

# Dipolar modulation in number counts of WISE-2MASS sources

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## ABSTRACT

We test the statistical isotropy of the universe by analyzing the distribution of WISE extragalactic sources that were also observed by 2MASS. We pay particular attention to color cuts and foreground marginalization in order to cull a uniform sample of extragalactic objects and avoid stars. We detect a dipole gradient in the number-counts with an amplitude of  $\sim 0.05$ , somewhat larger than expectations based on local structures corresponding to the depth and (independently measured) bias of our WISE-2MASS sources. The direction of the dipole,  $(l, b) \simeq (310^\circ, -15^\circ)$ , is in reasonably good agreement with that found previously in the (shallower) 2MASS Extended Source Catalog alone. Interestingly, the dipole direction is not far from the direction of the dipolar modulation in the CMB found by Planck, and also fairly closely matches large-scale-structure bulk-flow directions found by various groups using galaxies and type Ia supernovae. It is difficult, however, to draw specific conclusions from the near-agreement of these directions.

## 1 INTRODUCTION

Modern surveys of large-scale structure allow tests of some of the most fundamental properties of the universe – in particular, its statistical isotropy. One of the most fundamental such tests is measuring the dipole in the distribution of extragalactic sources. One expects a nonzero amplitude consistent with the fluctuations in structure due to the finite depth of the survey; this “local-structure dipole” in the nomenclature of Gibelyou & Huterer (2012) is of order 0.1 for shallow surveys extending to  $z_{\text{max}} \sim 0.1$ , but significantly smaller ( $A \lesssim 0.01$ ) for deeper surveys. The motion of our Galaxy through the cosmic microwave background (CMB) rest frame also contributes to the dipole, but only at the level of  $v/c \simeq 0.001$ ; while this kinematic dipole was detected in the CMB a long time ago, and more recently even solely via its effects on the higher multipoles in the CMB fluctuations (Aghanim et al. 2013), it has not yet been seen in large-scale-structure (LSS) surveys.

Measurements of the dipole in LSS therefore represent consistency tests of the fundamental cosmological model, and have in the past been applied to the distribution of sources in NVSS (Blake & Wall 2002; Hirata 2009; Rubart & Schwarz 2013; Fernández-Cobos et al. 2014). Detection of an anomalously large (or small) dipole in LSS could indicate new physics: for example, motion between the CMB and LSS rest frames, or the presence of super-horizon fluctuations (Zibin & Scott 2008; Itoh, Yahata & Takada 2010). Moreover, in recent years, measurements of the bulk motion of nearby structures have been conducted, out to several hundred megaparsecs, using CMB-LSS correlations (Kashlinsky et al. 2008), or out to somewhat smaller distances, using peculiar velocities (Watkins, Feldman & Hudson 2009; Feldman, Watkins & Hudson 2010).

In this study, for the first time we test statistical isotropy using WISE (Wide-field Infrared Survey Explorer) (Wright et al. 2010).

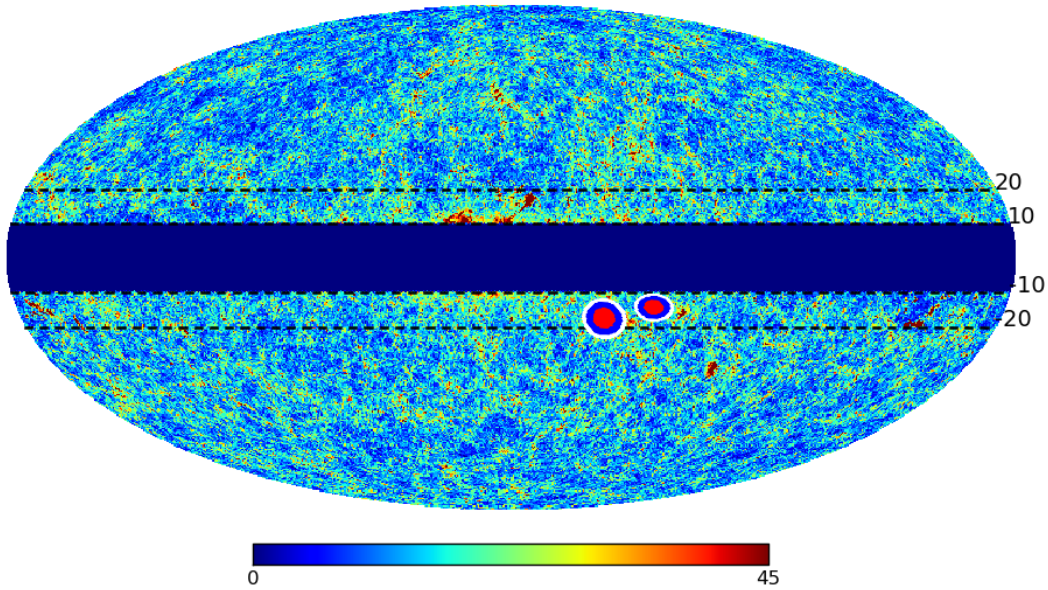
WISE is, at least at first glance, perfectly suited to tests of statistical isotropy since it is deep and covers nearly the full sky. Moreover, its selection functions have been increasingly well understood over the past few years based on its observations in four bands sensitive to 3.4, 4.6, 12, and 22  $\mu\text{m}$  wavelengths with resolution in the 6”–12” range (Yan et al. 2013; Ménard et al. 2013).

## 2 CULLING OF THE WISE DATASET

Our measurement of the dipole relies on a suitable selection of a representative sample of sources. The most important goal is to exclude Galactic sources – mainly stars. Galactic sources are expected to be concentrated around the Galactic plane, with density falling off to the north and south. While they are therefore expected to look like a  $Y_{20}$  *quadrupole* in Galactic coordinates, the residual contamination of the dipole may still be significant. Hence, in what follows we pay particular attention to magnitude and color cuts applied to WISE in order to leave a trustworthy set of extragalactic sources.

The Nov. 2013 release of WISE data includes 747 million objects in total. Individual objects were not identified in the raw data, so data selection is the key part of the analysis. We therefore apply carefully chosen criteria to define a map as uncontaminated by Galactic objects as possible. As argued in Kovács & Szapudi (2013), color cuts using only the WISE bands are not sufficient, so we have applied 2MASS<sup>1</sup> magnitudes ( $J_{2\text{mass}}$ ) to distinguish between stars and galaxies. In other words, every source we use is observed in both WISE and 2MASS, though we refer to our sample as “WISE” because using that survey is crucial to give our sample

<sup>1</sup> Two Micron All Sky Survey (Skrutskie et al. 2006).



**Figure 1.** Map of WISE-2MASS sources that we used with 10 degree Galactic cut (before masking out the contaminated region with the WMAP dust mask). The criteria are described in the text. The map shown is a Mollweide projection in Galactic coordinates with counts binned in pixels of about  $0.5^\circ$  on a side (HEALPix resolution NSIDE = 128). The two elliptical sets of contours represent the measured dipole direction when we applied a  $10^\circ$  (left) and  $20^\circ$  (right) Galactic cut, respectively (that is, with  $|b| < 10^\circ$  and  $|b| < 20^\circ$ ). The red, blue, and white colors in those contours represent the 68%, 95%, and 99% confidence regions for the direction.

greater depth. To cull a uniform, extragalactic sample of sources, we adopt the following color cuts:

- $W1 < 15.2$ ,
- $J_{2\text{mass}} < 16.5$ ,
- $W1 - J_{2\text{mass}} < -1.7$ .

Note that the first two criteria simply remove the faintest objects in the respective band. To account for the effects of extinction by dust, we correct the magnitudes for these two cuts using the SFD (Schlegel, Finkbeiner & Davis 1998) map<sup>2</sup>. The third criterion above represents the color cut that serves to separate galaxies from stars. The detailed analysis on the data selection was described in Kovács & Szapudi (2013); the resulting WISE map is shown in Fig. 1.

Unlike the previous studies that used WISE for cosmological tests (Kovács et al. 2013; Ferraro, Sherwin & Spergel 2014), our map does not show obvious contamination in regions affected by the appearance of the Moon. Therefore, we do not need to make further (and typically severe) cuts that remove these regions. We do use the WMAP dust map (Bennett et al. 2013) to mask out the pixels with remaining contamination; these mostly fall within  $\pm 15^\circ$  Galactic latitude. In addition, we cut out all pixels with  $E(B - V) > 0.5$  from the SFD map (most of these have already been excluded by the WMAP dust map). We also checked for any unusual gradients with Galactic latitude, especially around the Galactic plane, due to contamination from stars. These tests were consistent with zero gradient.

In the analysis, there are of order 2 million galaxies. We used

the GAMA DR2 (Driver & Gama Team 2008) catalog to find sources in the WISE dataset that are within  $3''$  of GAMA sources. We can thus determine the redshift distribution of our objects. In the 144 sq. deg. overlapping region on the sky, the matching rate is 96.9%. The redshift distribution of matched objects,  $N(z)$ , is shown in Figure 2; the mean is  $\bar{z} = 0.139$ . We use a smooth fit to the full distribution to obtain our theoretical expectation for the local-structure dipole below.

### 3 METHODOLOGY

#### 3.1 Dipole estimator

A robust and easy-to-implement dipole estimator was first suggested by Hirata (2009), who measured hemispherical anomalies of quasars, and later adopted by Gibelyou & Huterer (2012) to measure the dipole in a variety of LSS surveys. The number of sources in direction  $\hat{n}$  can be written as

$$N(\hat{n}) = [1 + A \hat{\mathbf{d}} \cdot \hat{\mathbf{n}}] \bar{N} + \epsilon(\hat{n}) \quad (1)$$

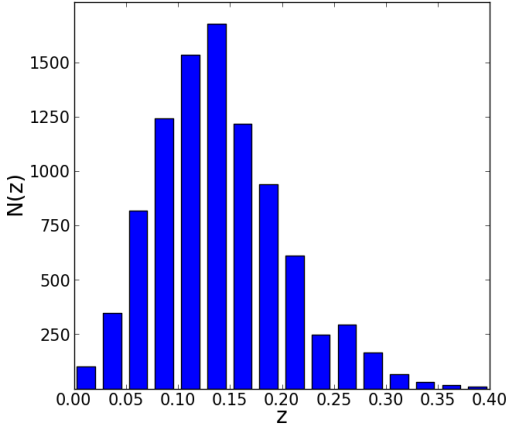
where  $A$  and  $\hat{\mathbf{d}}$  are the amplitude and direction of the dipole, and  $\epsilon$  is noise.

The modulation in number counts can be written as the sum of contributions from a dipole, fluctuations due to systematics, and a mean offset (Hirata 2009).

$$\delta N / \bar{N} = A \hat{\mathbf{d}} \cdot \hat{\mathbf{n}} + \sum_i k_i t_i(\hat{\mathbf{n}}) + C. \quad (2)$$

Here  $t_i(\hat{\mathbf{n}})$  represent the systematics maps, while the coefficients  $k_i$  give the amplitudes of the contributions of these systematics to the observed density field. The presence of the monopole term,  $C$ , allows us to account for covariance between the monopole

<sup>2</sup> [http://lambda.gsfc.nasa.gov/product/foreground/fg\\_sfd-get.cfm](http://lambda.gsfc.nasa.gov/product/foreground/fg_sfd-get.cfm)



**Figure 2.** Number counts of WISE sources as a function of redshift. We obtain redshift information by matching WISE sources to those from the GAMA DR2 catalog. As explained in the text, matching works very well.

and other estimated parameters, especially covariance between the monopole and any systematic templates. The best linear unbiased estimator of the combination  $(\mathbf{d}, k_i, C)$ , with corresponding errors, is obtained as follows. First, we rewrite the above equation as  $\delta N/N = \mathbf{x} \cdot \mathbf{T}(\hat{\mathbf{n}})$  where  $\mathbf{x} = (d_x, d_y, d_z, k_1, \dots, k_N, C)$ ,  $\mathbf{T}(\hat{\mathbf{n}}) = (n_x, n_y, n_z, t_1(\hat{\mathbf{n}}), \dots, t_N(\hat{\mathbf{n}}), 1)$ , and  $n_x^2 + n_y^2 + n_z^2 = 1$ . The best linear unbiased estimator of  $\mathbf{x}$  is

$$\hat{\mathbf{x}} = F^{-1}g \quad (3)$$

where the components of the vector  $g$  are  $g_i = \int T_i(\hat{\mathbf{n}}) \delta N^\Omega(\hat{\mathbf{n}}) d^2\hat{\mathbf{n}}$  and the Fisher matrix  $F$  is given by  $F_{ij} = \bar{N}^\Omega \int T_i(\hat{\mathbf{n}}) T_j(\hat{\mathbf{n}}) d^2\hat{\mathbf{n}}$ , where  $N^\Omega \equiv dN/d\Omega$  is the number of galaxies per steradian ( $\Omega$  is a solid angle). The integrals from which the vector  $g$  and the Fisher matrix  $F$  are calculated are discretized in our survey. We adopt a HEALPix Górski et al. (2005) pixelization with NSIDE=128, so that each pixel corresponds to about half a degree on a side and contains roughly 14 sources.

The formalism above returns the best-fit dipole components (first three elements of the vector  $\mathbf{x}$ ), together with their covariance (inverse of the corresponding Fisher matrix). We are however most interested in the likelihood of the amplitude of the dipole,  $A = (d_x^2 + d_y^2 + d_z^2)^{1/2}$ . We can construct a marginalized likelihood function for the amplitude  $A$  (Hirata 2009):

$$\mathcal{L}(A) \propto \int \exp \left[ -\frac{1}{2} (A\hat{\mathbf{n}} - \mathbf{d}_{\text{best}}) \text{Cov}^{-1} (A\hat{\mathbf{n}} - \mathbf{d}_{\text{best}}) \right] d^2\hat{\mathbf{n}} \quad (4)$$

where  $d^2\hat{\mathbf{n}}$  indicates integration over all possible directions on the sphere. Thus we readily obtain a full likelihood for the amplitude. In our results, we quote the 68% region around the best-fit amplitude.

### 3.2 Foreground Templates and Estimator Validation

Despite our carefully chosen magnitude and color cuts, it is likely that there is some star contamination to our extragalactic source map. Moreover, on a cut sky, the dipole is not completely decoupled from the monopole, quadrupole, and other multipoles, and hence we need to marginalize over some of them in order to get correct

results. We therefore include several templates – maps  $t_i(\hat{\mathbf{n}})$  in the parlance of Eq. (2) – with amplitudes  $k_i$  over which we marginalize:

- To deal with the remaining star contamination, we add a star map as a template. The star map was generated based on the Tycho 2 catalog (Høg et al. 2000), as suggested in Kovács et al. (2013). The inclusion of this template affects the measured dipole negligibly, reinforcing our confidence that star contamination does not affect the result.
- To account for the other multipoles, we add the monopole (corresponding to the constant  $C$  in Eq. (2) with no spatial dependence), as well as the quadrupole and octopole that include 5 and 7 extra parameters. We therefore marginalize over these 13 parameters in addition to the amplitude of the star map. We experimented with marginalization over a few more ( $\ell \geq 4$ ) multipoles, but for small Galactic cuts ( $b_{\text{cut}} \lesssim 15^\circ$ ), the shift in the dipole direction and magnitude were small.

We validated our estimator by running simulations with an input dipole of a given amplitude assuming various sky cuts and marginalizing over templates. We verified that the input dipole is recovered within the error bars.

### 3.3 Theoretical expectation

We calculate the theoretical expectation for the local-structure dipole using standard methods (see e.g. Sec. 2.2 of Gibelyou & Huterer (2012)). We calculate the angular power spectrum of large-scale structure for the given source distribution  $N(z)$ , and evaluate it at the dipole ( $C_\ell$  at  $\ell = 1$ ); this calculation does not assume the Limber approximation since the latter is inaccurate at these very large scales. The amplitude is then given as  $A_{\text{theory}} = (9C_1/(4\pi))^{1/2}$  (Gibelyou & Huterer 2012), while the theory error is given by cosmic variance for  $\ell = 1$ :  $\delta A_{\text{theory}}/A_{\text{theory}} = (1/2)\sqrt{2/((2\ell+1)f_{\text{sky}})} = (6f_{\text{sky}})^{-1/2}$ . Evaluating the theoretically expected dipole for the source distribution shown in Fig. 2, we get

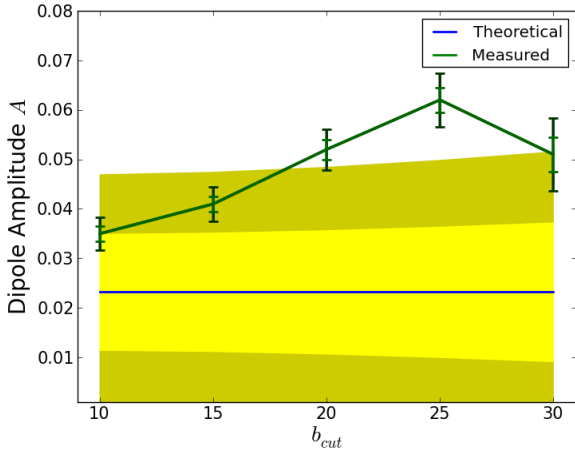
$$A_{\text{theory}} = (0.0233 \pm 0.0094 f_{\text{sky}}^{-1/2}) \times \left( \frac{\text{bias}}{1.41} \right) \quad (5)$$

Here we make explicit the dependence of the cosmic variance error on the fraction of the sky covered  $f_{\text{sky}}$ , and also on the bias of WISE sources. To obtain the latter, we followed Kovács & Szapudi (2013), and estimated the bias of the galaxy catalog using SPICE (Szapudi, Prunet & et al. 2001) and the Python CosmoPy<sup>3</sup> package. We note that the estimation of the bias is particularly sensitive to  $\sigma_8$  because they both act to renormalize the angular power spectrum, and in linear theory  $C_\ell^{gg} \propto (b\sigma_8)^2$ . We fix  $\sigma_8 = 0.8$  in our measurements, finding  $b = 1.41 \pm 0.07$ . This value is comparable to earlier findings (Rassat, Land & et al. 2007) that measured a value of  $b = 1.40 \pm 0.03$  for a 2MASS selected galaxy sample.

## 4 RESULTS

Our measurements of the dipole’s amplitude and direction, as a function of the (isolate) Galactic cut, are presented in Table 1. The best-fit direction of the dipole is also shown in Fig. 1 for

<sup>3</sup> <http://www.ifa.hawaii.edu/cosmopy/>



**Figure 3.** Theoretical prediction for the dipole amplitude (horizontal blue line), together with the measured values in WISE (green points). The two sets of error bars on the measurements correspond to 68% and 95% confidence; they have been calculated from the full likelihood in Eq. (4) and are rather symmetric around the maximum-likelihood value. The two large horizontal bands around the theory prediction correspond to 1- and 2-sigma cosmic variance error.

the  $10^\circ$  and  $20^\circ$  Galactic cut, the two cases roughly illustrating the dependence of the direction on the Galactic cut.

We first note a reasonably good consistency between the recovered directions, despite the fact that the number of sources decreases by a factor of  $\sim 1.4$  as we increase the Galactic cut in the range shown. We also note that the overall amplitude is roughly 1.5 - 2.7 times larger than the theoretically expected one, and is roughly 1-2 $\sigma$  high, where  $\sigma$  corresponds to cosmic variance since the measurement error is much smaller (see Table 1). Finally, we note that while the dipole amplitude does vary with  $b_{\text{cut}}$  more than its typical measurement errors, it is overall consistent at  $A_{\text{WISE}} \simeq 0.04\text{--}0.05$ , which is rather robustly stable given the large decrease of the number of sources with increasing Galactic cut.

It is interesting to note that 2MASS Extended Source Catalog data, as analyzed in Gibelyou & Huterer (2012) (redshift  $0 < z < 0.2$ ,  $N = 3.8 \times 10^5$ ), give  $A_{2\text{MASS}} = 0.104 \pm 0.004$ ,  $(l, b) = (268.4^\circ, 0.0^\circ)$  – amplitude higher than ours due to the greater contribution of the local-structure dipole for the shallower survey, direction not far. Relative to this previous work, we have therefore made progress by pushing down a factor of 2.5 in the dipole amplitude. This is a welcome development toward being able to probe the kinematic dipole due to our motion relative to the overall LSS rest frame, which will require reaching the level  $A \sim 10^{-3}$ , and therefore a deeper survey (or a deeper sample of WISE sources).

## 5 CONCLUSIONS

We measured the clustering dipole in the WISE survey, using a carefully culled sample that contains 2 million extragalactic sources with a known redshift distribution. The amplitude of the measured dipole is  $A \simeq 0.05 \pm 0.01$ , where we quote the central value corresponding to the  $20^\circ$  cut case and error that shows the dispersion of central values for  $15^\circ \leq b_{\text{cut}} \leq 25^\circ$ . The amplitude is therefore roughly twice as large as the theoretical expectation; see Eq. (5). The direction of the dipole is  $\simeq (310^\circ \pm 5, -15^\circ \pm 2)$ .

$b_{\text{cut}}$	$f_{\text{sky}}$	$A_{\text{WISE}}$	$A_{\text{theory}}$	$\hat{d}(l^\circ, b^\circ)$
$10^\circ$	0.65	$0.035 \pm 0.002$	$0.023 \pm 0.012$	$(326 \pm 3, -17 \pm 2)$
$15^\circ$	0.62	$0.042 \pm 0.002$	$0.023 \pm 0.012$	$(316 \pm 3, -15 \pm 2)$
$20^\circ$	0.57	$0.052 \pm 0.002$	$0.023 \pm 0.012$	$(308 \pm 4, -14 \pm 2)$
$25^\circ$	0.51	$0.062 \pm 0.003$	$0.023 \pm 0.013$	$(315 \pm 6, -12 \pm 2)$
$30^\circ$	0.45	$0.051 \pm 0.004$	$0.023 \pm 0.014$	$(335 \pm 6, -18 \pm 3)$

**Table 1.** Measurements of the dipole amplitude in WISE for various Galactic cuts ( $b_{\text{cut}}$ ) corresponding to fractions of the sky covered ( $f_{\text{sky}}$ ). In all cases we marginalized over several foreground templates, as described in the text. The full likelihood for the amplitude  $A_{\text{WISE}}$  is well approximated by a Gaussian whose mode and standard deviation we quote here. We also show the theoretical expectation  $A_{\text{theory}}$  due to the local-structure dipole, together with the corresponding cosmic variance given a bias  $b = 1.41$ .

What could explain the excess dipole measured relative to theoretical expectation? The systematics, while an obvious first suspect, are not necessarily at fault given the rather extensive care we took to account for them: we carefully culled the dataset by imposing cuts based on WISE and 2MASS magnitudes; we included cuts based on Galactic latitude and on the WMAP dust map, and we further marginalized over a carefully derived star-map template as well as templates corresponding to the quadrupole and octopole.

Another possibility is that the excess signal is cosmological. For example, a large void might generate the excess observed here (Rubart, Bacon & Schwarz 2014). Such a void was incidentally just detected in the analysis of the WISE data itself (Szapudi et al. 2014; Finelli et al. 2014). At this time it is too early to tell whether the WISE void is contributing significantly to the excess dipole that we measured, though a rough comparison with numbers in Rubart, Bacon & Schwarz (2014) appears to indicate that it is not.

It is also interesting to note that Planck found a best-fit modulation with both amplitude and direction roughly (within  $\sim 3\sigma$  of their errors) in agreement with ours (Ade et al. 2013):  $A_{\text{Planck}} = 0.078 \pm 0.021$ ,  $(l, b) = (227^\circ, -15^\circ) \pm 19^\circ$ . It is not clear at this time what, if any, significance to assign to the comparable-looking modulations in WISE and Planck since their sources are at vastly different redshifts ( $z \sim 0.15$  and  $\sim 1000$ ), and the agreement in amplitude and direction is only approximate. Finally, the direction we find is *also* close to the peculiar-velocity bulk-flow directions found using type Ia supernovae (Dai, Kinney & Stojkovic 2011; Kalus et al. 2013; Rathaus, Kovetz & Itzhaki 2013), galaxies (Feldman, Watkins & Hudson 2010; Turnbull et al. 2012; Ma, Gordon & Feldman 2011; Ma & Pan 2014), and the kinetic Sunyaev-Zeldovich effect (Lavaux, Afshordi & Hudson 2013). While the agreement between the directions is suggestive, it is not immediately clear how our WISE dipole is related to these. For example, interpreting the excess dipole amplitude  $\delta A \sim 0.03$  as a bulk motion is clearly out of the question, since it would correspond to a huge velocity of  $v \simeq 0.015c = 4500$  km/s, an order of magnitude larger than what typical bulk-motion measurements indicate.

With recent measurements of the cross-correlation of its sources with the CMB and the detection of a large underdense void, WISE is finally making major contributions to cosmology. Its nearly all-sky coverage is a huge asset and gives the survey a big advantage on that front over most other LSS surveys. In this paper we have taken another step in testing fundamental cosmology with WISE by measuring the clustering dipole in the distribution of its extragalactic sources. We look forward to further investigations of this result, especially in conjunction with other related findings in the CMB and LSS.

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