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Dipolar modulation in number counts of *WISE*–2MASS sources

Mijin Yoon,[1★] Dragan Huterer,[1] Cameron Gibelyou,[1] András Kovács[2,3] and István Szapudi[4]

[1] *Department of Physics, University of Michigan, 450 Church St, Ann Arbor, MI 48109-1040, USA*
[2] *Institute of Physics, Eötvös Loránd University, 1117 Pázmány Péter sétány 1/A, Budapest, Hungary*
[3] *MTA-ELTE EIRSA 'Lendület' Astrophysics Research Group, 1117 Pázmány Péter sétány 1/A, Budapest, Hungary*
[4] *Institute for Astronomy, University of Hawaii 2680 Woodlawn Drive, Honolulu, HI 96822, USA*

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ABSTRACT

We test the statistical isotropy of the Universe by analysing the distribution of *WISE* extragalactic sources that were also observed by 2MASS. We pay particular attention to colour 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 ∼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 cosmic microwave background 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.

Key words: cosmology: observations – large-scale structure of Universe – infrared: galaxies.

1 INTRODUCTION

Modern surveys of large-scale structure (LSS) 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 non-zero 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 the order of 0.1 for shallow surveys extending to $z_{\rm max} \sim 0.1$, 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 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 superhorizon 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 Letter, for the first time we test statistical isotropy using *Wide-field Infrared Survey Explorer* (WISE; 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 μm wavelengths with resolution in the 6–12 arcsec range (Ménard et al. 2013; Yan et al. 2013).

2 CULLING OF THE *WISE* DATA SET

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

★ E-mail: mijin@umich.edu

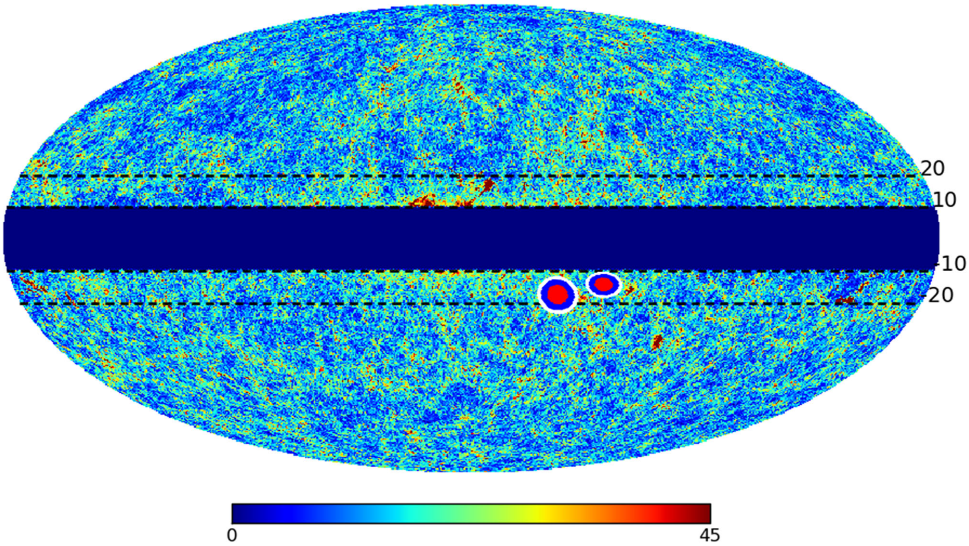

Figure 1. Map of *WISE*–2MASS sources that we used with 10 degree Galactic cut (before masking out the contaminated region with the *WMAP* dust mask). The criteria are described in the text. The map shown is a Mollweide projection in Galactic coordinates with counts binned in pixels of about 0°.5 on a side (HEALPIX resolution NSIDE = 128). The two elliptical sets of contours represent the measured dipole direction when we applied a 10° (left) and 20° (right) Galactic cut, respectively (that is, with $|b| < 10°$ and $|b| < 20°$). The red, blue, and white colours in those contours represent the 68, 95, and 99 per cent confidence regions for the direction.

follows we pay particular attention to magnitude and colour cuts applied to *WISE* in order to leave a trustworthy set of extragalactic sources.

The 2013 November 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 (2014), colour cuts using only the *WISE* bands are not sufficient, so we have applied 2MASS-PSC[1] magnitudes ($J_{2\mathrm{mass}}$) 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 greater depth. To cull a uniform, extragalactic sample of sources, we adopt the following colour cuts:

(i) $W1 < 15.2$,
(ii) $J_{2\mathrm{mass}} < 16.5$,
(iii) $W1 - J_{2\mathrm{mass}} < -1.7$.

These cuts, and in particular the cross-survey $W1 - J_{2\mathrm{mass}}$ cut, ensure two highly desirable properties of the selected sample: sufficient depth and spatial uniformity. Note also that the 2MASS Point Source Catalog (2MASS-PSC) contains many more objects than the previously used but shallower Extended Source Catalog (2MASS-XSC). With the benefit of *WISE* colours the cuts listed above ensure a robust selection of galaxies in 2MASS-PSC that are not in the XSC.

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. The third criterion above represents the colour cut that serves to separate galaxies from stars.

[1] Two Micron All Sky Survey (Skrutskie et al. 2006) Point Source Catalog.

The detailed analysis on the data selection was described in Kovács & Szapudi (2014); 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 ±15° 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) catalogue to find sources in the *WISE* data set that are within 3 arcsec of GAMA sources. We can thus determine the redshift distribution of our objects. In the 144 deg^2 overlapping region on the sky, the matching rate is 96.9 per cent. The redshift distribution of matched objects, $N(z)$, is shown in Fig. 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

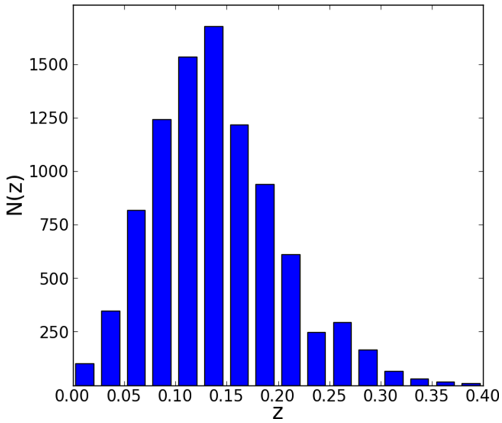

Figure 2. Number counts of *WISE* sources as a function of redshift. We obtain redshift information by matching *WISE* sources to those from the GAMA DR2 catalogue. As explained in the text, matching works very well.

in direction $\hat{\boldsymbol{n}}$ can be written as

$$N(\hat{\boldsymbol{n}}) = [1 + A\,\hat{\boldsymbol{d}} \cdot \hat{\boldsymbol{n}}]\bar{N} + \epsilon(\hat{\boldsymbol{n}}), \tag{1}$$

where A and $\hat{\boldsymbol{d}}$ are the amplitude and direction of the dipole, and ϵ is noise. One can further write the contribution from fluctuations as a mean offset (Hirata 2009).

$$\delta N/\bar{N} = A\,\hat{\boldsymbol{d}} \cdot \hat{\boldsymbol{n}} + \sum_i k_i t_i(\hat{\boldsymbol{n}}) + C, \tag{2}$$

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

$$\hat{\boldsymbol{x}} = \mathbf{F}^{-1}\boldsymbol{g}, \tag{3}$$

where the components of the vector $\boldsymbol{g}$ are $\boldsymbol{g}_i = \int T_i(\hat{n})\delta N^{\Omega}(\hat{n})\,\mathrm{d}^2\hat{n}$ and the Fisher matrix $\mathbf{F}$ is given by $F_{ij} = \bar{N}^{\Omega} \int T_i(\hat{n})T_j(\hat{n})\mathrm{d}^2\hat{n}$, where $N^{\Omega} \equiv \mathrm{d}N/\mathrm{d}\Omega$ is the number of galaxies per steradian (Ω is a solid angle). The integrals from which the vector $\boldsymbol{g}$ and the Fisher matrix $\mathbf{F}$ 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-fitting dipole components (first three elements of the vector $\boldsymbol{x}$), 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):

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

where $\mathrm{d}^2\hat{\boldsymbol{n}}$ indicates integration over all possible directions on the sphere and $\boldsymbol{d}_{\mathrm{best}}$ is the best-fitting dipole vector calculated using equation (3). Thus, we readily obtain a full likelihood for the amplitude. In our results, we quote the 68 per cent region around the best-fitting amplitude.

3.2 Foreground templates and estimator validation

Despite our carefully chosen magnitude and colour 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 $t_i(\hat{\boldsymbol{n}})$ in the parlance of equation (2) – with amplitudes k_i over which we marginalize:

(i) 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 catalogue (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.

(ii) To account for the other multipoles, we add the monopole (corresponding to the constant C in equation (2) with no spatial dependence), as well as the quadrupole and octopole that include five and seven 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 ($b_{\mathrm{cut}} \lesssim 15°$), 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. section 2.2 of Gibelyou & Huterer 2012). We calculate the angular power spectrum of LSS for the given source distribution $N(z)$, and evaluate it at the dipole (C_ℓ 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 $A_{\mathrm{theory}} = (9C_1/(4\pi))^{1/2}$ (Gibelyou & Huterer 2012), while the theory error is given by cosmic variance for $\ell = 1$: $\delta A_{\mathrm{theory}}/A_{\mathrm{theory}} = (1/2)\sqrt{2/((2\ell+1)f_{\mathrm{sky}})} = (6f_{\mathrm{sky}})^{-1/2}$, where f_{sky} is the fraction of sky covered by used data. Evaluating the theoretically expected dipole for the source distribution shown in Fig. 2, we get

$$A_{\mathrm{theory}} = (0.0233 \pm 0.0094\, f_{\mathrm{sky}}^{-1/2}) \times \left(\frac{b}{1.41}\right). \tag{5}$$

Here, we make explicit the dependence of the cosmic variance error on the fraction of the sky covered (f_{sky}), and also on the bias of *WISE* sources (bias parameter: b). To obtain the latter, we followed Kovács & Szapudi (2014), and estimated the bias of the galaxy catalogue using SPICE (Szapudi et al. 2001) and the PYTHON COSMOPY[2] package. We note that the estimation of the bias is particularly sensitive to σ_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

[2] http://www.ifa.hawaii.edu/cosmopy/

findings (Rassat 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 (isolatitude) Galactic cut, are presented in Table 1 and shown in Fig. 3. The best-fitting direction of the dipole is also shown in Fig. 1 for the 10° and 20° 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 ∼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 1–2σ high, where σ 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 $b_{\rm cut}$ more than its typical measurement errors, it is overall consistent at $A_{\rm WISE} \simeq$ 0.04–0.05, which is rather robustly stable given the large decrease of the number of sources with increasing Galactic cut.

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

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

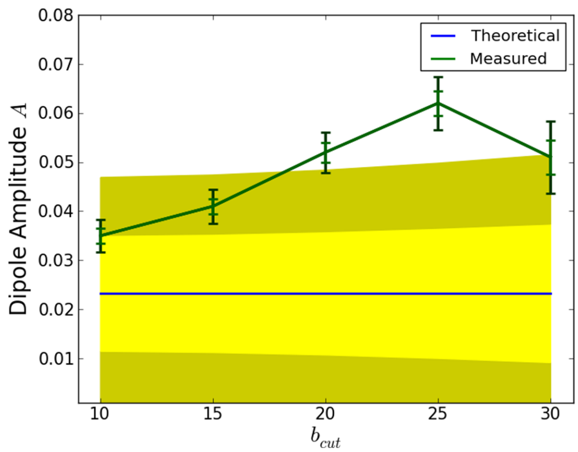

Figure 3. Theoretical prediction for the dipole amplitude (horizontal blue line), together with the measured values in *WISE* (green points). The two sets of error bars on the measurements correspond to 68 and 95 per cent confidence; they have been calculated from the full likelihood in equation (4)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

It is interesting to note that 2MASS Extended Source Catalog data, as analysed in Gibelyou & Huterer (2012) (redshift $0 < z < 0.2$, $N = 3.8 \times 10^5$), give $A_{\rm 2MASS} = 0.104 \pm 0.004$, $(l, b) = (268.4°, 0.0°)$ – the direction is not far from ours, but the amplitude is larger because 2MASS data used in this previous work is shallower than our *WISE*–2MASS sample. Relative to Gibelyou & Huterer (2012), we have therefore made progress by pushing down a factor of 2.5 in the dipole amplitude. This is a welcome development towards 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 two million extragalactic sources with a known redshift distribution. The direction of the dipole is $\simeq (310° \pm 5, -15° \pm 2)$. The amplitude of the measured dipole is $A \simeq 0.05 \pm 0.01$, where we quote the central value corresponding to the 20° cut case and error that shows the dispersion of central values for $15° \le b_{\rm cut} \le 25°$. While the amplitude is therefore roughly twice as large as the theoretical expectation given in equation (5), the large cosmic variance on the theoretical prediction calculated in Section 3.3 makes the measured amplitude ∼ 2.5σ high – in tension with theory but not sufficiently statistically significant to claim departures from the standard ΛCDM prediction.

Taking for the moment the excess dipole measured relative to theoretical expectation at face value, we can ask: What could explain it? 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 data set 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 (Finelli et al. 2014; Szapudi 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 et al. (2014) appears to indicate that it is not.

It is also interesting to note that Planck found a best-fitting modulation with both amplitude and direction roughly (within ∼3σ of their errors) in agreement with ours (Ade et al. 2013): $A_{\rm Planck} = 0.078 \pm 0.021$, $(l, b) = (227°, -15°) \pm 19°$. 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 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 et al. 2010; Ma, Gordon & Feldman 2011; Turnbull et al. 2012; 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^{-1}, 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 Letter, 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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