MEASUREMENT OF THE INTEGRATED SACHS–WOLFE EFFECT USING THE ALLWISE DATA RELEASE

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ABSTRACT

One of the physical features of a dark-energy-dominated universe is the integrated Sachs–Wolfe (ISW) effect on the cosmic microwave background (CMB) radiation, which gives us a direct observational window to detect and study dark energy. The AllWISE data release of the Wide-field Infrared Survey Explorer (WISE) has a large number of point sources which span a wide redshift range, including where the ISW effect is maximized. AllWISE data are thus very well-suited for the ISW effect studies. In this study, we cross-correlate AllWISE galaxy and active galactic nucleus (AGN) overdensities with the Wilkinson Microwave Anisotropy Probe CMB temperature maps to detect the ISW effect signal. We calibrate the biases for galaxies and AGNs by cross-correlating the galaxy and AGN overdensities with the Planck lensing convergence map. We measure the ISW effect signal amplitudes relative to the ΛCDM expectation of $\Lambda = 1$ to be $\Lambda = 1.18 \pm 0.36$ for galaxies and $\Lambda = 0.64 \pm 0.74$ for AGNs. The detection significances for the ISW effect signal are $3.3\sigma$ and $0.9\sigma$ for galaxies and AGNs, respectively, providing a combined significance of $3.4\sigma$. Our result is in agreement with the ΛCDM model.

Key words: cosmic background radiation – cosmology: observations – dark energy – large-scale structure of universe

1. INTRODUCTION

After the discovery of dark energy in the late nineties (Riess et al. 1998; Perlmutter et al. 1999), it became one of the most elusive mysteries in the current era of physics. The existence of dark energy has been overwhelmingly, albeit indirectly, demonstrated by measurements of low-redshift Type Ia supernovae, baryon acoustic oscillation, galaxy clustering, and strong lensing (e.g., Riess et al. 2009; Vikhlinin et al. 2009; Reid et al. 2010; Suyu et al. 2013), combined with the measurement of cosmic microwave background (CMB) anisotropies by the Wilkinson Microwave Anisotropy Probe (WMAP, Hinshaw et al. 2013) and Planck (Planck Collaboration 2015a) missions. All of these observations suggest our universe to be flat, expanding at an accelerated rate, and dominated by dark energy with approximately 70% of the energy density of the universe accounted for by dark energy.

The integrated Sachs–Wolfe (ISW) effect (Sachs & Wolfe 1967; Rees & Sciacca 1968) provides us with a method to directly detect the effect of dark energy on CMB photons. When CMB photons cross a gravitational potential well, they experience blueshift while falling in and redshift while going out. The large-scale gravitational potential well is frozen for a matter-dominated, dark-energy-free, flat universe. As a result, the net shift in energy experienced by the CMB photons amounts to zero. However, for a dark-energy-dominated universe, the large-scale gravitational potential well decays while the CMB photons are crossing the potential well. Consequently, the photons gain a small amount of energy as the redshift fails to completely compensate for the blueshift. This energy shift is approximately one order of magnitude smaller than the primary CMB anisotropies, and therefore a direct measurement of the ISW effect is not possible. However, the ISW effect results in a correlation between hotter regions in the CMB with the large-scale structure (LSS), which can be used as an indirect probe to detect this effect.

Several studies have been performed to detect the ISW effect signal by cross-correlating WMAP CMB temperature maps with various survey catalogs and radiation backgrounds, e.g., Sloan Digital Sky Survey (SDSS) luminous red galaxies (Fosalba et al. 2003; Padmanabhan et al. 2005; Granett et al. 2009; Pápai et al. 2011), 2MASS galaxies (Afshordi et al. 2004; Rassat et al. 2007; Francis & Peacock 2010), APM galaxies (Fosalba & Gaztañaga 2004), radio galaxies (Nolta et al. 2004; Raccanelli et al. 2008), and the hard X-ray background (Boughn & Crittenden 2004). The typical confidence level for the ISW effect detection in the above studies is $2–3\sigma$. Comprehensive analyses combining different data sets were carried out by Ho et al. (2008) to detect a $3.5\sigma$ ISW effect signal and by Giannantonio et al. (2008) to achieve the strongest detection to date at $4.5\sigma$. Planck Collaboration (2015c) detected a $4\sigma$ ISW effect cross-correlation between the Planck CMB data and a combination of various data sets. Using only the Planck 2015 data release, Cabass et al. (2015) measured an upper limit for the ISW effect signal amplitude to be $\Lambda < 1.1$ at a 95% confidence level relative to the ΛCDM expectation of $\Lambda = 1$.

The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) conducted an all-sky survey in four mid-infrared frequency bands spanning from 3.4 to 22 μm. This survey, which includes millions of galaxies and active galactic nuclei (AGNs), provides one of the most lucrative data sets to carry out ISW effect studies. Some earlier studies were conducted using WISE data to detect the ISW effect signal, using WISE preliminary release and WMAP 7 year data to find a $3.1\sigma$ detection with the best fit being $2.2\sigma$ higher than the ΛCDM prediction (Goto et al. 2012), using WISE all-sky data and WMAP 7 year data to find a $1\sigma$ detection consistent with the ΛCDM prediction (Kovács et al. 2013), and using WISE all-sky data and WMAP 9 year data to find a combined $3\sigma$ ISW effect detection for galaxies and AGNs (Ferraro et al. 2015).

Whereas some of the above mentioned studies reported the signal amplitude of the ISW effect to be in good agreement with the ΛCDM model (e.g., Kovács et al. 2013; Ferraro et al. 2015), some other studies found the ISW effect amplitude to be higher (by $1–2\sigma$) than that predicted by the ΛCDM model (e.g., Ho et al. 2008; Granett et al. 2009; Goto et al. 2012).
WISE has detected a large number of point sources over the whole sky and the final AllWISE data release goes roughly twice as deep into the redshift space than the previous all-sky data release according to the AllWISE Explanatory Supplement. This makes AllWISE data very well-suited to carry out a study of the ISW effect as the detected objects span a wide range in redshift space that includes where the ISW effect is maximized. In this study, we used the AllWISE and WMAP 9 year data sets to detect the ISW effect signal.

The organization of the paper is as follows. In Section 2, we briefly review the ISW effect. In Section 3, we describe the data sets and methods. We present our results in Section 4, followed by a discussion and our conclusions in Section 5. Throughout this study, we use Planck 2015 results (Planck Collaboration 2015a), $H_0 = 67.74 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.31$, and $\Omega_V = 0.69$, for our fiducial cosmology.

2. THE ISW EFFECT

The primary anisotropy in the CMB was created during the last scattering at redshift $z \sim 1100$ due to fluctuations of potential energy, photon density, and velocity. The ISW effect is a secondary CMB anisotropy created by the time variation of the gravitational potential along the line of sight (Figure 1). This can be expressed as an integral from the last scattering surface to present day as

$$\left(\frac{\delta T}{T}\right)_{\text{ISW}}(\hat{n}) = \frac{1}{c^2} \int \Phi(\hat{n} + \hat{\Psi})[\eta, \hat{\Phi}(\eta_0 - \eta)] e^{-\tau(z)}d\eta \approx -\frac{2}{c^2} \int \Phi[\eta, \hat{\Phi}(\eta_0 - \eta)] d\eta,$$

where $\eta$ is the conformal time given by $\eta = \int dt/a(t)$, $a(t)$ is the scale factor, $\Phi$ and $\Psi$ are the conformal time derivatives of the gravitational potentials $\Phi$ and $\Psi$, $\tau$ is the optical depth, and $e^{-\tau(z)}$ is the visibility function for CMB photons. Here, on the second line, we approximated $\tau \ll 1$ over the period when $\dot{\Phi} \neq 0$ to take $e^{-\tau} \approx 1$. We also assumed that anisotropic stresses are negligible, and thus we have $\Phi = \Psi$.

As mentioned before, the ISW effect signal is roughly 10 times smaller than the primary CMB anisotropies, and thus cleanly separating the ISW effect from the primary anisotropy is not possible. Moreover, the total ISW effect signal includes both positive and negative contributions due to all of the small-scale potential fluctuations along the line of sight. We can assume that the ISW effect contributions from the small-scale potential wells and hills cancel each other out within a large enough scale. Then, the significant contribution to the ISW effect signal comes from the LSS. In addition to the ISW effect, the Sunyaev–Zeldovich effect (Sunyaev & Zeldovich 1972) and the lensing of CMB photons by the matter distribution can also induce a secondary anisotropy that correlates with matter overdensity. However, these anisotropies are only important in small angular scales with multipole $l \gtrsim 100$. We can assume the ISW effect to be the dominant source of secondary anisotropy in the multipole range $l \lesssim 100$.

To detect the ISW effect signal, we can calculate the cross-correlation between the CMB temperature anisotropy and the overdensity of a tracer for matter distribution, e.g., galaxies and AGNs. For simplicity, we only use subscript or superscript “g” to denote terms related to the tracer distribution, which are equally applicable for galaxies and AGNs. The tracer overdensity along a given direction $\hat{n}$ is given by

$$\delta_g(\hat{n}) = \int d\eta \frac{dN}{dz} \delta_m(\hat{n}, \eta) dz,$$

where $dN/dz$ is the selection function of the survey normalized so that $dN/dz = 1$, and $\delta_m$ is the tracer bias function relating visible matter and dark matter distributions, and $\delta_m$ is the matter density perturbation.

Then, the overdensity-CMB cross-power spectrum is given by

$$C_{Tg}^T = C_{gT}^T = 4\pi T_{\text{CMB}} \int \Delta^2_m(k) I_{Tg}(k)I_{gT}(k)\frac{dk}{k},$$

where $\Delta^2_m(k)$ is the dimensionless matter power spectrum at redshift $z = 0$ given by $\Delta^2_m(k) = k^3P(k, z = 0)/2\pi^2$ (Cooray 2002). The weight functions for the tracer overdensity and the ISW effect are given by

$$I_{Tg}^T(k) = \int d\eta \frac{dN}{dz} D(\eta) j_l(k\chi(\eta))\, d\eta,$$

$$I_{gT}^T(k) = 3\Omega_m H_0^2 \int \frac{dz}{dz} D(z) j_l(k\chi(z))\, dz,$$

where $j_l$ is the spherical Bessel function, $\chi(z)$ is the comoving distance to redshift $z$ given by $\chi(z) = c[T(\eta_0 - \eta)]$, and $D(z)$ is the linear growth factor normalized so that $D(z = 0) = 1$.

3. DATA AND METHODS

3.1. CMB Map

We used the 9 year foreground reduced WMAP temperature maps provided by the LAMBDA website\(^2\) (Bennett et al. 2013). We only used the Q, V, and W bands (41, 61, and 94 GHz, respectively) as they have the smallest amount of galactic

\(^1\) http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/index.html

\(^2\) http://lambda.gsfc.nasa.gov/
contamination. As we are only interested in \( l \leq 100 \), the maps were re-binned into HEALPix (Hierarchical Equal Area isoLatitude Pixelization; Górski et al. 2005) maps with the resolution parameter \( n_{\text{side}} = 128 \). We have used the KQ75y9 extended temperature analysis mask with \( f_{\text{sky}} = 0.65 \), which excludes point sources detected by WMAP. The final mask is the combination of the WMAP mask and a mask for the WISE data described in Section 3.3. This final mask was applied to both of the maps before taking the cross-correlation.

3.2. WISE Data

The WISE mission surveyed the whole sky in four bands: 3.4 (W1), 4.6 (W2), 12 (W4), and 22 \( \mu \)m (W4). In this study, we used the AllWISE data release, which combines the 4-band cryogenic phase with the NEOWISE post-cryo phase (Mainzer et al. 2011). This data release is deeper than the previous all-sky data release by roughly a factor of two in the W1 and W2 bands as the NEOWISE post-cryo phase only used these two bands. The AllWISE source catalog has over 747 million objects with signal-to-noise ratio \( (S/N) \geq 5 \) for profile-fit flux measurement in at least one band. We only select sources from the catalog using W1 and W2 magnitudes with \( S/N \geq 5 \) for the W1 band and \( S/N \geq 3 \) for the W2 band.

The coverage of WISE is not uniform throughout the sky. The mean number of exposures for the AllWISE data release is \( 30.17 \pm 0.02 \) in W1 and \( 30.00 \pm 0.03 \) in W2 with each exposure being \( 7.7 \) s long for both bands. According to the AllWISE Explanatory Supplement, the catalog is 95% complete for \( W1 < 17.1 \). Therefore, we applied this magnitude cut to ensure uniformity and completeness for our galaxy sample.

In this study, galaxies are defined as sources in the AllWISE catalog that are not classified as stars or AGNs. To remove stars from the object catalog, we used the following color cut: \([W1 − W2 < 0.4 \text{ & } W1 < 10.5]\) (Jarrett et al. 2011). We also removed any object with \( W1 − W2 < 0 \) to effectively remove galactic stars (Goto et al. 2012; Ferraro et al. 2015). To select AGNs from the catalog, we used the color cut criterion (Assef et al. 2013)

\[
W1 − W2 > 0.662 \exp[0.232(W2 − 13.97)^2].
\] (6)

For some of the objects in the AllWISE catalog, the W1 source flux uncertainty could not be measured because of the presence of a large number of saturated pixels in the 3-band cryo frames containing the source. These sources lie along a narrow strip of ecliptic longitude and are marked by null values for \( \text{wlmsigmpro} \). These objects are removed from the sample. We also discarded any object with \( \text{cc\_flags} \neq 0 \) in W1 or W2, as a non-zero value for \( \text{cc\_flags} \) indicates a spurious detection (diffraction spike, persistence, halo, or optical ghost). After applying the \( S/N \) and magnitude cuts, we are left with approximately 383 million objects. Of these objects, roughly 192 million (50.0%) are classified as galaxies, 189 million as stars (49.3%), and 2.6 million (0.7%) as AGNs according to the adopted color cut criteria.

3.3. Mask

We constructed the mask for the overdensity-CMB cross-correlation analysis with HEALPix resolution parameter \( n_{\text{side}} = 128 \). The \text{moon\_lev} flag in the AllWISE catalog indicates the fraction of frames contaminated by moonlight among the number of frames where the flux from a source was measured. We added HEALPix pixels with more than 20% sources with \( \text{moon\_lev} > 2 \) to the mask. HEALPix pixels with more than 10% sources with \( \text{cc\_flags} \neq 0 \) out of the total source count within the pixel are also added to the mask. As mentioned in Section 3.2, some objects in the AllWISE catalog with null values for \( \text{wlmsigmpro} \) were removed from the sample, and we excluded regions with more than 1% of such sources. We also excluded regions with galactic latitude \( |b| < 10^\circ \) to effectively remove areas of galactic contamination. For the AGN overdensity map, some HEALPix pixels \((<0.2\%)\) had an abnormally high source count and we added these pixels to the mask for the AGN overdensity map. After applying the combined final mask, the unmasked sky fraction becomes \( f_{\text{sky}} = 0.46 \) (Figure 2). This unmasked region contains approximately 106 million galaxies and 1.5 million AGNs.

3.4. Theoretical Computation

It is computationally difficult to evaluate the spherical Bessel integrals in Equations (4) and (5) through brute force. For efficient computation, we reformulated these integrals as logarithmically discretized Hankel transforms following Hamilton (2000). In this form, the integrals can be evaluated through fast-Fourier-transform (FFT) convolutions using the FFTLOG algorithm (Talman 1978).
Finally, we used CAMB with HALOFIT (Lewis et al. 2000; Smith et al. 2003) to generate the nonlinear matter power spectra for our fiducial cosmology.

4. RESULTS

4.1. Redshift Distribution

We performed source matching between the SDSS DR12 (Alam et al. 2015) galaxy sample and our AllWISE galaxy sample with a matching radius of $3''$. The matching radius was chosen based on the angular resolutions for the WISE $W_1$ and $W_2$ bands, which are $6''1$ and $6''4$, respectively. We only chose approximately 82 million galaxies with $r > 22.2$ (95% completeness limit; Abazajian et al. 2004) from the SDSS DR12 Photoz catalog. The common sky fraction for our mask and SDSS coverage region is $f_{\text{sky}} = 0.24$ and contains approximately 56 million AllWISE galaxies. We find matching pairs for roughly 29% of the AllWISE galaxy sample. The redshift distribution was then inferred from the SDSS photometric redshift of the matched galaxies (Figure 3). The low matching percentage of the AllWISE galaxies with SDSS is expected because high-redshift galaxies are optically fainter with redder $r-W_1$ color and the majority of the unmatched AllWISE galaxies can be massive ellipticals at $z \geq 1$ (Yan et al. 2013). As the 95% completeness magnitude limit for WISE, $W_1 < 17.1$, goes quite deep into redshift space, many high-redshift, WISE-selected galaxies fall beyond the SDSS 95% completeness limit of $r < 22.2$ (Figure 4).

To obtain the redshift distribution of the AGN sample, we executed source matching with approximately 750,000 objects flagged as “QSO” in the SDSS DR12 SpecObjAll catalog, which has spectroscopic redshifts for roughly 4.4 million objects. The matching radius was also taken as $3''$. Out of roughly 848,000 WISE selected AGNs in the common coverage region, we found matching pairs for approximately 15% of them.

It should be noted that SDSS had an uneven target selection strategy over different redshifts leading to a bias in the redshift distribution of the SDSS objects. Therefore, the redshift distribution obtained by source matching with SDSS objects would also be similarly biased. However, the ISW effect sensitivity function is widespread over a broad range of redshift peaking at $z_{\text{peak}} \approx 0.66$ (Figure 3) and the ISW effect measurement by cross-correlation is not very sensitive to errors in the estimation of redshift distribution (Afshordi 2004).

4.2. Bias Measurement

We used weak lensing of the CMB by our tracers of the matter overdensity to measure the bias. This method has two advantages over measuring the bias from the auto-correlation of the tracers: (1) it takes into account contamination by stars or artifacts, and (2) it is less prone to systematic errors giving a more robust estimation of the bias. The observed CMB temperature $T(\hat{n})$ is the lensed remapping of the original CMB temperature field $T_0(\hat{n} + d) = T(\hat{n})$, where $d$ is the deflection field. Then, CMB lensing convergence is defined as $\kappa \equiv -\nabla \cdot d/2 = -\nabla^2 \phi/2$, where $\phi$ is the lensing potential. The lensing convergence can be expressed as the line-of-sight integral of matter fluctuation as

$$\kappa(\hat{n}) = \int \delta(\chi \hat{n}, z(\chi)) W^c(\chi) \, d\chi,$$

where $W^c$ is the lensing window function given by (Cooray & Hu 2000):

$$W^c(\chi) = \frac{3 \Omega_m H_0^2}{2 \pi^2} \frac{\chi}{a(\chi)} \frac{\chi_b - \chi}{\chi_b}. $$
Here, $a(\chi)$ is the scale factor and $\chi_{m} \approx 14$ Gpc is the comoving distance to the last scattering surface.

The cross-correlation between the lensing convergence and matter overdensity field can be calculated using the Limber approximation (Limber 1953; Kaiser 1992), which works well for our angular scale of interest $l \gtrsim 100$, as

$$C_{l}^{s} \approx \int \frac{1}{\chi^{2}} W^{s}(\chi) W^{s}(\chi) P \left(k = \frac{l + 1/2}{\chi}, z \right) \frac{d\chi}{dz} dz, \quad (9)$$

where $P(k, z)$ is the nonlinear matter power spectrum at redshift $z$ for our fiducial cosmology and $W^{s}$ is the tracer distribution window function given by

$$W^{s}(\chi) = \frac{dz}{d\chi} \frac{dN}{dz} b(\chi). \quad (10)$$

We used the lensing convergence map provided by the Planck data release$^4$ 2 (Planck Collaboration 2015b) to cross-correlate it with the overdensity maps of our LSS tracers to measure their effective biases. The correlation between the WISE and Planck lensing convergence was investigated by Geach et al. (2013) and Planck Collaboration (2014), where these authors found $\sim 7\sigma$ detection for both galaxies and AGNs. Here, we repeated a similar analysis. We converted the lensing convergence and overdensity maps to HEALPix resolution $n_{\text{side}} = 512$. The mask for this analysis was taken to be a combination of the mask for the ISW effect analysis and the lensing convergence mask provided in the Planck lensing package. The unmasked sky fraction for this combined mask is $f_{\text{sky}} = 0.45$. We obtained the pseudo-power spectrum $C_{l}^{\text{rg}}$ of lensing-overdensity cross-correlation using the ANAFAST facility of the HEALPix package. We deconvolved the effect of masking and pixelization using the MASTER approach (Hivon et al. 2002) as

$$C_{l}^{\text{rg}} = \frac{B_{l}}{B_{l}'} \sum_{l'} M_{l'l'}^{B} C_{l'}^{\text{rg}}, \quad (11)$$

where $M_{l'l'}^{B}$ is the mode–mode coupling kernel for the applied mask and $B_{l}$ is the pixel window function for $n_{\text{side}} = 512$. We

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**Figure 5.** Cross-correlation between Planck lensing convergence and WISE galaxies (left) and AGNs (right). Vertical error bars are obtained from 100 simulated lensing convergence maps provided in the Planck lensing package and the horizontal error bars show bin widths for the band powers. The different bias models used for fitting are shown using lines and described in the corresponding legends. See Table 1 for the errors of the best-fit parameters for different models.

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| LSS Tracer      | Bias Model $b(z)$ | $b_{0}$ | $\chi^{2}$ |
|-----------------|-------------------|--------|------------|
| Galaxy sample   | $b_{0}$           | $1.17 \pm 0.02^a$ | 10.6       |
|                 | $b_{0}(1 + z)$    | $0.86 \pm 0.01^a$ | 9.7        |
| AGN sample      | $b_{0}$           | $2.90 \pm 0.07^a$ | 36.3       |
|                 | $b_{0}(0.55 + 0.289(1 + z)^2)$ | $1.44 \pm 0.04^a$ | 37.0       |

| Note. | The errors are computed by fitting the likelihood function $L(d, t(b_{0}), C) \propto \exp[(d - t)C^{-1}(d - t)]$ to a Gaussian distribution and taking the standard deviation of the fit as the error. Here, $d$ is the vector containing the measured band powers, $t$ is the vector containing the expected band powers for a given bias model, and $C$ is the covariance matrix. |

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$b_{0}$ is the mode–mode coupling kernel for the applied mask and $B_{l}$ is the pixel window function for $n_{\text{side}} = 512$. We

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$^4$ https://irsa.ipac.caltech.edu/Missions/planck.html
We obtained the best fit for each model by maximizing the likelihood function

$$\mathcal{L}(\mathbf{d}, \mathbf{t}, \mathbf{C}) \propto \exp \left[ -\frac{1}{2} (\mathbf{d} - \mathbf{t})^T \mathbf{C}^{-1} (\mathbf{d} - \mathbf{t}) \right] .$$  \hfill (14)$$

where \( \mathbf{d} \) is the vector containing the measured band powers, \( \mathbf{t} \) is the vector containing the expected band powers of the cross-correlation for each bias model, which depend on the model parameters, and \( \mathbf{C} \) is the covariance matrix. Here, we have assumed that individual data points are Gaussian distributed. Maximizing the likelihood function is equivalent to minimizing \( \chi^2 = (\mathbf{d} - \mathbf{t})^T \mathbf{C}^{-1} (\mathbf{d} - \mathbf{t}) \) and the likelihood ratio between two models are given by \(-2 \ln(\mathcal{L}_1/\mathcal{L}_2) = \Delta \chi^2 \). The best-fit parameters for each model are given in Table 1. We used the best-fit bias models, i.e., the linear evolution model for galaxies and the constant bias model for AGNs, in the CMB temperature-overdensity cross-correlation analysis.

### 4.3. Cross-correlation Measurement

We measured the cross-correlation of the WMAP CMB maps in the Q, V, and W bands and the AllWISE galaxy and AGN overdensity maps. The complex geometry of the mask induces off-diagonal correlations between the multipoles. We deconvolved the effect of masking and pixelization from the pseudo-power spectrum \( \tilde{C}_l^{Tg} \), which is obtained through ANAFAST, as

$$C_l^{Tg} = \frac{1}{B_{\ell} F_{\ell}} \sum_i M_{il}^{-1} \tilde{C}_l^{Tg} ,$$  \hfill (15)$$

where \( M_{il} \) is the mode–mode coupling kernel for our adopted mask, \( B_{\ell} \) is the pixel window function for \( n_{\text{side}} = 128 \), and \( F_{\ell} \) is the WMAP beam transfer function. WMAP provides beam transfer functions for each differencing assembly in a band. We took an average of the beam transfer functions for all of the differencing assemblies in a given band to obtain the beam

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**Figure 6.** Examples of simulated WMAP CMB maps in the Q band (top), V band (middle), and W band (bottom) using our fiducial cosmology and WMAP beam transfer function. They used different random \( a_{\text{rand}} \), but the same \( C_l \), generated using CAMB for our fiducial cosmology.

**Figure 7.** Monte Carlo covariance matrices for galaxy-CMB (top) and AGN-CMB (bottom) cross-correlation band powers in the Q band. Covariance matrices for the V and W bands are not included as they are similar.
transfer function for each band as \( F_l^2 = \sum_i^N (F_l^{(i)})^2 / N \), where \( N \) is the number of differencing assemblies in each WMAP band and the index \( i \) goes over all of the differencing assemblies. We binned the deconvolved power spectra into eight logarithmic bins (band powers) using a binning operator \( P_{bl} \) given by

\[
P_{bl} = \begin{cases} 
\frac{1}{2\pi} \frac{l(l+1)}{(b+1) - (b)} & \text{if } l_{low}^{(b)} \leq l < l_{low}^{(b+1)}, \\
0, & \text{otherwise},
\end{cases}
\]

where \( l_{low}^{(b)} \) denotes the lower boundary of the \( b \)th bin. We took the bin boundaries as \( l = 2, 5, 8, 12, 17, 26, 41, 64, \text{ and } 100; \text{ thus, the first band includes } l = 2, 3, 4, \text{ etc. We avoided } l \geq 100 \text{ as the ISW effect is not sensitive at these small scales.}

To estimate the Monte Carlo error bars and covariance matrices, we ran 5000 simulations for each WMAP band. We used our fiducial cosmological parameters and WMAP beam transfer function to obtain the simulated CMB maps using SYNFAST included in the HEALPix package. Then, we added noise to each pixel by adding a random value from a Gaussian distribution with zero mean and standard deviation given by \( \sigma = \sigma_0 / \sqrt{N_{obs}} \), where \( \sigma_0 = 2.188, 3.131, \text{ and } 6.544 \text{ mK for the Q, V, and W bands, respectively, and } N_{obs} \text{ is the effective number of observations for the corresponding pixel in the WMAP survey}. Some examples of the simulated CMB maps for different WMAP bands are shown in Figure 6. We cross-correlated these simulated maps with AllWISE galaxy and AGN overdensity maps to obtain the covariance matrices according to Equation (13). The error bars are taken to be the square roots of the diagonal elements of the covariance matrix. The neighboring bins are anti-correlated by 3%–20% in the lower multipole range and correlated by roughly 20%–30% in the higher end of the multipole range (Figure 7).

We find that the band powers are consistent across different WMAP bands (Figure 8). This indicates that the CMB maps are not likely to have significant foreground contamination.

We obtained the amplitude \( A \) of the signal by minimizing \( \chi^2 = (d - At)^T C^{-1} (d - At) \), where \( d \) is the vector containing the measured band powers, \( t \) is the vector containing corresponding power spectra of the \( \Lambda \)CDM model, and \( C \) is the Monte Carlo covariance matrix. Then, the signal amplitude and its error are given by

\[
A = d^T C^{-1} t [t^T C^{-1} t]^{-1}, \quad \sigma_A = [t^T C^{-1} t]^{-1/2}.
\]

We calculated the significance of the detection from

\[
S/N = \sqrt{\chi^2_{null} - \chi^2_{fit}} = d^T C^{-1} t [t^T C^{-1} t]^{-1/2} = \frac{A}{\sigma_A}
\]

where \( \chi^2_{fit} \) is for the best fit and \( \chi^2_{null} \) is for the null hypothesis with \( t = 0 \).

We detected the ISW effect signal for AllWISE galaxies with 3.3\( \sigma \) significance for all three WMAP bands. The combined ISW effect signal amplitude for the three WMAP bands is \( A = 1.18 \pm 0.36 \), which agrees very well with the \( \Lambda \)CDM prediction of \( A = 1 \). For AGNs, the ISW effect amplitude is \( A = 0.64 \pm 0.74 \) with 0.9\( \sigma \) significance, which is also in agreement with the \( \Lambda \)CDM model. The signal amplitude and some basic statistical properties for each WMAP band are given in Table 2.

5. DISCUSSION AND CONCLUSIONS

In this study, we detected the ISW effect signal from the cross-correlation between the WMAP CMB temperature map and the matter overdensity map using AllWISE galaxies and AGNs as tracers for matter distribution. The ISW effect detection significances for galaxies and AGNs are 3.3\( \sigma \) and 0.9\( \sigma \), respectively, with a combined significance of 3.4\( \sigma \) and good agreement with the \( \Lambda \)CDM model for both tracers.

Among other ISW effect studies using WISE data, Goto et al. (2012) detected the ISW effect amplitude to be 2.2\( \sigma \) higher than that for the \( \Lambda \)CDM model; these authors used the WISE preliminary release and WMAP 7 year data. Ferraro et al. (2015) used the WISE all-sky release and WMAP 9 year data to detect...
the ISW effect signal at 3σ and in good agreement with the ΛCDM cosmology. Our result fully agrees with the finding of Ferraro et al. (2015).

The measured biases of the tracers in our study for constant and linear redshift evolution bias models are lower than those calculated by Ferraro et al. (2015) by approximately 13%–20%. Ferraro et al. (2015) used the lensing potential map from Planck data release 1 (2013), whereas we used the lensing convergence map provided by Planck data release 2 (2015). The 2013 lensing potential map was obtained by combining only the 143 and 247 GHz channels, whereas the 2015 lensing convergence map was constructed by applying a quadratic estimator to all nine frequency bands. Kuntz (2015) used both of the Planck data releases to measure the cross-correlation between the CMB lensing and Canada–France–Hawaii Telescope Lensing Survey galaxy catalog and found that the cross-correlation amplitude measured using the 2015 data is roughly 19% lower than that measured using the 2013 data. This result is consistent with the discrepancy in the bias measurement between the study of Ferraro et al. (2015) and our study.

The redshift distribution of the AllWISE galaxies might have missed a large fraction (~70%) at the higher-redshift end of the distribution due to the shallower depth of SDSS galaxies. However, this missing fraction does not significantly affect our final amplitude measurement. We checked the robustness of our measurement against errors in redshift distribution estimation by using the redshift distribution of W1 selected galaxies from the WISE all-sky release provided by Yan et al. (2013; as used by Ferraro et al. 2015) instead of our own estimation. This distribution spans a wide range of redshift up to z ~ 0.9. We found the ISW effect amplitude for the galaxy sample to be

A = 1.28 ± 0.39 for this galaxy redshift distribution, which is very close (within 0.3σ) to the original measurement.

Contamination due to foreground emission in the CMB maps might lead to systematic error in the ISW effect detection in the form of spurious correlation with LSS tracers. However, the amount of foreground contamination would be different across the frequency bands. In our measurement, we find the cross-correlations between the LSS tracers and the CMB maps in three WMAP bands to be consistent with each other. This consistency rules out any significant contamination by foreground emission in the CMB maps.

The significance of the ISW effect signal amplitude for our AGN sample is low (0.9σ). This low significance is partially because the AGN sample mostly spans the redshift range z ≥ 1, where the universe is not yet dominated by dark energy. As a result, the ISW effect is less sensitive to this redshift range and the expected signal becomes low. On the other hand, due to the much smaller sample size of the AllWISE AGNs, the shot noise is higher than that for the galaxy sample. This high shot noise limits the detection significance, especially in higher multipoles.

Dark energy is one of the most active fields in modern cosmology as many of its properties still remain unknown. Although the existence of dark energy is significantly demonstrated by various indirect measurements, the ISW effect is one of the only direct observational probes to study dark energy. In this study, we detected the ISW effect signal by cross-correlating WMAP CMB temperature maps with AllWISE galaxies and AGNs. These detections rule out a matter-dominated, dark-energy-free universe by a combined significance of 3.4σ. Future surveys covering a large portion of the sky with extensive redshift coverage and a sufficient number of frequency bands for photometric redshift estimation can push this detection significance to the 5σ level and attain the precision necessary to pinpoint the physical properties of dark energy.

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Software: HEALPix (http://healpix.sourceforge.net).

Table 2

| LSS Tracer | WMAP Band | A     | S/N | χ²  | dof | Δχ²_{CDM} | Δχ²_{null} |
|-----------|-----------|-------|-----|-----|-----|----------|-----------|
| Galaxy sample | Q | 1.18 ± 0.35 | 3.3 | 6.09 | 7 | 0.26 | 11.17 |
| V         | 1.19 ± 0.36 | 3.3 | 6.40 | 7 | 0.32 | 11.31 |
| W         | 1.17 ± 0.36 | 3.3 | 6.52 | 7 | 0.21 | 10.58 |
| Q         | 0.65 ± 0.74 | 0.9 | 9.12 | 7 | 0.21 | 0.77 |
| AGN sample | V         | 0.62 ± 0.74 | 0.8 | 9.86 | 7 | 0.28 | 0.70 |
| W         | 0.65 ± 0.74 | 0.9 | 9.32 | 7 | 0.22 | 0.79 |

Note. The “dof” column refers to the degrees of freedom of the χ² distribution. Δχ²_{null} shows Δχ² of the best fit from the null hypothesis t = 0 and Δχ²_{CDM} shows Δχ² of the best fit from the ΛCDM prediction.
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