrain galaxy bias, b , and an overall multiplicative bias in the κ_{CMB} map, which we call A_{κ} . This is possible because the amplitude of the galaxy-CMB lensing cross-correlation scales with bA_{κ} , while the amplitude of the galaxy clustering correlation function scales with b^2 .

We consider two scenarios along these lines while fixing the cosmological model to the fiducial model introduced in Sec. I. In the first scenario we fix $A_{\kappa} = 1$ and constrain the galaxy bias in each redshift bin while marginalizing over the photo- z uncertainties. The second scenario is identical to the first, but we let A_{κ} be free. In both cases we adopt the priors on systematics parameters presented in Table II.

2. Growth function

We use the measured correlation functions to constrain the cosmological growth function using two different methods. For both of these methods we assume $A_{\kappa} = 1$.

The first approach is the procedure introduced in G16 (also applied in [59]), which we compute here to compare with that analysis. For this method, we fix all the cosmological and nuisance parameters to the fiducial values listed in Table II. We define the growth-removed auto- and cross-spectra, indicated with a slashed symbol, via:

$$\mathcal{C}^{\delta_{\text{g}}\delta_{\text{g}}}(\ell) = \int d\chi \frac{q_{\delta_{\text{g}}}^i\left(\frac{\ell+\frac{1}{2}}{\chi}, \chi\right) q_{\delta_{\text{g}}}^i\left(\frac{\ell+\frac{1}{2}}{\chi}, \chi\right)}{\chi^2 D^2[z(\chi)]} P_{\text{NL}}\left(\frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\right) \quad (19)$$

$$\mathcal{C}^{\delta_{\text{g}}\kappa_{\text{CMB}}}(\ell) = \int d\chi \frac{q_{\delta_{\text{g}}}^i\left(\frac{\ell+\frac{1}{2}}{\chi}, \chi\right) q_{\kappa_{\text{CMB}}}(\chi)}{\chi^2 D^2[z(\chi)]} P_{\text{NL}}\left(\frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\right), \quad (20)$$

where $D(z)$ is the linear growth function. The angular power spectra are then transformed into $w(\theta)$ using Eq. 6, and our growth estimator is given by the ratio between⁷ the observed and theoretical slashed correlation functions, averaged over a range of angular scales $[\theta_{D_{\text{G}}}^{\min}, \theta_{D_{\text{G}}}^{\max}]$:

$$D_{\text{G}} = \left\langle \frac{w_{\text{observed}}^{\delta_{\text{g}}\kappa_{\text{CMB}}}(\theta)}{w_{\text{theoretical}}^{\delta_{\text{g}}\kappa_{\text{CMB}}}(\theta)} \sqrt{\frac{w_{\text{theoretical}}^{\delta_{\text{g}}\delta_{\text{g}}}(\theta)}{w_{\text{observed}}^{\delta_{\text{g}}\delta_{\text{g}}}(\theta)}} \right\rangle_{\theta_{D_{\text{G}}}^{\min} < \theta < \theta_{D_{\text{G}}}^{\max}}. \quad (21)$$

We measure this quantity for the five tomographic bins, which allows us to measure the evolution of the growth function in redshift bins (i.e. $D_{\text{G}}(z_i)$). The advantage of this estimator is that the measured quantity is independent of galaxy bias since bias is canceled out by taking the ratio. Due to the filtering that removes $\ell < 30$ in the κ_{CMB} map, the fiducial model $w_{\text{theoretical}}^{\delta_{\text{g}}\kappa_{\text{CMB}}}(\theta)$ reaches zero near $\theta = 100'$, so we restrict our measurements to scales $\theta < \theta_{D_{\text{G}}}^{\max} = 100'$. For $\theta_{D_{\text{G}}}^{\min}$, we conservatively choose the larger scale between the auto- and cross-correlation scale cuts of Sec. IV B for each redshift bin.

In order to test for possible deviations from the baseline Λ CDM model across the five redshift bins, we assume the shape of the linear growth function $D(z)$ to be fixed by the fiducial cosmology, and we fit for a redshift-independent quantity A_{D} such that it minimizes:

$$\chi^2 = \sum_{ij}^5 (D_{\text{obs}}(z_i) - A_{\text{D}} D_{\text{fid}}(z_i)) \mathbf{C}_{ij}^{-1} (D_{\text{obs}}(z_j) - A_{\text{D}} D_{\text{fid}}(z_j)), \quad (22)$$

with $D_{\text{obs}}(z_i) \equiv D_{\text{G}}$ for this method. We take 50,000 multivariate Gaussian draws from the analytical covariance matrix

⁷ This ratio only works in the limit when the redshift slices are narrow.

to produce simulated $w^{\delta_g \delta_g}(\theta)$ and $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ data vectors, calculate $D(z)$ for each draw, and compute the covariance matrix C_{ij} over the ensemble of realizations.

The second method for measuring the growth function consists of simultaneously fitting A_{D} , galaxy bias, and photo- z bias to the observed auto- and cross-correlations using an Markov chain Monte Carlo (MCMC) approach. This method has an advantage of allowing us to vary over other systematic effects, such as photo- z errors. For this method, we fix the cosmological parameters to the fiducial values in Table II but vary the growth amplitude, galaxy biases and lens photo- z biases over the priors given in the same table.

3. Cosmological parameter estimation

Finally, we use the measurements of both $w^{\delta_g \kappa_{\text{CMB}}}$ and $w^{\delta_g \delta_g}$ presented in this work to constrain cosmological parameters. We generate posterior samples using the MULTINEST algorithm [60] as implemented in the CosmoSIS [61] package. We let the photo- z bias (i.e. lens $n(z)$ shift), galaxy bias and 6 cosmological parameters (Ω_{m} , A_{s} , n_{s} , Ω_{b} , h , Ω_{ν}) vary simultaneously, while we fix $A_{\kappa} = A_{\text{D}} = 1$. Here, A_{s} is the amplitude of the matter power spectrum, n_{s} is the spectral index, Ω_{b} is the baryon density, h is the unitless Hubble constant and Ω_{ν} is the neutrino density. Priors on these parameters are summarized in Table II. In this study we will focus on the constraints on Ω_{m} and $S_8 \equiv \sigma_8 \sqrt{\Omega_{\text{m}}/0.3}$, where σ_8 is the RMS amplitude of mass fluctuations on $8h^{-1}$ Mpc scale. S_8 is defined to be approximately the most constrained cosmological parameter combination for galaxy weak lensing measurements.

E. Blinding

This analysis was blinded throughout the study using a combination of various blinding schemes. First, the analysis pipeline was built using FLASK simulations and the paper was originally written assuming these data vectors. We then switched to a scheme where we multiplied the CMB lensing map by an unknown factor in the range between 0.8 and 1.2, and shifted the cosmological parameter constraints that we obtained by an arbitrary number and removed the axes when generating figures. After the data passed all systematic checks, the measurements were repeated using a CMB lensing map without the random factor applied, and the cosmological parameter constraints were calculated without shifts.

V. SYSTEMATIC ERROR ANALYSIS

Systematic errors can impact the relationship between the measured and predicted correlation functions in three ways: (1) by affecting the observed density of galaxies on the sky, (2) by affecting the CMB lensing map, and (3) by affecting the inferred redshift distributions of the galaxies. Systematics affecting the observed density of DES REDMAG1C galaxies were explored by [53] as part of the [42] analysis. The main

PARAMETER	FIDUCIAL	PRIOR
COSMOLOGY		
Ω_{m}	0.309	[0.1, 0.9]
$A_{\text{s}}/10^{-9}$	2.14	[0.5, 5.0]
n_{s}	0.967	[0.87, 1.07]
w	-1.0	FIXED
Ω_{b}	0.0486	[0.03, 0.07]
h_0	0.677	[0.55, 0.91]
$\Omega_{\nu} h^2$	6.45×10^{-4}	[0.0006, 0.01]
Ω_{κ}	0	FIXED
τ	0.066	FIXED
GROWTH AMPLITUDE		
A_{D}	1.0	[0.1, 4.0]
LENSING AMPLITUDE		
A_{κ}	1.0	[0.1, 4]
GALAXY BIAS		
b^i	1.45, 1.55, 1.65, 1.8, 2.0	[0.8, 3.0]
LENS PHOTO- z ERROR		
$\Delta_{z,g}^1$	0.010	(0.008, 0.007)
$\Delta_{z,g}^2$	-0.004	(-0.005, 0.007)
$\Delta_{z,g}^3$	0.009	(0.006, 0.006)
$\Delta_{z,g}^4$	0.001	(0.0, 0.01)
$\Delta_{z,g}^5$	0.0	(0.0, 0.01)

TABLE II. The fiducial parameter values and priors for cosmological and nuisance parameters used in this analysis. Square brackets denote a flat prior over the indicated range, while parentheses denote a Gaussian prior of the form $\mathcal{N}(\mu, \sigma)$. The Gaussian priors on photo- z errors are determined by [62]. The fiducial cosmological parameter values are taken from the [41], but here we assume 3 massive neutrinos to stay consistent with other DES-Y1 analyses. For the photo- z bias, peaks of the posterior distributions in the DES joint galaxy clustering and lensing analysis [42] are used as fiducial values.

source of systematic error impacting the CMB lensing map is contamination by the tSZ effect which has been discussed and modeled in [44]. Systematic errors in the photometric redshift distributions of REDMAG1C galaxies were explored by [62], also as part of the [42] analysis. Below, we draw heavily from these companion papers to constrain the systematic contamination of the measured correlation functions.

A. Galaxy density and CMB lensing biases

We first consider systematics impacting galaxy density and the CMB lensing map. It is useful to divide these systematics into two categories: those that produce a bias that is uncorrelated with the true density fluctuations, and those that produce a bias that is correlated with them. For those systematic biases that are uncorrelated with the true density fluctuations, in order to generate a bias in $w^{\delta_g \kappa_{\text{CMB}}}$, the systematic must contaminate *both* the galaxy density and κ_{CMB} ; if it only impacts one of these observables, its impact on the correlation function should average to zero. One of the strengths of cross-correlation measurements such as $w^{\delta_g \kappa_{\text{CMB}}}$ is that there are not many systematics that could contaminate both of the observed fields. However, there are some potential sources of bias that

could do this. One example is dust, which is one of the foreground components of the CMB temperature measurements, and one can expect potential residuals in a single-frequency temperature map that can then propagate into the CMB lensing map. Dust also affects the photometry of the observed galaxies and is correlated with galactic latitude. This contamination can then induce density fluctuations through the change of mean density with latitude. Consequently, dust extinction may contaminate simultaneously galaxy density and CMB lensing, and could therefore contaminate measurement of $w^{\delta_g \kappa_{\text{CMB}}}$. In what follows we will consider dust extinction and stellar density maps as potential contaminants.

On the other hand, there are some sources of contamination which *are* correlated with the true density fluctuations. In this case, the contaminant needs not affect both galaxy density and CMB lensing in order to bias $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$. At ~ 150 GHz (roughly the frequencies of the SPT and *Planck* maps used to generate the CMB lensing map), the tSZ effect results in a decrement in the observed CMB temperature around clusters. This non-Gaussian feature gets picked up as a false lensing signal by the quadratic estimator. Since hot gas is correlated with galaxies, we expect the tSZ effect to induce a bias in the measured correlation functions. The CIB, which is dominated by emission from dusty star forming galaxies, is another extragalactic foreground that injects non-Gaussian features in our temperature maps. While the CIB emission spectrum peaks at a higher frequency, minor correlations with 150 GHz observations are expected, which again lead to false lensing signal. Since both the CIB and tSZ originate from large-scale structure, we expect them to introduce biases in κ_{CMB} that are correlated with density fluctuations. Maps for both tSZ and CIB contamination are built and described in detail by [44]. That work also identified the tSZ effect as the dominant source of systematic affecting the cross-correlation measurement between κ_{CMB} and δ_g . While the angular scale cuts proposed by [44] and restated in Sec. IV B are chosen to mitigate these biases, they do not remove them entirely, and the residuals must be quantified.

Of all the systematic effects that could potentially be present in our maps and catalogs, only the ones which are correlated with *both* the observed CMB lensing map and the galaxy catalog affect our cross-correlation measurements. We can therefore measure the quantity:

$$\frac{w^{\kappa_{\text{CMB}}^{\text{obs}}} S(\theta) w^{\delta_g^{\text{obs}}} S(\theta)}{w^{\text{SS}}(\theta)} \quad (23)$$

to quantify the amplitude of the bias (to first order), which we expect to be zero for systematic maps that are not correlated with both the CMB lensing map and galaxy catalogs. However for astrophysical systematic effects such as tSZ and CIB which could potentially be contaminating the CMB temperature map, physical correlations with $\kappa_{\text{CMB}}^{\text{true}}$ are expected, and therefore Equation 23 is not expected to equal 0. Therefore, for these systematic effects, we directly measure the correlations $w^{\delta_g \kappa_{\text{SZ}}}(\theta)$ and $w^{\delta_g \kappa_{\text{CIB}}}(\theta)$ to quantify the bias. As described in more detail in [44], we estimate κ_{SZ} by passing a template tSZ map through the lensing pipeline of [15]; similarly, κ_{CIB} is estimated by passing a 545 GHz CIB map [63] through the

[15] lensing pipeline.

We first focus on those systematics that are uncorrelated with the true density. We show in the top half of Fig. 2 the ratio between $w^{\kappa_{\text{CMB}}^{\text{obs}}} S(\theta) w^{\delta_g^{\text{obs}}} S(\theta) / w^{\text{SS}}(\theta)$ measured for dust extinction and stellar contamination, and the uncertainty on the measured galaxy density-CMB lensing correlation and verify that this ratio is significantly smaller than 1 and consistent with 0 across all angular scales. We can see that the impact on the measurements is generally small compared with the statistical error bars, so that we can conclude there is no evidence for any of these contaminants making a significant impact on our results.

We then consider the correlated sources of systematics: tSZ and CIB, and we show their contributions to Eq. 23 in the bottom half of Fig. 2. Here we indeed see non-zero residuals coming from tSZ but most of this bias is removed by applying our default scale cuts, and the remaining bias is within 0.35σ , where σ is the statistical uncertainty.

We note that [53] investigated the impact of several observational systematics in addition to dust extinction and stellar density that could introduce spurious fluctuations in redMAGiC galaxy number density on large-scales. Using a set of 20 survey property maps,⁸ in addition to stellar contamination and galactic extinction, they studied the dependence of number density as a function of these observational properties. The results of these tests indicated that redMAGiC galaxies were not largely impacted by these systematics. Furthermore, as mentioned above, since we do not expect the DES-specific survey systematics (exposure time, sky brightness, airmass, seeing, survey depth variations) to correlate with κ_{CMB} , we do not expect these to bias $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$.

B. Photo- z systematics

Unlike biases in the galaxy density or CMB lensing maps, we explicitly model biases in the estimated redshift distributions of the galaxies as described in Sec. II.

The [42] analysis constrained biases in the inferred redshift distributions of the redMAGiC galaxies using angular cross-correlations with spectroscopic data from the Sloan Digital Sky Survey (DR8), particularly BOSS luminous red galaxies. This analysis is presented in [62]. These resultant priors on the photo- z bias parameters $\Delta_{z,g}^i$ for the five redshift bins are listed in Table II. We let these values vary when calculating the growth amplitude and cosmological parameter constraints in Sec. VI B 2 and VI C.

VI. RESULTS

We show in Fig. 3 the measured auto-correlation functions of the redMAGiC galaxy sample and its cross-correlation with

⁸ These were exposure time, sky brightness, airmass, seeing and survey 10 σ depth, in four different broad bands.

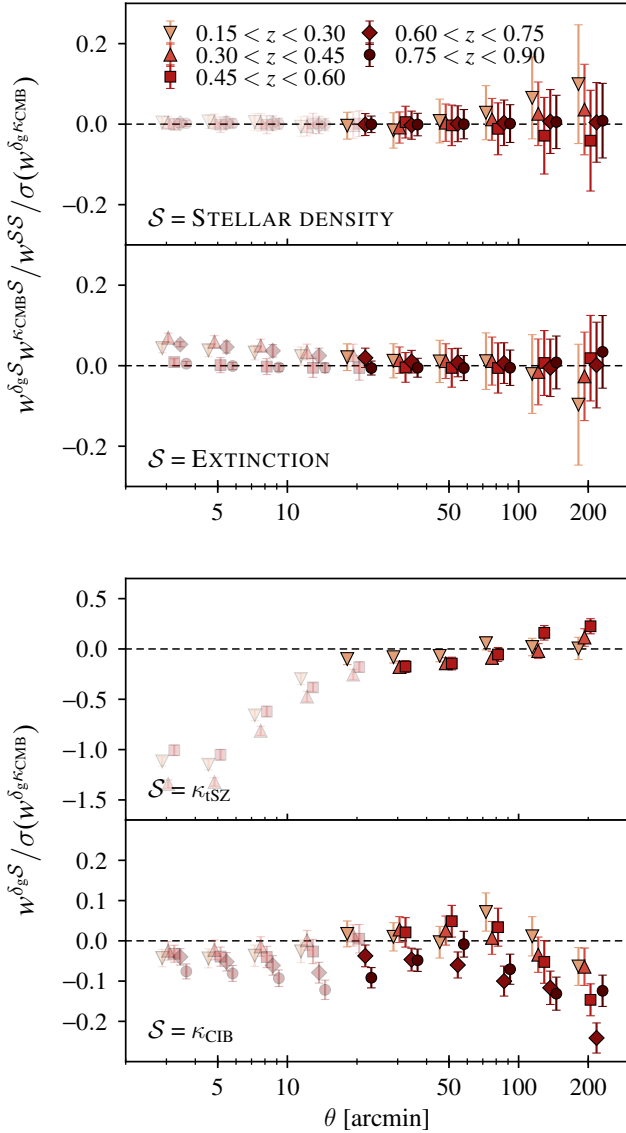


FIG. 2. Top two panels: Contributions due to uncorrelated systematics to the galaxy-CMB lensing cross-correlations, as described by Eq. 23, in units of the statistical errors on the observed cross-correlation. Lower two panels: Contributions due to correlated systematics, given by the cross-correlations between the κ_{CMB} systematics (κ_{tSZ} and κ_{CIB}) and δ_{g} , also in units of the statistical error. We observe that within the angular scales we consider the ratios are < 1 for all redshift bins for all systematic maps (the faded points are removed from the analysis due to the imposed scale cuts). Since the tSZ template is generated only using REDMAPPER clusters up to $z = 0.6$, the correlations for the higher two redshift bins have been ignored (see [44]). Note the different scales used for κ_{tSZ} and κ_{CIB} .

the SPT+*Planck* CMB lensing map. The small-scale data points shown with faded symbols are the scales removed by the scale cuts as discussed in Sec. IV B. The theoretical predictions assuming the fiducial cosmology listed in Table II are shown as the black lines. In the following sections we extract cosmological information using these measurements.

We note that we made few modifications in Sec. VIA and VIB after we unblinded the data. We first added constraints on the galaxy bias from $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$ alone with the cosmology fixed to *Planck* best-fit values (instead of DES-Y1). The motivation for this was to allow us to directly compare the constraints on galaxy bias when varying over the cosmological parameters, but combining with the *Planck* baseline likelihood. Accordingly, we also changed the assumed cosmology when computing the best-fit biases from $w^{\delta_{\text{g}}^{\delta_{\text{g}}}}(\theta) + w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$. Additionally, we recomputed the galaxy biases inferred from galaxy clustering and galaxy-galaxy lensing using the same data vectors but combined with *Planck* baseline likelihood.

A. Galaxy bias and lensing amplitude

We first fix the cosmological parameters to the fiducial values and vary the galaxy bias and lens photo- z error parameters simultaneously, imposing the priors shown in Table II. We focus on constraining galaxy bias, assuming a fixed lensing amplitude of $A_{\kappa} = 1$. When using both $w^{\delta_{\text{g}}^{\delta_{\text{g}}}}(\theta)$ and $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$, we obtain $b^1 = 1.47^{+0.08}_{-0.08}$, $b^2 = 1.67^{+0.06}_{-0.04}$, $b^3 = 1.68^{+0.04}_{-0.04}$, $b^4 = 2.03^{+0.04}_{-0.05}$, and $b^5 = 2.14^{+0.05}_{-0.08}$, with $\chi^2 = 107.3$ for 82 data points. The high value of χ^2 is primarily driven by the galaxy clustering measurements (see [53]).

When we additionally treat the CMB lensing amplitude A_{κ} as a free parameter, we obtain $b^1 = 1.46^{+0.09}_{-0.07}$, $b^2 = 1.68^{+0.06}_{-0.05}$, $b^3 = 1.68^{+0.04}_{-0.04}$, $b^4 = 2.02^{+0.05}_{-0.04}$, $b^5 = 2.12^{+0.08}_{-0.06}$. The recovered posterior on the lensing amplitude is $A_{\kappa} = 1.00^{+0.16}_{-0.09}$, with a total $\chi^2 = 107.2$. The similarity between the constraints on the galaxy bias values that we obtain with A_{κ} fixed to 1 and free suggests that the galaxy bias constraints in this analysis are dominated by $w^{\delta_{\text{g}}^{\delta_{\text{g}}}}(\theta)$. These results are summarized in Table III.

Next, we consider constraints on galaxy bias from $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$ alone. We reject the hypothesis of no lensing with a significance⁹ of 19.9σ when no scale cuts are imposed and 9.9σ after imposing scale cuts. The constraints on galaxy bias from this analysis are summarized in Table IV. Not surprisingly, the constraints on galaxy bias from $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$ alone are significantly weaker than in the case when the measurements are combined with $w^{\delta_{\text{g}}^{\delta_{\text{g}}}}(\theta)$. Similar constraints on galaxy biases are obtained when cosmological parameters are varied, but cosmological priors from *Planck* baseline likelihood are imposed (right column of Table IV).

The bias constraints from $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$, as well as those from the DES-Y1 galaxy clustering [53] and galaxy-galaxy lensing analyses [64] when combined with *Planck* baseline likelihood are shown in Fig. 4. We find that considerably tighter constraints can be obtained from $w^{\delta_{\text{g}}^{\delta_{\text{g}}}}(\theta)$ relative to $w^{\delta_{\text{g}}^{\gamma_i}}(\theta)$ and $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$. The constraining power of $w^{\delta_{\text{g}}^{\kappa_{\text{CMB}}}}(\theta)$ relative to $w^{\delta_{\text{g}}^{\gamma_i}}(\theta)$ increases with higher redshift galaxy samples. This

⁹ The significance is calculated using $\sqrt{\chi^2_{\text{null}}}$, where χ^2_{null} is the value of χ^2 computed under the null model, i.e. with galaxy bias $b = 0$.

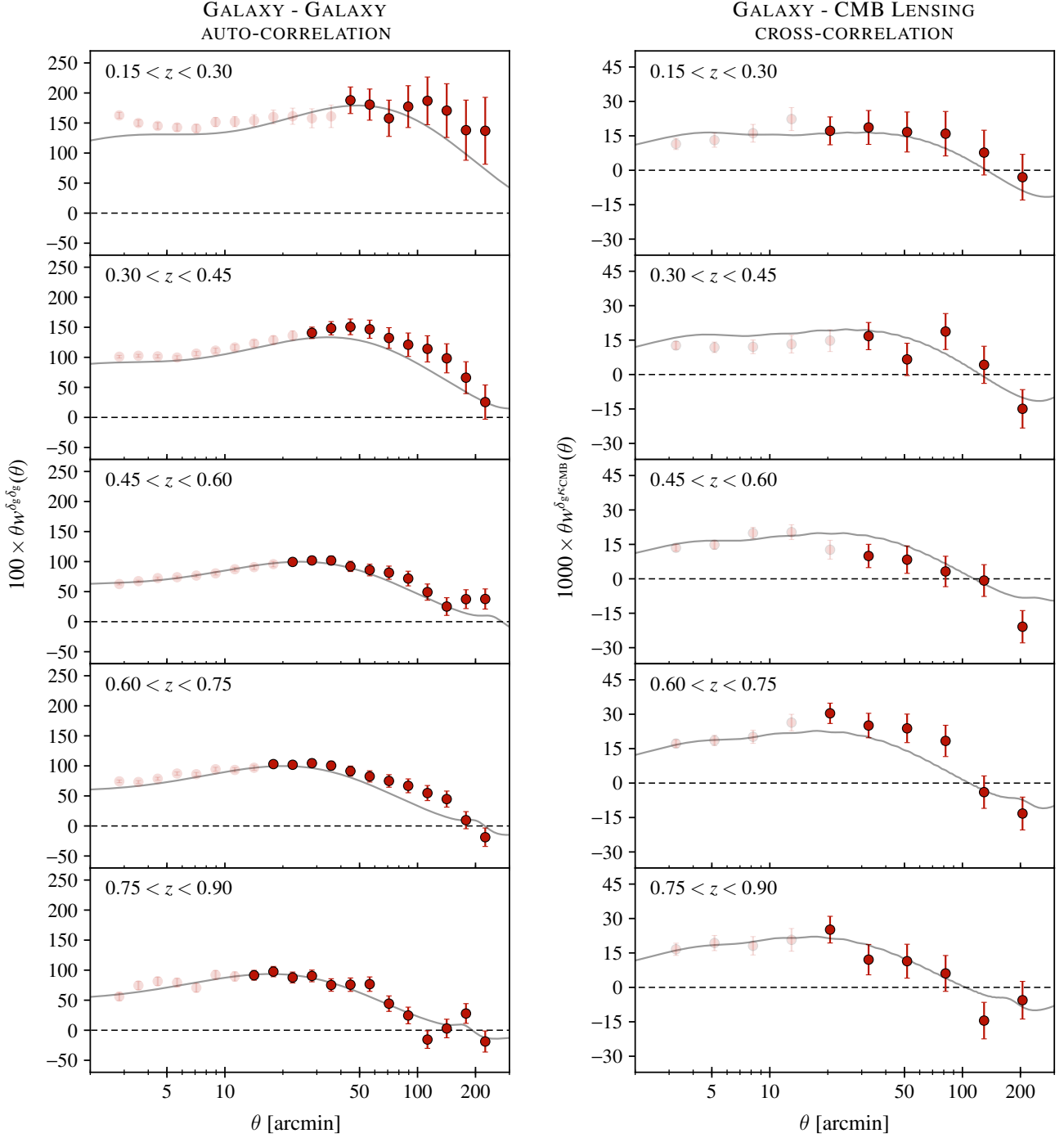


FIG. 3. Measured auto- and cross-correlation functions between the `redMAGiC` galaxy sample described in Sec. III A and CMB lensing from [15]. The faint angular bins have been excluded from the fits, consistently with [53] and with [44]. The theory modeling shown uses the mean bias and cross-correlations amplitudes found in Sec. VI and Table III, assuming the fiducial cosmology listed in Table II. The error bars shown are the diagonal elements of the covariance matrix $\sqrt{C_{ii}}$, and therefore, the correlations between the bins are ignored. In contrast, the best-fit amplitudes are calculated including the off-diagonal elements and therefore the best-fit lines and data points may not match visually in certain bins.

SAMPLE	BIAS ($A_k = 1$)	BIAS ($A_k \neq 1$)
$0.15 < z < 0.30$	$1.47^{+0.08}_{-0.08}$	$1.46^{+0.09}_{-0.07}$
$0.30 < z < 0.45$	$1.67^{+0.06}_{-0.04}$	$1.68^{+0.06}_{-0.05}$
$0.45 < z < 0.60$	$1.68^{+0.04}_{-0.04}$	$1.68^{+0.04}_{-0.04}$
$0.60 < z < 0.75$	$2.03^{+0.04}_{-0.05}$	$2.02^{+0.05}_{-0.04}$
$0.75 < z < 0.90$	$2.14^{+0.05}_{-0.08}$	$2.12^{+0.08}_{-0.06}$
$A_k = 1.00^{+0.16}_{-0.09}$		

TABLE III. Summary of the constraints on the galaxy bias parameters using $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ and assuming *Planck* best-fit Λ CDM cosmology. We consider two cases: fixing the lensing amplitude to 1 (left), and setting A_k free (right). We obtain χ^2 of 107.3 and 107.2 respectively for 82 data points. Since most of the constraining power is coming from $w^{\delta_g \delta_g}(\theta)$, we find similar values for the galaxy biases for the two cases. The difference between the values reported here and in [53] is due to the cosmology assumed.

SAMPLE	FIXED	+ <i>Planck</i> BASELINE
$0.15 < z < 0.30$	$1.54^{+0.44}_{-0.38}$	$1.47^{+0.51}_{-0.38}$
$0.30 < z < 0.45$	$1.45^{+0.33}_{-0.42}$	$1.30^{+0.46}_{-0.32}$
$0.45 < z < 0.60$	$1.10^{+0.36}_{-0.21}$	$1.06^{+0.34}_{-0.20}$
$0.60 < z < 0.75$	$2.69^{+0.23}_{-0.28}$	$2.78^{+0.17}_{-0.35}$
$0.75 < z < 0.90$	$2.17^{+0.45}_{-0.42}$	$2.31^{+0.35}_{-0.52}$

TABLE IV. Summary of the constraints on the galaxy bias parameters from $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ only with fixed cosmology, and in combination with the *Planck* baseline likelihood. In both cases photo- z biases are varied over with the priors from [42]. The χ^2 that we obtain are 27.6 and 26.1 for 27 data points.

is because the number of available background galaxies decreases as we increase the redshift of the lens galaxy sample. In contrast, the signal improves for $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ due to the better overlap with the CMB lensing kernel as shown in Fig. 1.

B. Growth constraints

Next, we study the broader cosmological implications of our measurement: we first assume cosmology to be fixed at high redshift, e.g. by the *Planck* CMB observations, and test whether the linear growth function inferred from our measurement at low redshift is consistent with the baseline Λ CDM model predictions. We test this using the two methods described in Sec. IV D 2.

1. The D_G estimator

We first measure the linear growth function $D(z)$ using the D_G estimator. We compute D_G for all five tomographic bins, applying the conservative angular scale cuts listed in Sec. IV B, and additionally removing scales above $100'$ (see Sec. IV D 2 for details). The results are shown in Fig. 5. In addition, we also calculate the best-fit amplitude A_D by combining all the bins, from which we obtain $A_D = 1.16^{+0.20}_{-0.20}$, which agrees with the fiducial Λ CDM expectation of $A_D = 1$.

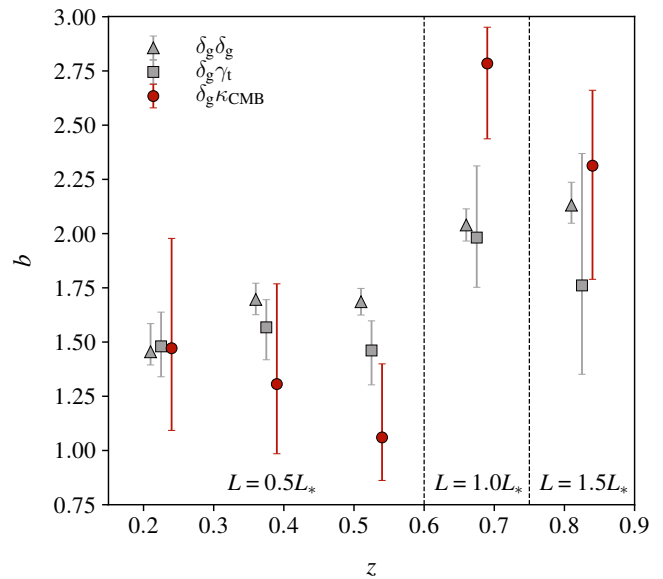


FIG. 4. Galaxy bias estimation of REDMAGiC galaxies from different probes, as a function of redshift when combined with *Planck* baseline likelihood. The results from $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ assuming $A_k = 1$ are shown in red. Additionally plotted are the measurements from galaxy clustering [53] (gray triangles) and galaxy-galaxy lensing [64] (gray squares).

In comparing the result presented here (using 1289 deg^2) with that of G16 that used DES-SV data covering 140 deg^2 , we see that we obtain similar constraining power. This is due to:

1. The conservative scale cuts imposed in this study to minimize $w^{\delta_g \kappa_{\text{ISZ}}}(\theta)$ bias.
2. The lower number density of REDMAGiC than the galaxy sample used by G16, in exchange for better photo- z errors.
3. The lower temperature ℓ_{max} used ($\ell_{\text{max}} = 3000$) in the lensing reconstruction process in [15] to avoid contamination by astrophysical foregrounds (whereas the SPT lensing map used in the G16 analysis had $\ell_{\text{max}} = 4000$).

Therefore, we have exchanged signal-to-noise ratio with increased robustness of the measurement.

We have tested that the general scale cuts used by [44] are also appropriate for the D_G estimator. We have confirmed this by running the estimator on contaminated theory data vectors, for which we found that the bias on the recovered growth is always $< 0.5\sigma$ if the standard scale cuts of Sec. IV B are used. This is not the case for less conservative cuts, which we therefore discard: for example, using the full range of scales down to $2'$ biases D_G at the 2σ level. The bias at small angular scales is mainly driven by the tSZ contamination in the CMB lensing map, as discussed in [44].

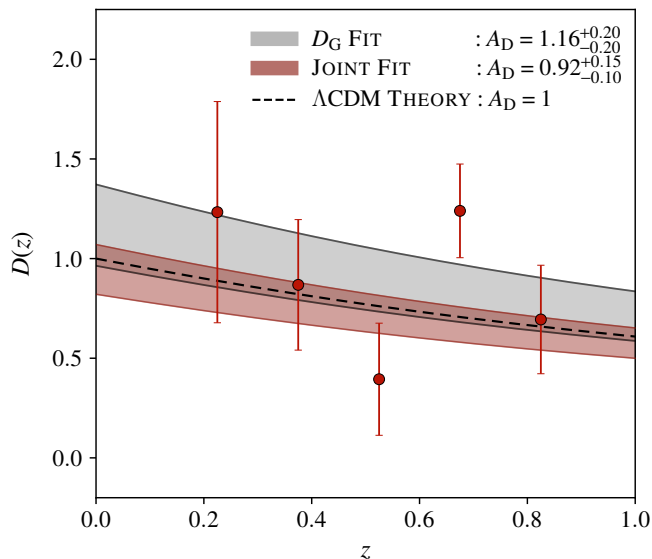


FIG. 5. Growth function estimates from the combination of auto- and cross-correlation functions, at the fiducial cosmology. The red points show the measured value of D_G in each redshift bin, with error bars representing the diagonal elements of the covariance matrix described in Sec. IV D 2. The grey band represents the 1σ confidence interval on the best-fit amplitude A_D , assuming the fiducial Λ CDM template shown in black (solid), and the red shaded regions describe the 1σ uncertainties from the joint-fit analysis described in Sec. VIB 2.

2. Joint growth fit results

Here we keep the cosmological parameters fixed to the fiducial model, but marginalize over the five independent linear galaxy bias parameters (one for each redshift bin), the photo- z uncertainties and the linear growth parameter A_D using the priors presented in Table II. We measure the linear galaxy bias to be $b^1 = 1.45^{+0.30}_{-0.15}$, $b^2 = 1.73^{+0.26}_{-0.22}$, $b^3 = 1.80^{+0.17}_{-0.29}$, $b^4 = 2.04^{+0.35}_{-0.21}$, $b^5 = 2.15^{+0.36}_{-0.24}$ and find a constraint of $A_D = 0.92^{+0.15}_{-0.10}$ for the amplitude of the growth function. These measurements of the bias are in agreement with the results shown in Table III. The recovered growth function agrees with the fiducial Λ CDM expectation, as the measurement of A_D is consistent with 1.0. We observe that the errors on the galaxy bias are larger compared to a direct best-fit estimation presented in Sec. VIA. This is due to the fact that the bias and A_D parameters are correlated. In turn, the fact that the joint-fit method gets a different value of A_D with respect to the D_G method is because it explicitly takes into account the correlations between bias and growth.

C. Cosmological parameter estimation

In this section, we present the full cosmological analysis using the $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ data vectors and marginalizing

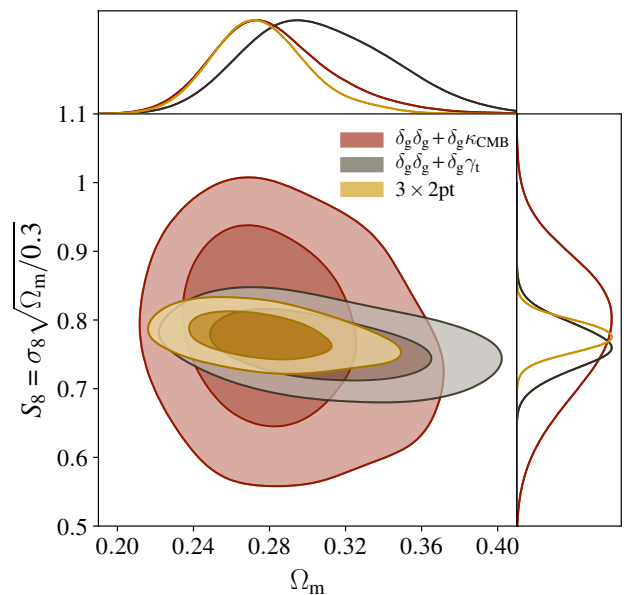


FIG. 6. Constraints on Ω_m and S_8 from the measurements of this paper and combinations of other two-point correlation functions. We show the constraints from $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ (red), $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \gamma_t}(\theta)$ (gray) and $3 \times 2\text{pt}$ (gold).

over all the cosmological parameters and nuisance parameters (galaxy bias and photo- z bias, but we fix $A_D = A_\kappa = 1$).

The priors used in this analysis are summarized in Table II, and are the same as used in [42] to maintain consistency between the analyses.

In Fig. 6 we show the constraints obtained on matter density Ω_m and S_8 when all six cosmological parameters, photo- z errors and linear galaxy biases for the five redshift bins are marginalized over. This is then compared with the constraints from the combination of $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \gamma_t}(\theta)$ as presented in [42]. We observe that these two measurements slice through the parameter space slightly differently. Using $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ we obtain $\Omega_m = 0.276^{+0.029}_{-0.030}$ and $S_8 = 0.800^{+0.090}_{-0.094}$, whereas the combination of $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \gamma_t}(\theta)$ gives us $\Omega_m = 0.294^{+0.047}_{-0.029}$ and $S_8 = 0.759^{+0.037}_{-0.031}$. These two results can also be compared with the constraints from $3 \times 2\text{pt}$ (the combination of $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \gamma_t}(\theta) + \xi_{+/-}(\theta)$)[42], which gives $\Omega_m = 0.267^{+0.030}_{-0.017}$, $S_8 = 0.773^{+0.026}_{-0.020}$. These results are highly consistent with each other as shown on Fig. 6.

The measurement used in this analysis are combined with the $w^{\gamma_t \kappa_{\text{CMB}}}(\theta)$ presented in [43] and the results from [42] in [45], using the methodology outlined in [44].

VII. CONCLUSIONS

We have presented measurements of the DES REDMAGiC galaxy-CMB lensing cross-correlation as a function of redshift. Our measurement rejects the hypothesis of no-lensing

at $19.9\sigma^{10}$ significance prior to any scale cuts and 9.9σ using the conservative scale cuts from [44]. The conservative scale cuts reduce the signal to noise of the measurements in exchange for mitigation of systematic biases.

We test for the impact of possible systematics in the cross-correlations, considering contaminants to both the DES galaxy and the CMB lensing maps. We find that, on the scales we consider, all these contaminants have a small impact on our measurements compared with the statistical uncertainties. The largest effect comes from the tSZ contribution to the CMB lensing maps, which becomes large at smaller angular scales, and is the main limiting factor dictating our scale cuts [44]. Improving the modeling and subtraction of this contaminant will be the key to extracting the full statistical power of the temperature based CMB lensing maps in the future.

In obtaining the galaxy bias parameters, we find that galaxy-clustering measurements place significantly tighter constraints than galaxy-galaxy lensing or galaxy-CMB lensing correlations. However, the two cross-correlations are nonetheless important in breaking degeneracies in parameter space.

We use our measurements to infer cosmological information in a number of ways. We first constrain the linear growth function using the D_G estimator introduced by G16, finding a relative growth amplitude of $A_D = 1.16^{+0.20}_{-0.20}$. This compiles measurements of growth in various tomographic bins, accounting for their covariance. We then extend this result and constrain the relative growth amplitude with a joint-fit method, marginalizing over galaxy biases and photo- z uncertainties, and considering the full covariance of the observables. In this case, we find $A_D = 0.92^{+0.15}_{-0.10}$. Both of these results are consistent with the Λ CDM predictions of $A_D = 1$.

Using these measurements, we finally run a full MCMC analysis over the Λ CDM cosmological parameters to also place marginalized constraints on the two parameters that are most directly related to the matter density field: Ω_m and $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$. Using the combination of $w^{\delta_g \delta_g}(\theta)$ and $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ we obtain $\Omega_m = 0.276^{+0.029}_{-0.030}$ and $S_8 = 0.800^{+0.090}_{-0.094}$. This can be compared with the results obtained using galaxy clustering and galaxy-galaxy lensing (i.e. $w^{\delta_g \delta_g}(\theta) + w^{\delta_g \gamma_l}(\theta)$), which gives $\Omega_m = 0.294^{+0.047}_{-0.029}$ and $S_8 = 0.759^{+0.037}_{-0.031}$. We find that the constraining power is comparable despite the conservative scale cuts we have applied in this analysis, and we expect to obtain better signal in the future as we use galaxy samples at higher redshifts due to the better overlap with the CMB lensing kernel.

The constraining power of DES measurements of galaxy-CMB lensing correlations has the potential to improve in future analyses. The DES-Y3 will cover the full 5000 deg^2 of the DES footprint at approximately the same depth as Y1. Since the extended area does not overlap with the SPT footprint, we expect the gain in the signal-to-noise to be small

in terms of improvements in sky coverage. However, our analysis choice in this study is conservative; we have chosen the scale-cuts to minimize the biases in exchange for signal-to-noise ratio. To improve this measurement further, it will be essential to (1) characterize the bias to a higher accuracy, such that the signal loss is minimized, or (2) to improve the reconstruction of the CMB lensing map so that it is less prone to biases [see e.g. 65, for a discussion of modifications to temperature-based lensing reconstruction to minimize tSZ bias]. Furthermore, newer data sets from SPT (SPTpol and SPT-3G [66]) have lower noise levels than SPT-SZ, and therefore, lensing maps generated from these data sets will have lower noise. Improvements along these lines will allow us to maximally extract the signal from this cross-correlation, and to reach the best possible accuracy on cosmology.

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¹⁰ We note that while certain systematics could add to the apparent signal and artificially inflate the significance, in this case the main contamination without scale cuts is tSZ, which artificially reduces $w^{\delta_g \kappa_{\text{CMB}}}$. In other words, in the absence of tSZ and scale cuts, the significance of this measurement would be higher than 19.9σ .

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¹¹ <https://bitbucket.org/joezuntz/cosmosis>

¹² <https://getdist.readthedocs.io/en/latest/>

¹³ <https://github.com/dhanson/quicklens>

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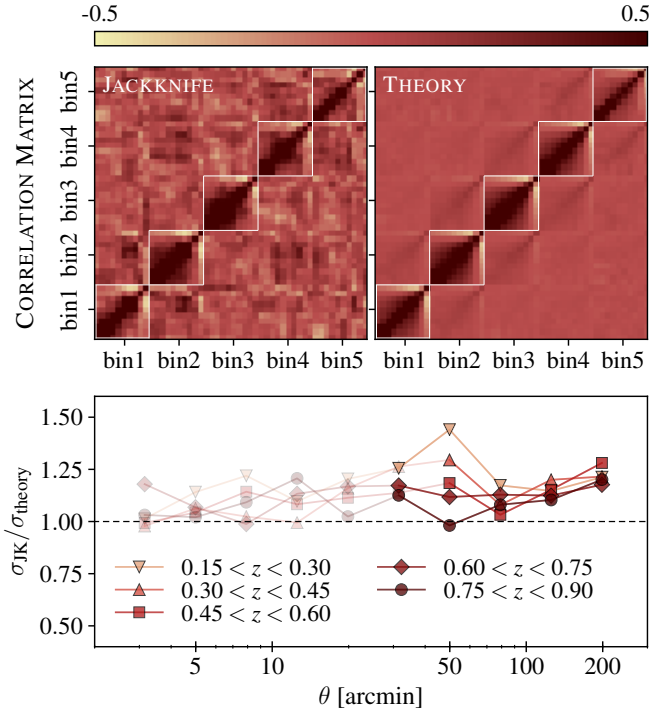


FIG. 7. Covariance matrix for $w^{\delta_g \kappa_{\text{CMB}}}(\theta)$ obtained using the jackknife method (upper left) and analytically (upper right). Each redshift bin includes 10 angular bins. The ratio of the diagonal elements are shown in the lower panel. The gray panel denotes $\pm 30\%$ margin compared to the analytical covariance.

Appendix A: Covariance matrix validation

Here we compare the analytical covariance matrix developed in [46] (and extended to include κ_{CMB} in [44]) with the data-based covariance obtained using the jackknife method.

From the data we compute the jackknife covariance as

$$C_{ij}^{\text{jk}} = \frac{N_{\text{jk}} - 1}{N_{\text{jk}}} \sum_k (d^k - \bar{d})_i (d^k - \bar{d})_j, \quad (\text{A1})$$

where N_{jk} is the number of jackknife patches used. Fig. 7 shows the comparison between the jackknife and analytical covariances. We obtain diagonal covariance elements that are on average $\sim 17\%$ higher than the analytical covariance over the angular scales of interest. Based on the discussion in [75] and [76], we consider that these are in sufficient agreement given that the jackknife method is a noisy estimate of the underlying covariance.