Cross-correlation of Planck CMB lensing with DESI galaxy groups

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ABSTRACT
We measure the cross-correlation between galaxy groups constructed from DESI Legacy Imaging Survey DR8 and Planck CMB lensing, over overlapping sky area of 16876 deg². The detections are significant and consistent with the expected signal of the large-scale structure of the universe, over sample groups of various redshift, mass, richness $N_g$ and over various scale cuts. The overall S/N is 40 for a conservative sample with $N_g \geq 5$, and increases to 50 for the sample with $N_g \geq 2$. Adopting the Planck 2018 cosmology, we constrain the density bias of groups with $N_g \geq 5$ as $b_g = 1.31 \pm 0.10, 2.22 \pm 0.10, 3.52 \pm 0.20$ at $0.1 < z \leq 0.33, 0.33 < z \leq 0.67, 0.67 < z \leq 1$ respectively. The group catalog provides the estimation of group halo mass and therefore allows us to detect the dependence of bias on group mass with high significance. It also allows us to compare the measured bias with the theoretically predicted one using the estimated group mass. We find excellent agreement for the two high redshift bins. However, it is lower than the theory by $\sim 3\sigma$ for the lowest redshift bin. Another interesting finding is the significant impact of the thermal Sunyaev Zel’dovich (tSZ). It contaminates the galaxy group-CMB lensing cross-correlation at high redshift bins. However, it is lower than the theory by $\sim 3\sigma$ for the lowest redshift bin. Another interesting finding is the significant impact of the thermal Sunyaev Zel’dovich (tSZ). It contaminates the galaxy group-CMB lensing cross-correlation at high redshift bins. However, it is lower than the theory by $\sim 3\sigma$ for the lowest redshift bin.

Key words: large scale structure of Universe – cosmology: observations – cosmic background radiation

1 INTRODUCTION
There is a wealth of cosmological information in secondary anisotropies resulting from perturbations to Cosmic Microwave Background (CMB) light after the time of recombination. A particularly interesting source of secondary anisotropy is the gravitational lensing (Seljak 1996; Seljak & Zaldarriaga 1999; Hu 2000; Hu & Okamoto 2002; Okamoto & Hu 2003), which deflects the paths of photons from the last-scattering surface. These deflections, on the order of a few arc-minutes, alter the CMB primary anisotropies by a non-Gaussian and anisotropic component to the primordial distribution of temperature anisotropies. Through such non-Gaussian and anisotropic features, the gravitational field can be reconstructed from the observed CMB maps (Seljak & Zaldarriaga 1999; Hu & Okamoto 2002; Okamoto & Hu 2003; Lewis & Challinor 2006). The first detection of CMB lensing is by the Atacama Cosmology Telescope (ACT) (Das et al. 2011). High signal-to-noise measurements of CMB lensing have been obtained by several collaborations, including a full-sky map of lensing convergence by the Planck satellite mission (Planck Collaboration et al. 2020a,b), a 2500 deg² CMB lensing map from combined South Pole Telescope (SPT) and Planck temperature data (Omori et al. 2017), a measurement of the lensing B-mode CMB polarization by POLARBEAR (Ade et al. 2014), and most recently a lensing map over 2100 deg² by ACT (Darwish et al. 2021).

The CMB lensing signal is an integral of all deflections sourced by the large-scale structure (LSS) between the last-scattering surface and the observer, thus it contains rich cosmological information with its auto-correlation. Meanwhile, it is physically correlated with other LSS tracers such as galaxy and galaxy cluster distribution, and cosmic shear. On one hand, these cross-correlations are immune to certain systematics in the auto-correlation, such as the additive errors in both CMB lensing and cosmic shear. On the other hand, they provide essential information, such as the redshift information, to improve the cosmological applications of CMB lensing. CMB lensing-cosmic shear cross-correlation has been detected by various data sets (Hand et al. 2015; Liu & Hill 2015; Kirk et al. 2016; Singh et al. 2017; Harnois-Déraps et al. 2018; Omori et al. 2019b; Namikawa et al. 2019; Marques & Bernui 2020; Robertson et al. 2021). Cross-correlations of CMB lensing with galaxies (e.g. recent works by Singh et al. (2017); Schmittfull & Seljak (2018); Bianchini & Reichardt (2018); Baxter et al. (2018); Raghunathan et al. (2018); Giusarma et al. (2018); Omori et al. (2019a,b); Krolewski et al. (2020); Marques & Bernui (2020); Darwish et al. (2021); Kitanidis & White (2021); Hang et al. (2021); Shetkar Saraf et al. (2021); Fang et al. (2021); Krolewski et al. (2021); Alonso et al. (2021); Yan et al. (2021); White et al. (2021)), galaxy groups and clusters (Madhavacheril et al. 2015; Baxter et al. 2015; Geach & Peacock 2017; Baxter et al. 2018; Madhavacheril et al. 2020), and quasars (Lin et al. 2020) have also been detected. Recently, the cross-correlation
between CMB lensing and a new LSS tracer (low-density positions (LDPs)) (Dong et al. 2019), has been detected with S/N ~ 55 (Dong et al. 2021).

Recently Yang et al. (2021) (hereafter Y21) identified ~ 10^7 galaxy groups from the DESI imaging surveys (Dey et al. 2019), over ~ 20,000 deg^2 and z < 1. Compared with the majority of galaxies in the DESI imaging surveys, these galaxy groups have better photo-z information and less imaging systematics, making them attractive in CMB lensing-LSS cross-correlation measurement. Furthermore, Y21 also provides an estimation of the halo mass. Such information is crucial in validating/interpreting the cross-correlation measurement. For these reasons, we measure the cross-correlation between the galaxy group positions (number density) of the Y21 catalog and Planck CMB lensing (Planck Collaboration et al. 2020b). With ~40% overlapping sky coverage and 2×10^5 galaxy groups of richness N_g ≥ 5 over 0.1 < z < 1.0, we detect the cross-correlation signal with S/N ≈ 40. The S/N increases to 50 if we relax the richness cut to N_g ≥ 2. Thanks to a large number of clusters and groups, we have improved the S/N of cluster/group-CMB cross-correlation measurement by a factor ≥ 5, over previous measurements (Madhavacheril et al. 2015; Baxter et al. 2015; Geach & Peacock 2017; Baxter et al. 2018; Madhavacheril et al. 2020). An important improvement to previous works is that, we are now able to directly compare the measured group bias b_g with the theoretically predicted one using the estimated halo mass of each group. The agreement is excellent for the two higher redshift bins.

This paper is structured as follows. We first review in Sec. 2 the theoretical foundations of CMB lensing and galaxy clustering; we then describe the DESI imaging DR8 group data and Planck legacy data we used in Sec. 3, and the analysis methods we follow in Sec. 4. The main results of this paper, together with their cosmological implications, are presented in Sec. 5. We finally conclude in Sec. 6.

2 THEORETICAL BACKGROUND

Galaxy/galaxy group overdensity δ_g and CMB lensing convergence κ are both projections of 3D density fields, expressed as line-of-sight integrals over their respective projection kernels. The angular cross-correlation power spectrum, adopting the Limber approximation (Limber 1953), is

\[ C_\ell^g = \int d\chi W^g(\chi)W^g(\chi')P_{mg}(k = \ell + 1/2; z). \]  

(1)

The Limber approximation is inaccurate for ζ < 10, but such very large-scale modes are excluded from our fitting anyway, due to poor S/N. The above expression assumes spatial flatness. Here W^g and W^R are the projection kernels for κ and the group number density fields.

\[ W^g(z) = n(z) = \frac{c}{H(z)}W^R(\chi). \]  

(2)

\[ W^R(z) = \frac{3}{2c}Q_{m0}H_0^2 \frac{H(z)}{(1 + z)}\chi(z_s - \chi)\chi_s = \frac{c}{H(z)}W^R(\chi). \]  

(3)

Here $\chi$ is the comoving distance to redshift z and $\chi_s = \chi(z_s \approx 1089)$ is the distance to the surface of the last scattering. n(z) is the normalized redshift distribution of galaxy groups. These kernels are plotted in Fig. 2. P_{mg} is the 3D cross power spectrum between matter and group number overdensity. We define the group bias through $b_g \equiv P_{mg}/P_{mm}$. $\delta_g$ is approximately scale-independent at the large scales of interest.

3 DATA

3.1 Planck CMB lensing maps

We use the lensing convergence maps and analysis masks provided in the Planck 2018 release (Planck Collaboration et al. 2020b). To minimize the impact of tSZ, we adopt the baseline lensing map as the one reconstructed from the tSZ-deprojected temperature-only SMICA map. This map has a lower S/N than the lensing map reconstructed combining temperature and polarization. We also repeat the analysis for this map. Hereafter the two maps will be referred to as BASE and with tSZ, respectively.

The spherical harmonics coefficients of lensing convergence are provided in HEALPix (Zonca et al. 2019; Görski et al. 2005) format with maximum order $\ell_{max} = 4096$, and the associated analysis masks are given as HEALPix maps with resolution $N_{side} = 2048$ (Planck Collaboration et al. 2020b). We are only interested in large scale clustering and we prefer to avoid small scale complexities such as scale-dependent bias, baryonic effect, and massive neutrino (DES Collaboration et al. 2021; Heymans et al. 2021; Asgari et al. 2021). Therefore we downgrade the mask to $N_{side} = 512$, with the lensing harmonics up to $\ell_{max} = 1000$. The downgraded Planck lensing map is shown in Fig. 1. Notice that direct downgrading may result in a large aliasing effect, due to overwhelming reconstruction noise at pixellation scale. Thus we first apply a Wiener filter provided by the Planck 2018 release to the original convergence map, then downgrade it to $N_{side} = 512$.

3.2 DESI group samples

The Y21 catalog is constructed from the DESI Legacy Imaging Survey DR8, with a halo-based group finder. Each group is assigned an estimated total halo mass (estimated based on abundance matching), {ra, dec} of the brightest galaxy, photometric redshift, richness $N_g$ (the number of member galaxies in each group), etc (Yang et al. 2021). Fig. 2 shows the redshift distribution of groups with $N_g \geq 5$, in the three tomographic bins (0.1 < z ≤ 0.33, 0.33 < z ≤ 0.67, 0.67 < z < 1). Table 1 lists the total number of groups in each

![Figure 1. Planck 2018 CMB lensing map filtering by Wiener filter. The map is constructed in HEALPix pixelization scheme, with resolution parameter $N_{side} = 512$ (6.9 arcmin). The mask (grey area) is Planck tSZ-deprojected CMB lensing mask.](http://pla.esac.esa.int/pla/#cosmology)
Figure 2. Redshift distribution with three tomographic bins of galaxy group samples in the photo-z range (0.1,1.0). The histogram is the photo-z distribution and the corresponding color curve is the estimated true redshift distribution (normalized) with photo-z error $\sigma_z = 0.05$. Projection kernels for the group sample (solid curves) and CMB lensing (dashed black curve), expressed in Eq. (2) and Eq. (3) respectively, both normalized to unit maximum.

| $z$ | of groups with $N_g \geq 5$ | $\log M_{dv}$ |
|-----|-----------------|----------------|
| 0.1 < $z$ ≤ 0.33 | 20151147 | 800906 | 13.1 |
| 0.33 < $z$ ≤ 0.67 | 49901082 | 1134482 | 13.4 |
| 0.67 < $z$ ≤ 1.0 | 20829772 | 101676 | 13.9 |

Table 1. The information of groups in the DESI Imaging Survey DR8. Column (2) lists the number of groups in the original catalog. Column (3) lists the number of groups with at least 5 members. Column (4) is the mass we divide the samples into two mass bins (low and high) in each redshift bin, and both mass bins have equal size of groups.

redshift bin. The first two redshift bins have 0.8M and 1.1M groups respectively. The last redshift bin has only 0.1M groups. But these groups have stronger clustering and redshifts closer to the peak of the lensing kernel. Therefore they produce significant cross-correlation S/N. We also divide groups in each redshift bin into two mass bins of an equal amount of groups. Fig. 3 show the mass distribution of groups with three redshift bins. $\log M_{dv}$ is defined as the mass of dividing the groups into two mass bins that have an equal quantity of groups. As expected, $\log M_{dv}$ increases with redshift, what we could observe in higher redshift are more massive galaxy groups.

3.3 Survey mask

As described in Y21, the galaxy mask is constructed from a set of uniformly distributed random catalogs provided in the DESI DR8 website\(^2\)\(^3\). We adopt the identical group mask as in Yang et al. (2021).

Each random point contains the exposure times for $g, r, z$ bands based upon the sky coordinate drawn independently from the observed distribution. We choose random points whose exposure time in all three bands is greater than zero to produce the survey masks which populate the same sky coverage and geometry with the galaxy catalog. In addition to the Tractor morphology selection, minimum data quality flags are employed to remove the flux contaminations from nearby sources (FRACFLUX) or masked pixels (FRACMASKED):

$$\frac{f_{\alpha}}{\langle f_{\alpha} \rangle} \geq f_{\text{threshold}} = 0.5 ,$$

where $i \equiv g, r, z$. FRACIN is to select the objects for which a large fraction of the model flux is in the $N_{\text{side}} = 512$ contiguous pixels where the model was fitted. We also remove any objects close to the bright stars by masking out objects with the following bits number in the DR8 MASKBITS column: 1 (close to Tycho-2 and GAIA bright stars), 8 (close to WISE W1 bright stars), 9 (close to WISE W2 bright stars), 11 (close to fainter GAIA stars), 12, and 13 (close to an LSIGA large galaxy and a globular cluster, respectively).

In addition, we project the 3D group number density distribution to 2D sky map along the line-of-sight in the $N_{\text{side}} = 2048$ resolution, then downgrade the pixelized map to $N_{\text{side}} = 512$, and exclude areas with an observed coverage fraction smaller than $f_{\text{threshold}}$. This step is to minimize the impact from the footprint-induced fake overdensity. For the pixels with coverage fraction above this threshold, we assign to each mask pixel $\alpha$ its coverage fraction $f_{\alpha}$, and use this value as a weight in the clustering measurements that follow

$$\delta_\alpha = \frac{N_\alpha / f_\alpha}{\langle N_\alpha / f_\alpha \rangle} - 1 .$$

Here $N_\alpha$ is the number of groups in the $\alpha$-th pixel. The average $\langle \cdots \rangle$ is over all pixels with $f \geq f_{\text{threshold}}$. The number overdensity maps are constructed in HEALPix pixelization scheme with resolution parameter $N_{\text{side}} = 512$ (6.9 arcmin), and the coverage fraction of groups is 0.43.

The total mask that we use for the cross-correlation analysis is defined as the modified group mask in combination with the Planck convergence map mask. After the total masking, there are 16876 deg\(^2\) sky area ($f_{sky} = 0.41$) and 2 million galaxy groups left. The reason we choose the combined mask is, we count the pixel pairs between the galaxy group overdensity map and CMB lensing convergence map. The combined mask can correctly count for the number of usable pairs.

\(^2\) http://legacysurvey.org/dr8/files/#random-catalogs

\(^3\) “Tractor” is the fitting procedure that DESI used officially. The Tractor code runs within the geometrical region of a brick to produce catalogs of extracted sources. In DR8, six morphological types are used. Five of these are used in the Tractor fitting procedure: point sources, round exponential galaxies with a variable radius (“REX”), deVaucouleurs (“DEV”) profiles (elliptical galaxies), exponential (“EXP”) profiles (spiral galaxies), and composite profiles that are deVaucouleurs + exponential (with the same source center). The sixth morphological type is “DUP,” which is set for Gaia sources that are coincident with, and so have been fit by, an extended source. Website: https://legacysurvey.org/dr8/description/tractor-catalogs
Number of realizations and error propagation to the fitting parameters. Here we measure the galaxy groups cross-correlate with the CMB lensing maps in harmonic space.

4.1 Cross-correlation measurements

Starting with the above maps, we use HEALPix to measure the spherical harmonic coefficients \( \delta_{\ell m} \) (group overdensity) and \( \kappa_{\ell m} \). The observed cross-power spectrum is then

\[
C_{\ell}^{gK} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} \delta_{\ell m} \kappa_{\ell m}^{*} .
\]  

(6)

Given the existence of the survey mask, the raw power spectrum obtained above is biased. This problem can be corrected by deconvolving the survey mask, or by measuring the correlation function instead. Alternatively, the survey mask can be included in the theory side. We take this later approach, detailed in §4.2.

The lensing map is reconstruction noise dominated. The group distribution-CMB lensing cross-correlation coefficient is much smaller than unity, due to mismatch in their redshift distribution. For the two reasons, cosmic variance arising from the group-CMB lensing cross-correlation is negligible in the covariance matrix. Therefore we estimate the covariance using 300 Planck CMB lensing simulations (Planck Collaboration et al. 2020b). We obtain the mean-field \( \langle a_{\ell m} \rangle \) by using first 60 simulations and then subtract them from the remaining 240 simulations to obtain mean-field subtracted maps. We measure the cross-power spectra of these 240 maps with the overdensity maps, and estimate the covariance matrix by

\[
\text{Cov}_{\ell\ell'} = \frac{1}{N-1} \sum_{n=1}^{N=240} \left[ (C_{n}^{gK}(\ell) - \overline{C}_{n}^{gK}(\ell)) \times (C_{n}^{gK}(\ell') - \overline{C}_{n}^{gK}(\ell')) \right].
\]

(7)

Here \( \overline{C}_{n}^{gK}(\ell) \) is the average cross-power spectrum. Fig. 4 shows the normalized covariance matrix in each mass bin and tomographic bin. We note the covariance will require correction due to the limited number of realizations and error propagation to the fitting parameters (Hartlap et al. 2007). We test Eq. 32 and 33 in Wang et al. (2020).

The correction factors are \( \sim 0.95 \) and \( \sim 1.03 \). As a result, the total correction is \( \sim 1.07 \) to the covariance, meaning our errors of power spectra are underestimated by about 4%, reducing our S/N by \( \sim 1 \). Fig. 5 shows the correlation matrix for cross power spectra at \( 0.1 < z \leq 0.33, 0.33 < z \leq 0.67, 0.67 < z \leq 1 \), respectively. As one can see, the off-diagonal blocks can be negligible. That means we could sum the S/N in each redshift bin as defined in Eq. (13).

4.2 Theoretical template and halo bias fitting

The theoretical template for \( C_{\ell}^{gK} \) is approximated as \( b_{g} C_{\ell}^{gK,th} \). \( C_{\ell}^{gK,th} \) include the modification to the power spectrum caused by both the survey mask and the Planck Wiener filter. The first step is to calculate the cross-power spectrum without the survey mask and the Wiener filter, using Eq. (1) and setting the bias \( b = 1 \). We use the Core Cosmology Library (CCL: Chisari et al. (2019)) for the calculations, with a fiducial Planck 2018 cosmology (Planck Collaboration et al. 2018): \( \Omega_{m} = 0.315, \Omega_{\Lambda} = 0.685, n_{s} = 0.965, h = H_{0}/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.674 \) and \( \sigma_{8} = 0.811 \). We use HaloFit (Smith et al. 2003; Takahashi et al. 2012; Mead et al. 2015) to calculate \( P_{mm} \). By default CCL uses Takahashi et al. (2012). The galaxy redshift distribution \( n(z) \) are calculated for each tomographic bin and mass bin, combining the photo-z distribution and a Gaussian photo-z error PDF with \( \sigma_z = 0.05 \). The second step is to generate 100 full-sky maps of the power spectrum calculated in the first step. We then apply the Wiener filter and mask to these maps. We then obtain 100 cross-power spectra with the survey mask and Wiener. To correct for the pixelation effect of full-sky, a factor of \( 12 N_{side}^{2} / 4 \pi \) is needed to obtain the correct power spectrum normalization. We use the average one as the theoretical template \( C_{\ell}^{gK,th} \). Fig. 6 shows the theoretical templates for the three redshift bins and two mass bins. The results of the two mass bins are slightly different due to the slightly different redshift distribution.

The only free parameter in the theoretical model is the group density bias \( b \). The \( \chi^2 \) for the fitting is

\[
\chi^2 = \sum_{\ell\ell'} \left[ \left( C_{\ell}^{gK,th} - b C_{\ell}^{gK,o} \right) \text{Cov}_{\ell\ell'}^{-1} \left( C_{\ell'}^{gK,th} - b C_{\ell'}^{gK,o} \right) \right].
\]

(8)

\[ \text{Fig. 3.} \] Mass distribution of galaxy groups in three tomographic bins within photo-z range \((0.1,1.0)\). The value \log M_{dv} \ is defined as the mass of dividing the groups into two mass bins, low-mass and high-mass, that have the same quantity of groups.
The best-fit value and the associated error are $\sigma_{\beta} = \left( \sum_{\ell,\ell'} C_{\ell}^{g,th} \text{Cov}^{-1}_{\ell\ell'} C_{\ell'}^{g,o} \right)^{1/2}$. It is calculated with 300 Planck CMB lensing simulation maps by Eq. (7). The percentage refers to ratio of the maximum absolute value on the off-diagonal elements to the diagonal elements.

Here the sum is over the data points of each redshift/mass bin. Namely bias of each redshift/mass bin is independent of each other. The degree-of-freedom of the fitting is $\text{d.o.f} = N_D - N_f = N_D - 1$, where $N_D$ is the number of data points, $N_f$ is the number of fitting parameter. The best-fit value and the associated error are

$$b = \frac{\sum_{\ell,\ell'} C_{\ell}^{g,th} \text{Cov}^{-1}_{\ell\ell'} C_{\ell'}^{g,o}}{\sum_{\ell,\ell'} C_{\ell}^{g,th} \text{Cov}^{-1}_{\ell\ell'} C_{\ell'}^{g,th}} \text{,} \quad (9)$$

$$\sigma_{\beta} = \left[ \sum_{\ell,\ell'} C_{\ell}^{g,th} \text{Cov}^{-1}_{\ell\ell'} C_{\ell'}^{g,th} \right]^{1/2} \text{.} \quad (10)$$

Figure 4. The normalized covariance matrix $C_{ij}/\sqrt{C_{ii} C_{jj}}$ for $C_{\ell \ell}^{g}$. It is calculated with 300 Planck CMB lensing simulation maps by Eq. (7). The percentage refers to ratio of the maximum absolute value on the off-diagonal elements to the diagonal elements.

Figure 5. The correlation matrix for cross power spectra at three redshift intervals. Here multipole 0-12 denote bins in the spectrum of the first redshift interval and 12-24, 24-36 denote those of second and third redshift intervals.

Here is the bias predicted by the theory, given the halo mass $M$ and $z$. We compare the measured bias with the prediction of three halo bias models (Jing 1998; Sheth et al. 2001; Tinker et al. 2010), calculated by Colossus (Diemer 2018). We define dark matter halos as having an overdensity of 180 times the background density of the universe. This mass definition is used for both Colossus and Y21 catalog.

**4.3 The theoretically predicted halo bias**

The measured bias can be compared with the one from the theoretical prediction, given the estimated halo mass. We estimate the later by taking into account of the associated weighting in the Limber integral,

$$b^{\text{th}} = \frac{\sum_{i} b(M_i, z_i) W^X(z_i) \chi(z_i)}{\sum_{i} W^X(z_i) \chi(z_i)} \text{.} \quad (11)$$

Here $i$ denotes the $i$-th galaxy groups, $b(M, z)$ is the bias predicted by the theory, given the halo mass $M$ and $z$. We compare the measured bias with the prediction of three halo bias models (Jing 1998; Sheth et al. 2001; Tinker et al. 2010), calculated by Colossus (Diemer 2018).

Figure 6. The theoretical cross power spectra for each sub-samples which set the bias equals to 1, calculated with CCL. Note that all theoretical calculations include Wiener filter and mask in the cross power spectra, with the former suppressing the power mainly at small scales, and the latter suppressing the power at all scales.
RESULTS

We have to take care of the mass estimation uncertainty in
estimating $b^h$. Y21 uses the mock group catalog from the mock
galaxy redshift survey (MGRS hereafter) to estimate the uncertainty,
and finds an uncertainty of $\sim 0.2$ dex when $M \geq 10^{13.5}$ and $\sim 0.45$
dex at the low mass end. Fig. 7 we show the assigned halo mass $M_L$
(based on the total group luminosity $L_{tot}$) versus the true halo mass $M_h$
in the $B = 2.5$ case, for $N_g \geq 3(5)$. Besides a $\sim 0.3$ scatter
in log $M$, the averaged log $M_L$ is also systematically higher than
the true log $M_h$. We model the $M_L$-$M_h$ relation with a log-normal
PDF, with the systematic shift $(\log M_h - \log M_L)$ and statistical
scatter ($\sigma_{\log M}$) measured from Fig. 7. We replace $M_f$ in Eq. (11) as
$M_h$ randomly drawn from this log-normal distribution, given $M_L$
and $z$.

5 RESULTS

Fig. 8 shows the measured $C_\ell^{g, o}$ with richness cut $N_g \geq 5$,
for three redshift bins at $0.1 < z \leq 1.0$ and two mass bins. We
also show the best-fit theory curves, along with the best-fit bias and
$\chi^2_{\text{null}}$/d.o.f. Note that the effects of the Wiener filter and survey mask
are presented in both the measurement and in the theory curves,
instead of deconvolving the mask effect in the data part. We divide the
$\ell$ bins from $\ell = 10$ to $1000$ in log space. We choose the small
scale cut at $\ell=1000$ to avoid modeling small scale $P(k)$. The large
scale cut is to show the power of wide survey. The data and model
are very consistent within $10 < \ell < 1000$ as shown in Fig. 8.

5.1 The detection significance

The detections are significant at all six redshift-mass bins. We
quantify the detection significance with two definitions of signal-
to-noise ratio (S/N). One is data-driven, and describes the detection
significance of a non-zero signal. This S/N $\equiv \sqrt{\chi^2_{\text{null}}}$. Here
\begin{equation}
\chi^2_{\text{null}} = \sum_{\ell'} C_{\ell}^{g, o} C_{\ell'}^{-1} C_{\ell'}^{g, o}.
\end{equation}

The six redshift-mass bins achieve 10-20$\sigma$ detections of non-zero
cross-correlation signal. Since the covariance between different
redshift-mass bins is negligible, the total S/N combining all red-

Figure 7. The comparisons between the assigned halo mass $M_L$ (based on
the total group luminosity $L_{tot}$) and the true halo mass $M_h$. The true halo masses $M_h$ are a small subset of groups in the mock group catalog constructed
from MGRS. The dashed curves are shown for the average of true halo mass
log $M_h$ deviates from the average of assigned halo mass in 10 log $M_h$ bins.
The assigned halo mass is overestimated concerning the black $y = x$ solid line. The lower panels plot the scatter from the dashed lines, with red and
green colors representing the richness cuts $N_g \geq 3$ and $N_g \geq 5$, respectively.

Figure 8. Measured cross power spectra Planck CMB tSZ-deprojected lensing
map and the baseline group sample with richness cut $N_g \geq 5$ at 3 redshift
bins and 2 mass bins. The data of each galaxy sub-sample is well fitted by the
Planck 2018 cosmology prediction with a scale-independent bias (solid
curves). The bias is constrained with better than 10% accuracy and shows
clear mass and redshift dependence. Note that the effect of the Wiener filter
and survey mask is presented in both the measurement and in the theory
curves.
shift/mass bins is

$$\left(\frac{S}{N}\right)_{\text{total}} = \sqrt{\sum_{\beta} \left(\frac{S}{N}\right)_{\beta}^2}.$$  \hfill (13)

Here $\beta = 1, \cdots, 6$ denotes the six redshift and mass bins. The total $S/N$ for richness cut $N_g \geq 5$ is 39.8 for null discrimination and 38.7 for signal detection (Fig. 9).

The other definition of $S/N$ is fitting-driven, with $S/N = \sqrt{\chi^2_{\text{null}} - \chi^2_{\min}}$. Here

$$\chi^2_{\min} = \sum_{\ell\ell'} (C_{\ell\ell'}^{gg,\alpha} - b_{\text{bestfit}} C_{\ell\ell'}^{g,g,\text{th}}) C_{\ell\ell'}^{-1}(C_{\ell\ell'}^{g,g,\alpha} - b_{\text{bestfit}} C_{\ell\ell'}^{g,g,\text{th}}).$$  \hfill (14)

The $S/N$ defined in this way has the relation $\chi^2_{\min} = \chi^2_{\text{null}}$ for $\chi^2_{\min} \approx \chi^2_{\text{null}}$. Namely $S/N$ defined in both ways is basically the same (39.8 versus 38.7, for $N_g \geq 5$ galaxy groups, Fig. 9). The group bias is constrained with 5%–10% accuracy. It shows a significant increase with the halo mass and redshift, consistent with our theoretical expectation. And the p-value is 0.33 (0.22), 0.56 (0.14), 0.17 (0.17) for low-mass (high-mass) sample at $0.1 < z \leq 0.33$, $0.33 < z \leq 0.67$, $0.67 < z \leq 1$, respectively.

$\chi^2_{\min}$

5.2 Comparison with the theory prediction

The predictions of three halo bias models are listed in Table 2, while the comparison with the measurements are shown in Fig. 10. The agreement is excellent at the two high redshift bins, providing strong support on the robustness of the measurement and demonstrating the usefulness of the group catalog.

However, at the lowest redshift bin ($0.1 < z \leq 0.33$), the measured halo biases are $\sim 23\%$ ($3.1\sigma$) lower than the theoretical expectations for the low-mass bin, and $\sim 16\%$ ($2.6\sigma$) lower for the high-mass bin. We have checked that this is not caused by statistical photo-$z$ errors or magnification bias. It may be caused by a systematic bias in group redshift estimation (e.g., due to the galaxy color-redshift degeneracy (Zou et al. 2019)). If the true group redshift is higher, the resulting signal at the same large angular scale is smaller (Fig. 6), leading to the wrong interpretation of a smaller $b_g$. But the required bias in redshift is $\sim 0.1$ (Fig. 6), likely too large to be realistic.

We further discuss three remaining possibilities. (1) One is the misidentification of field galaxies of different redshifts as a group due to the line of sight projection effect. Such projection is most severer for low redshift group identification. The above two possibilities also affect the group-galaxy clustering, so it can be further tested by cross-correlating these galaxy groups with spectroscopic redshift galaxies. This is an issue for future investigation. (2) Another possibility is the existence of systematic overestimation of the halo mass. However, later tests with other group richness cut imply that it is unlikely the cause. Further complexity is that, for the low-mass bin, the low bias is caused by groups in the SGC (§B). But for the high-mass bin, the low bias is caused by NGC groups. The discrepancy between

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{z} & \textbf{SMT2001} & \textbf{Tinker2010} & \textbf{Jing1998} \\
\hline
0.1 < \text{z} \leq 0.33 & 1.27/ 1.76 & 1.15 / 1.65 & 1.28 / 1.90 \\
0.33 < \text{z} \leq 0.67 & 1.68 / 2.47 & 1.55 / 2.41 & 1.78 / 2.79 \\
0.67 < \text{z} \leq 1 & 2.84 / 3.85 & 2.81 / 4.02 & 3.27 / 4.59 \\
\hline
\end{tabular}
\caption{Halo bias models by SMT2001, Tinker2010 and Jing1998. These three models are as a function of redshift and halo mass. The table shows $b(M < M_{\text{div}}) / b(M \geq M_{\text{div}})$ in three tomographic bins.}
\end{table}
NGC/SGC group implies that the low bias issue is related to the identification of galaxy groups under different observing conditions of NGC/SGC. This issue will be further discussed in §B. (3) The third possibility is that what we really measure is the amplitude \( \sigma \) of the groups can largely rule out the photo-z outliers. So we only need to show the photo-z scatter will not strongly bias our results. We test the cases of \( \sigma_z = 0.01, 0.05, 0.1 \), and find that the impact on the best-fit bias can be ignored. \( \sigma_z = 0.01 \) is the most optimistic value for galaxy groups photo-z estimation, and 0.1 is the worst. We choose the \( \sigma_z = 0.05 \) as the fiducial one. The fractional error caused by the \( \sigma_z \) is on the theoretical templates, and also corresponds to the error on the estimated bias \( b_g \). Under different choices of \( \sigma_z \), the biggest impact on the theoretical template is for the lowest redshift bin, the fractional error is \( \sim 3.5\% \) for \( \sigma_z = 0.1 \), and \( \sim 1.7\% \) for \( \sigma_z = 0.01 \). This is insignificant compared to the statistical error which is about 10% at the lowest redshift. For the other two redshift bins, the fractional errors are less than 1%.

Another parameter is the \( \ell \) range (\( \ell_{\min} < \ell < \ell_{\max} \)) for the fitting. These \( \ell \) cuts are for general considerations of mitigating potential complexities at small scales (e.g. baryonic physics) and large

### Table 3.
The impact of \( f_{\text{threshold}} \) in defining the overdensity map on the analysis. Values in the parentheses are for the high-mass bins. The d.o.f. is 11. The agreement in the best-fit biases and \( \chi^2_{\text{min}} \) show that the fiducial \( f_{\text{threshold}} = 0.5 \) is valid for the analysis.

| \( z \) | \( f_{\text{threshold}} \) | \( b_{\text{best fit}} \) | \( \chi^2_{\text{min}} \) |
|-------|-------------|-----------------|-----------------|
| 0.1 < \( z \) \leq 0.33 | 0.3 | 0.95 ± 0.09 (1.48 ± 0.11) | 12.3 (13.7) |
| | 0.5 | 0.95 ± 0.09 (1.48 ± 0.11) | 12.5 (14.2) |
| | 0.7 | 0.95 ± 0.09 (1.47 ± 0.11) | 11.8 (14.7) |
| 0.33 < \( z \) \leq 0.67 | 0.3 | 1.60 ± 0.09 (2.43 ± 0.11) | 9.3 (15.9) |
| | 0.5 | 1.60 ± 0.09 (2.42 ± 0.11) | 9.7 (15.9) |
| | 0.7 | 1.58 ± 0.09 (2.42 ± 0.11) | 9.2 (16.4) |
| 0.67 < \( z \) \leq 1.0 | 0.3 | 2.94 ± 0.23 (4.05 ± 0.26) | 15.9 (15.0) |
| | 0.5 | 2.91 ± 0.23 (4.03 ± 0.26) | 15.4 (15.2) |
| | 0.7 | 2.92 ± 0.23 (4.03 ± 0.25) | 15.4 (14.5) |

We test the impact of several parameters in the analysis. One is the threshold \( f_{\text{threshold}} \) in defining the group number overdensity map. Larger \( f_{\text{threshold}} \) leads to larger/more masks in the map. Table 3 lists the best-fit bias results for \( f_{\text{threshold}} = 0.3, 0.5, 0.7 \). It shows that the impact of \( f_{\text{threshold}} \) is negligible, and the fitting result is stable around the fiducial \( f_{\text{threshold}} = 0.5 \).

Another parameter is the adopted photo-z scatter. The motivation of testing different photo-z scatter is, even though we don’t have a true \( n(z) \) for the group catalog, the selection on the galaxy-richness of the groups can largely rule out the photo-z outliers. So we only need to show the photo-z scatter will not strongly bias our results. We test the cases of \( \sigma_z = 0.01, 0.05, 0.1 \), and find that the impact on the best-fit bias can be ignored. \( \sigma_z = 0.01 \) is the most optimistic value for galaxy groups photo-z estimation, and 0.1 is the worst. We choose the \( \sigma_z = 0.05 \) as the fiducial one. The fractional error caused by the \( \sigma_z \) is on the theoretical templates, and also corresponds to the error on the estimated bias \( b_g \). Under different choices of \( \sigma_z \), the biggest impact on the theoretical template is for the lowest redshift bin, the fractional error is \( \sim 3.5\% \) for \( \sigma_z = 0.1 \), and \( \sim 1.7\% \) for \( \sigma_z = 0.01 \). This is insignificant compared to the statistical error which is about 10% at the lowest redshift. For the other two redshift bins, the fractional errors are less than 1%.

Another parameter is the \( \ell \) range (\( \ell_{\min} < \ell < \ell_{\max} \)) for the fitting. These \( \ell \) cuts are for general considerations of mitigating potential complexities at small scales (e.g. baryonic physics) and large
scales (e.g. imaging systematics (Rezaie et al. 2020)). Furthermore, in practice the S/N is negligible at \( \ell < 10 \) due to large cosmic variance, and is also negligible at \( \ell > 1000 \) due to overwhelming reconstruction noise in Planck lensing map. Therefore we adopt the fiducial \((\ell_{\text{min}}, \ell_{\text{max}}) = (10, 1000)\). Fig. 11 shows the consistency tests by varying \( \ell_{\text{max}} = 50, 150, 400, 1000 \), while fixing \( \ell_{\text{min}} = 10 \). The best-fit \( b \) is in general insensitive to \( \ell_{\text{max}} \), but we notice a trend of decreasing \( b \) with increasing \( \ell_{\text{max}} \), for the two low redshift and low-mass bins. If we only use the large scale data, the discrepancy between the measured bias and the theoretical prediction at low redshift may vanish. However, since the errorbars increase with aggressive \( \ell_{\text{max}} \) cut, the deviation between \( b \) of different \( \ell_{\text{max}} \) cut is only \~ 1\sigma. Fig. 12 shows the consistency tests for \( \ell_{\text{min}} = 10, 20, 30, 40, 50 \), while fixing \( \ell_{\text{max}} = 1000 \). The best-fit \( b \) has negligible dependence on \( \ell_{\text{min}} \). Therefore we demonstrate the robustness of our analysis against the choice of \((\ell_{\text{min}}, \ell_{\text{max}})\).

5.4 Richness dependence

We check the richness cut \( N_g \) adopted for this work. \( N_g \) has two-fold impacts on our results. First, lower \( N_g \) results in more groups, therefore higher measurement S/N. The S/N increases from S/N = 40 of \( N_g = 5 \) to S/N = 50 of \( N_g = 2 \) (Fig. 9). But on the other hand, lower \( N_g \) leads to lower purity in the group sample. This does not decrease the S/N, since even field galaxies contribute to the cross-correlation signal. However, it complicates the comparison with theory. This is the reason that we choose \( N_g = 5 \) as the fiducial richness cut. Nevertheless, since the average richness is a good proxy of halo mass, we expect the measured bias to increase with the richness. Therefore, despite the purity issue, measuring the dependence of cross-correlation on the richness cut is still a useful internal check of the measurement.

The results for \( N_g = 2, 3, 4, 5 \) are shown in Fig. 13. For high mass bins, the best-fit halo biases are insensitive to \( N_g \). This result is expected, since the measured group bias is determined by the majority of halos whose masses are above but close to the mass cut. But for low mass bins, \( b_g \) shows a significant increase with increasing \( N_g \), for all three redshifts. The majority of halos now have richness \( N_g \) and the mean halo mass/bias then decreases with \( N_g \).

The \( N_g \geq 2 \) group sample reveals an interesting problem. The low redshift and low mass bin have the best-fit bias \( b_g = 0.46 \pm 0.04 \). This extremely low bias can not be explained with the standard LCDM cosmology, since the halo bias has a lower bound around \( 0.7 \) (e.g. Jing (1998)). It can not be explained by an overall shift in the photo-z, since the required shift is too large to be realistic. A more plausible cause is the misidentification of field galaxies in overlapping lines of sight as groups. In this case, the contamination to “low” redshift groups is most likely from high redshift field galaxies, leading to weaker clustering at large angular scales (Fig. 6) and underestimation of group bias. This possibility should be further checked with future DESI spectroscopic redshift data, which will enable the measurement between these groups with galaxy distribution in true redshift.

5.5 Detection of the significant impact of tSZ

The thermal Sunyaev Zel’dovich (tSZ) effect can in principle contaminate the reconstructed lensing maps and bias the lensing-galaxy cross-correlation measurement. Previous work such as (Baxter et al. 2018; Kitanidis & White 2021; Dong et al. 2021) do not detect a significant impact of tSZ. Omori et al. (2019a) constructed a lensing systematic map through the tSZ map to better quantify its impact. They found that its impact on SPT+Planck CMB lensing-galaxy cross-correlation is significant at \( \lesssim 10^4 \), but insignificant at \( \geq 20 \).

To check the impact of tSZ, we also measure the cross-correlation of groups with the Planck minimum-variance (MV) lens map reconstructed from the SMICA CMB map. The S/N is 44.5 for null discrimination and 43.4 for signal detection. However, we find significant difference to the baseline case (with the lensing map reconstructed from tSZ-deprojected CMB temperature map). In terms of the group biases, they are \~ 30% higher at all redshift and mass bins, and the differences are all significant (\~ 5\sigma, Fig. 14). This finding is interesting. The major difference to previous works is that we use galaxy groups instead of galaxies. These groups have mean mass \~ 10^{13} M_\odot/h, and we have detected the tSZ effect with high significance (Chen et al. 2021). The tSZ effect associated with these galaxy groups is likely responsible for our finding. 10

This tSZ contamination is by itself useful for understanding gasphysics. But the full investigation of its impact requires both

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10 The contamination to the lensing map is quadratic in tSZ, \( \kappa(\tilde{\ell}) = \sum_{\ell_2} f(\tilde{\ell}, \ell_2) y(\tilde{\ell}_1, \ell_2) \delta_g(\tilde{\ell}_1) \). Here \( y(\tilde{\ell}_1, \ell_2) \) is the tSZ y-parameter and \( \delta_g \) is the group-CMB lensing cross-correlation. Therefore group/cluster scale tSZ effect \( (\ell_1 \gtrsim 1000) \) can propagate into degree scale cross-correlation measured in this work. Furthermore, since the same combinations of variables also contribute to the tSZ signal, this term vanishes in the cross-correlation with field galaxies since they do not occupy the same halos. This difference may be responsible for the different tSZ impacts on the galaxy-CMB lensing and group-CMB lensing.
measuring the tSZ effect of these groups with the Planck y-map, and propagating it into the Planck lensing map. These are beyond the scope of this work. Therefore for the purpose of this paper, we choose to use the tSZ-deprojected lensing map as our baseline analysis. To do so, we sacrifice the detection significance (45σ to 39σ), but gain cross-correlation measurement free of tSZ-related bias.

6 CONCLUSIONS AND DISCUSSION

In this work, we present the measurements of the DESI groups/clusters × Planck CMB lensing cross-correlations with tomographic analysis. We achieve an overall S/N ≈ 40 for groups of richness $N_g \geq 5$. This allows us to measure the group density bias and its redshift/mass dependence to ~10% accuracy. Besides routine consistent tests of the measurement, the value-added group catalog allows comparing the measured bias with the theory prediction. The agreement is excellent for $z > 0.33$ groups, but with a ~3σ discrepancy for $z < 0.33$ groups.

The above measurement of group bias is mainly for the validation of cross-correlation measurement. We have not attempted to constrain cosmology with the above measurements. One reason is due to uncertainties in the true redshift distribution of galaxy groups. The situation can be significantly improved by DESI. DESI will directly measure the redshifts of some group member galaxies. For the rest, through cross-correlation with DESI galaxies, the group redshift distribution can be tightly constrained. DESI redshift information will also improve uncertainties in estimating the group purity and completeness. Another issue is the impact of tSZ contamination on the lensing map. We find a significant difference whether we use the tSZ-deprojected map. For the same groups, we have detected a strong tSZ signal by stacking groups with the Planck y-map. We will further estimate whether the directly detected tSZ is consistent with the found impact on group-CMB lensing cross-correlation.

With these extra pieces of information, we expect the usefulness of group-CMB lensing cross-correlation in constraining cosmology.

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DATA AVAILABILITY

No new data were generated or analyzed in support of this research. The data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: MAGNIFICATION BIAS

Magnification bias modulates the number density of galaxies. Lensing magnifies the surface area and therefore decreases the number density by $1/\mu - 1 - 2\kappa$. But it also amplifies the galaxy flux and changes the galaxy number density above a flux limit or within a flux bin. Overall the observed galaxy number density $\delta_{g}^{\text{obs}}$ is changed from the intrinsic overdensity $\delta_{g}^{\text{int}}$ to

$$\delta_{g}^{\text{obs}} = \delta_{g}^{\text{int}} + g_{\mu} \kappa,$$  \hspace{1cm} (A1)

Here $g_{\mu}$ depends on the galaxy flux/magnitude (Yang et al. 2017; Kitanidis & White 2021; von Wietersheim-Kramsta et al. 2021). It then biases the group-convergence angular power spectrum,

$$C_{\ell}^{gK} \rightarrow C_{\ell}^{gK} + C_{\ell}^{g\mu}.$$  \hspace{1cm} (A2)

Here $C_{\ell}^{g\mu}$ denotes the convergence-magnification power spectra.

The contamination ($C_{\ell}^{g\mu}/C_{\ell}^{gK}$) increases with redshift, but remains $<1\%$ (Fig. A.1). The induced systematic shift in the group bias $b_{g}$ is

$$\delta b_{g} = \frac{\sum_{\ell} C_{\ell}^{gK} C_{\ell}^{g\mu}}{\sum_{\ell} C_{\ell}^{gK,\text{th}} C_{\ell}^{gK,\text{th}}}. \hspace{1cm} (A3)$$

We find $\delta b_{g} = -0.0040 (0.0051), -0.0149 (0.0197), -0.0430 (0.0519)$ from low to high redshift bins. The values in the parentheses are for the high-mass bins. Here we adopt $g_{\mu} = -2$, since the selection criteria of groups have a weak dependence on the galaxy flux and the area magnification should be dominant in its magnification bias. Compared with the statistical error $\sigma_{b}$, the systematic shift caused by magnification bias is $\lesssim 0.2 \sigma_{b}$. Therefore it is negligible.

APPENDIX B: NGC/SGC

Consistency tests have also been performed for the north galactic cap (NGC) and south galactic cap (SGC) (Zhao et al. 2021; Zarrouk et al. 2021), to test the concordance of different observational conditions, sample selections, or potential breakdown of cosmological isotropy.

Fig. B.1 shows the best-fit biases for NGC and SGC respectively. The $0.33 < z < 0.67$ redshift bin results are consistent. But for the $0.1 < z < 0.33$ redshift bin and low-mass bin, the SGC bias is lower than the NGC bias by $\sim 1\%$. Although it is statistically insignificant, it is likely the cause of the discrepancy between the theory and the measurement discussed in $\S 5.2$. However, for the high-mass bin, the SGC bias is higher than the NGC bias, although the difference is within $1\%$. A similar discrepancy is also found for the low-mass bin at $0.67 < z \lesssim 1$. Detailed investigation of these discrepancies is beyond the scope of this paper, but they may be related to the different observational conditions which affect the

![Figure A.1](image-url)
group identification. The mass and redshift distributions are indeed different between the NGC and SGC samples (Fig. B.2). The mean number density/mass/redshift are 120/deg$^2$, 3.65×10$^{13}$M$_\odot$, 0.38 for NGC, and 134/deg$^2$, 3.63×10$^{13}$M$_\odot$, 0.39 for SGC. These differences result in 0.82% difference in the theoretically predicted bias (〈b〉 = 2.42 for NGC and 2.44 for SGC).

We show the mass and redshift distributions of low-mass NGC and SGC groups in 0.1 < z ≤ 0.33. The amount of groups in NGC and SGC is 1089259 and 947505, respectively. However, it is yet to be investigated in the future whether this discrepancy is due to cosmic inhomogeneity or observational systematicity.

In Fig. B.2 B.3, we compare the mass distribution and redshift distribution (in the unit of square degree) between the NGC and SGC in the first redshift bin and the low-mass sub-sample. We find that the group distribution is inhomogeneous and the number of groups in NGC is greater than in SGC. We also find that the distribution of high mass is complementary at $M \sim 10^{13}$ between NGC and SGC. The difference of redshift and mass distribution could cause a big difference of bias in this sub-sample.

**APPENDIX C: UNCERTAINTIES IN S/N ESTIMATION**

When combining measurements at different redshift and mass bins into the total S/N, we have approximated that the measurement errors are uncorrelated between bins. This certainly applies to different redshift bins. However, for the low-mass and high-mass samples of the same redshift, it is valid only where their shot noises dominate over their intrinsic clusterings. Numerically we find that shot noise dominates at $\ell \geq 100$. So summing over (S/N)$^2$ to obtain the total S/N is valid. Nevertheless, at $\ell \leq 100$, the cross-correlation measurement errors between low and high-mass bins are indeed correlated.

A simple sum over (S/N)$^2$ could lead to overestimation of the total S/N. To test the robustness of the estimated S/N, we merge the two mass bins within each redshift bin, and measure the cross power spectra (Fig. C.1). S/N of the merged group sample is $\sqrt{\nu_{\text{null}}}$ = 32.1 and $\sqrt{\nu_{\text{null}}^2 - \nu_{\text{min}}^2} = 31.0$. This is slightly lower than S/N = 39.8(38.7) by the estimation with $\sqrt{(S/N)^2_{\text{low}} + (S/N)^2_{\text{high}}}$. The reduction in S/N may be caused by correlated measurement error between the low and high-mass bins. However, this is not the only
Figure C.1. Similar to Fig. 8, but merging the low-mass and high-mass bins. The merged group sample produces S/N = 32.1 for null discrimination and 31.0 for signal detection, slightly lower than the combined S/N of low and high-mass bins. We further discuss uncertainties of estimating S/N in the main text.

cause of S/N reduction. When we merge two groups, we lose the extra information on the mass and the mass-dependent clustering, so the S/N of the merged group sample is expected to be lower. Fig. 8 shows that the low-mass and high-mass cross power spectra may have different shapes. This may be responsible for the larger $\chi^2_{\text{min}}$/d.o.f. and lower S/N of the merged sample. Nevertheless, since there is no significant difference between the two estimations of S/N, we leave the investigation of their origin into future works.

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