The dipole anisotropy of WISE × SuperCOSMOS number counts

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ABSTRACT

We probe the validity of the isotropy hypothesis of the Universe, one of the foundations of modern Cosmology, with the WISE × SuperCOSMOS data set. This is performed by searching for dipole anisotropy of galaxy number counts in different redshift shells in the 0.10 < z ≤ 0.35 range. We find that the dipole direction is in concordance with most of previous analyses in the literature, however, its amplitude is only consistent with ΛCDM-based mocks when we adopt the cleanest sample of this catalogue, except for the z < 0.15 data, which exhibits a persistently large dipole signal. Hence, we obtain no significant evidence against the large-scale isotropy assumption once the data are purified from stellar contamination, yet our results in the lowest redshift range are still inconclusive.

Key words: Cosmology: observations; Cosmology: theory; (cosmology:) large-scale structure of the Universe;

1 INTRODUCTION

The current standard model of cosmology, called ΛCDM, assumes Friedman-Lemaître-Robertson-Walker its background metric, and that the Universe is approximately homogeneous and isotropic on large scales, a feature of the so-called ‘Cosmological Principle’ (CP). Despite the good agreement between ΛCDM and a plethora of cosmological observations (e.g. Ade et al. 2016; Alam et al. 2016), direct tests of the CP need to be performed in order to assess whether it is a valid cosmological assumption or just mathematical simplification. Persistent lack of isotropy or homogeneity on large scales would require a complete reformulation of the current cosmological scenario, and thus of our understanding of the Universe.

It is well accepted that the spatial distribution of cosmic objects becomes statistically homogeneous on scales around 100–150 Mpc/h (Hogg et al. 2005; Scrimgeour et al. 2012; Pandey & Sarkar 2016; Laurent et al. 2016; Ntelis et al. 2017), and that the CMB temperature dipole is the only major non-primordial anisotropy we observe in the Universe, since it is interpreted as our peculiar motion relative to CMB instead of an actual cosmological signal (Kogut et al. 1993; Aghanim et al. 2014). However, this dipole has yet to be identified in the large-scale structure (LSS) with sufficient significance. Some estimates of the dipole in projected distributions of galaxies were carried out, but no evidence for signals larger than allowed by the standard cosmological model (within 3σ confidence level) was found using optical or infrared catalogues (Itoh et al. 2010; Gibelyou & Huterer 2012; Appleby & Shafieloo 2014; Yoon et al. 2014; Alonso et al. 2015; Bengaly et al. 2017), although similar analyses in the radio frequency presented more ambiguous results (Blake & Wall 2002; Rubart & Schwarz 2013; Tiwari & Nurser 2016; Colin et al. 2017).

In light of these results, we probe the isotropy of the large-scale structure using the recently published WISE × SuperCOSMOS (hereafter WIXSC) catalogue (Bilicki et al. 2016)\(^2\) by looking for a dipole term in its projected distribution of galaxies in a similar framework as in Gibelyou & Huterer (2012). We also check for concordance between the observational data and their respective mocks assuming the ΛCDM matter power spectrum as a fiducial model, similarly to previous analyses (Gibelyou & Huterer 2012; Alonso et al. 2015; Bengaly et al. 2017). As the WIXSC sample contains photometric redshift (photo-z) information for its galax-

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\(^{1}\) We will refer to it as the kinematic dipole hereafter.

\(^{2}\) http://ssa.roe.ac.uk/WISExSC05
ies, we can perform a tomographic analysis of the number count dipole at \( z > 0.10 \) for the first time, thus allowing us to probe how the dipole evolves when reaching deeper scales and, furthermore, whether it agrees with their expected amplitudes in the \( \Lambda \text{CDM} \) paradigm in each redshift shell. Strong discrepancies between the real data and these simulations would hint at potential evidence against the cosmic isotropy assumption, unless we are restricted by persisting systematics. We therefore extend the analysis of Bengaly et al. (2017) where another WISE-based catalogue was used, namely WISE-2MASS (W2M, Kovács & Szapudi 2015), which not only was shallower than WI\( \times \)SC but also did not include redshift information, even of photometric nature, and it comprised 10 times fewer sources.

2 DATA SELECTION

The WI\( \times \)SC photo-\( z \) catalogue (Bilicki et al. 2016) is based on a cross-match of two all-sky samples, WISE (Wright et al. 2010) and SuperCOSMOS (Peacock et al. 2016). This dataset is flux-limited to \( B < 21, R < 19.5 \) (both AB), and \( 13.8 < W1 < 17 \) (3.4 \( \mu \)m, Vega) and provides photo-\( z \)s for all the included sources, ranging from \( 0 < z < 0.4 \) (mean \( \langle z \rangle \approx 0.2 \)) with typical scatter \( \sigma_z/(1+z) = 0.033 \) (15\% median photo-\( z \) error). The data come with a fiducial mask which removes low Galactic latitudes (\( |b| \leq 10^\circ \) up to \( |b| \leq 17^\circ \) by the Bulge), areas of high Galactic extinction (\( E(B-V) > 0.25 \)), as well as other contaminated regions. Here we however apply more strict cuts to avoid selection effects due to extinction, namely \( E(B-V) > 0.10 \), and require \( 0.10 < z_{\text{phot}} < 0.35 \) to remove low-redshift prominent structures as well as the high-redshift tail of WI\( \times \)SC, where the data is very sparse.

The basic WI\( \times \)SC dataset by Bilicki et al. (2016) was additionally purified from stellar (blends) and quasar contamination via specific colour cuts, which were dependent on the distance from the Bulge in the case of star removal. This gave a sample with

2.4. WISE X SuperCOSMOS

- The WI\( \times \)SC photo-\( z \) catalogue is based on a cross-match of WISE and SuperCOSMOS.
- The dataset is flux-limited to \( B < 21, R < 19.5 \) AB, and \( 13.8 < W1 < 17 \) 3.4 \( \mu \)m Vega.
- Photo-\( z \)s are available for all included sources, with a mean \( \langle z \rangle \approx 0.2 \) and a typical scatter \( \sigma_z/(1+z) = 0.033 \) (15\% median).
- The data come with a fiducial mask that removes low Galactic latitudes, high extinction areas, and contaminated regions.

2.5. Additional Purification

- The WI\( \times \)SC dataset was further purified from stellar (blends) and quasar contamination using specific colour cuts.
- These cuts were dependent on the distance from the Bulge, especially for star removal.

2.6. Limitations

- The dataset is limited to \( 0 < z < 0.4 \) with a mean \( \langle z \rangle \approx 0.2 \).
- The median photo-\( z \) error is 0.033.

2.7. Analysis

- Tomographic analysis of the number count dipole at \( z > 0.10 \) was performed for the first time.
- Discrepancies between real data and simulations would hint at potential evidence against the cosmic isotropy assumption, unless restricted by systematics.

The analysis extends the work of Bengaly et al. (2017) using the WISE-2MASS catalogue, which was shallower than WI\( \times \)SC and lacked redshift information. The analysis here includes more strict cuts to avoid selection effects due to extinction.
a relatively uniform surface density over the sky, although some patterns of residual stellar contamination were still present. As purity is more important for our purposes than completeness, we thus applied an additional colour cut of $W1 - W2 > 0.2$, which should guarantee very efficient star removal (Jarrett et al. 2017). We will call this W1xSC sample with the additional cleanup 'Fiducial' from now on. In an alternative approach to galaxy identification in W1xSC, Krakowski et al. (2016) used the Support Vector Machines (hereafter SVM) classification algorithm and obtained a purer galaxy sample than the main W1xSC one but less complete. The SVM dataset comes with probability estimates of sources belonging to a given class, and we applied a conservative cut of $p_{\text{cut}} > 2/3$, so that our selected objects have at least twice the probability of being a galaxy rather than any other class.

After applying the W1xSC mask as well as our additional cuts on $E(B - V)$ and photo-$z$, we obtained samples of 9.5 and 8.3 million galaxies for the Fiducial and SVM datasets, respectively, over $f_{\text{sky}} = 0.545$, of median redshifts $z_{\text{med}} \approx 0.22$ (Fiducial) and $z_{\text{med}} \approx 0.20$ (SVM), as shown in Figure 3. Number count density maps of these samples for the full redshift range $0.10 < z < 0.35$ are featured in Fig. 1, whereas Fig. 2 displays only the galaxies within the $0.10 < z < 0.15$ range. All maps were plotted using HEALPix (Gorski et al. 2005) resolution of $N_{\text{side}} = 128$ (pixel size of $\sim 0.5^\circ$).

### 3 METHODOLOGY

The isotropy of galaxy number counts is estimated with the delta-map method developed in Bengaly et al. (2017) (see also Alonso et al. 2015), in which the sky is decomposed into $71^2$ large HEALPix cells ($N_{\text{side}} = 8$), and hemispheres are constructed using the respective pixel centres as symmetry axes. The delta-map is then computed as

$$\Delta_i = 2 \times \left( \frac{n_i^U - rD}{n_i^D + rD} \right),$$

where $n_i^D = N_i^D/(4\pi f_{\text{sky}})$ are counts in the $i$-th hemisphere, $i \in 1,...,7168$, $j$ represents the hemispheres indexes “up” ($U$) and “down” ($D$) defined according to this pixelisation scheme, whereas $N_i^D$ and $f_{\text{sky}}$ are the total number of objects and the observed fraction of the sky encompassed in each of these hemispheres, respectively.

The dipole of the galaxy number counts is obtained from expression 1 by expanding the delta-map into spherical harmonics and then setting all $a_{lm}$’s to zero except for the $a_{lm}$ cases, from which we obtain $\Delta_{lm} = -\sum a_{lm} Y_{lm}$. Therefore, we quote the maximum value of this quantity as our dipole amplitude $A$, in addition to the direction where it points to. In this work, the W1xSC catalogue is additionally decomposed into redshift shells before the delta-map calculation: cumulative ones i.e. $0.10 < z < 0.15; 0.10 < z < 0.20; ...; 0.10 < z < 0.35$, and disjoint ones: $0.10 < z < 0.15; 0.15 < z < 0.20; ...$. As we have $10^6$ galaxies in each of these shells, the Poisson Noise contribution to the dipole is sub-dominant with respect to its total signal, being thus quoted as its uncertainty.

The statistical significance of the delta-map dipoles is calculated from W1xSC mock catalogues produced with the flask code3 (Xavier et al. 2016). These mocks are full-sky lognormal realisations of the density field in redshift shells based on the input angular power spectra $C_{ij}^{(0)}$ ($z_i$ and $z_j$ denoting different redshift shells) provided by camb sources (Challinor & Lewis 2011), which are Poisson-sampled according to the W1xSC selection function. The input $C_{ij}^{(0)}$ were computed for redshift distributions that are convolutions of the $\delta z = 0.05$ shells with Gaussian distributions with $\sigma_z/(1+z) = 0.033$ (representing W1xSC photo-$z$ errors) using ACDM best-fit parameters (Ade et al. 2016), and they include linear redshift space distortions, gravitational lensing distortions of the volume elements and non-linear contributions modelled by HaloFit (Smith et al. 2003; Takahashi et al. 2012). We applied a linear scaling factor to each $C_{ij}^{(0)}$—playing a role similar to galaxy bias—which was used to match the variances of counts in pixels to the ones observed in the real data.

We additionally compared the Fiducial dataset source distribution to SDSS (York et al. 2000) in a $1^\circ$-wide strip centred on declination $\delta = 30^\circ$ and estimated that it still contained a fraction $f_{\text{star}}$ of stars that is well fitted by $f_{\text{star}} = 0.71 \exp(-0.09|b|) + 0.013$. Therefore, we Poisson sampled stars according to this distribution and included them in our mocks. By adjusting the selection function normalisation and the $C_{ij}^{(0)}$ scaling factors, we made our simulations match the Fiducial dataset in terms of $f_{\text{star}}$: mean number of objects (galaxies + stars) and variance in the pixels.4

Following this prescription, we produced 1000 full-sky mocks of both Fiducial and SVM datasets in each $\delta z = 0.05$ photo-$z$ bin, spanning the $0.10 < z < 0.35$ range, using the same resolution of the real data maps ($N_{\text{side}} = 128$). From these realisations, we computed the fraction of realisations featuring a dipole amplitude at least as large as the real data for each $z$-bin analysed, hereafter quoted as $p$-values, once the mask described before is properly taken into account.

### 4 RESULTS

The dipoles resulting from the delta-map analyses of the two W1xSC samples are shown for the full redshift range in Fig. 4, while the dipole directions and amplitudes for each redshift bin are presented in Table 1 for both Fiducial and SVM datasets. We readily verify the dipole amplitude decreases when probing the number counts on deeper scales, as it goes from $A \approx 0.10$ in the thinnest $(0.10 < z \leq 0.15)$ to $A \approx 0.03$ in the thickest $(0.10 < z \leq 0.35)$ cumulative shell, thus confirming the discussion and results of Gibeliovou & Huterer (2012).

We also stress that the directions of the number count dipoles in cumulative redshift shells, specially the redshift range $0.10 < z \leq 0.35$ of the SVM dataset, are in good agreement with similar analyses in the literature. For instance, Bengaly et al. (2017) obtained a dipole anisotropy of $(l, b) = (323^\circ, -5^\circ)$ with $A = 0.0507$ in the W2M catalogue, which peaks at $z \sim 0.14$, whereas Yoon et al. (2014) and Alonso et al. (2015) found, using different methods, the directions $(l, b) = (310^\circ, -15^\circ)$ and $(320^\circ, 6^\circ)$ with $A = 0.051$ and $A = 0.028$ from the W2M and 2MASS photo-$z$ (2MPZ, Bilicki et al. 2014), with $(z) \approx 0.08$) datasets, respectively. On the other hand, the Fiducial sample dipole is more consistent with the direction found in Appleby & Shafieloo (2014), i.e., $(l, b) = (315^\circ, 30^\circ)$, whose authors adopted the 2MPZ sample as well. A quantitative assessment of the concordance between these dipole directions is featured in Tab. 2, where we can calculate the probabilities $P_\theta$ that the

3 http://www.astro.iag.usp.br/~flask

4 The simulation input files are available at: http://www.astro.iag.usp.br/~flask/sims/wisc17.tar.gz
The CMB dipole, located at $(l, b) = (21^\circ, 70^\circ)$, we note that all these directions are moderately distant from $\pm 10^\circ$. Still, the agreement between different methods and observational extensions of the analysis carried out in Bengaly et al. (2017) with our diagnostic of cosmological anisotropy. The observational sample consisted of two datasets, namely ‘Fiducial’ and ‘SVMe’, which differ in how galaxies were identified in them: through colour cuts in the former, and by means of automated classification in the latter. Thanks to the availability of redshift information, we were able to perform this test in tomographic $z$-bins, which gave a natural extension of the analysis carried out in Bengaly et al. (2017) with the WISE-2MASS sample. We found marginal agreement or better between the dipole directions we obtained and those from previous analyses in the literature. In addition, we obtained that only the Fiducial sample presented a dipole amplitude consistent with mock realisations when $z > 0.15$. However, the results are still inconclusive for the shallowest redshift ranges, where both datasets show excellently aligned dipoles with amplitudes larger than those of simulations.

5 CONCLUSIONS

In this work, we examined the isotropy of the large-scale structure through the directional dependence of galaxy number counts in the WISE $\times$ SuperCOSMOS catalogue. To do so, we adopted a hemispherical comparison method whose dipole contribution provided our diagnostic of cosmological anisotropy. The observational samples consisted of two datasets, namely ‘Fiducial’ and ‘SVMe’, which differ in how galaxies were identified in them: through colour cuts in the former, and by means of automated classification in the latter. Thanks to the availability of redshift information, we were able to perform this test in tomographic $z$-bins, which gave a natural extension of the analysis carried out in Bengaly et al. (2017) with the WISE-2MASS sample. We found marginal agreement or better between the dipole directions we obtained and those from previous analyses in the literature. In addition, we obtained that only the Fiducial sample presented a dipole amplitude consistent with mock realisations when $z > 0.15$. However, the results are still inconclusive for the shallowest redshift ranges, where both datasets show excellently aligned dipoles with amplitudes larger than those of simulations.

Albeit we still cannot probe the kinematical dipole with this dataset catalogue because of its limited specifications (Yoon & Huterer 2015).
The dipole anisotropy of WISE × SuperCOSMOS number counts

| Dipole | CMB | BengalyFid | BengalySVM | BengalyW2M | Alonso15 | Yoon14 | Appleby14 | LowzFid | LowzSVM |
|--------|-----|------------|------------|------------|----------|-------|-----------|---------|---------|
| CMB    | -   | 0.132      | 0.581      | 0.457      | 0.369    | 0.455 | 0.21      | 0.264   | 0.269   |
| BengalyFid | 0.132 | -         | 0.336      | 0.289      | 0.206    | 0.374 | 0.068     | 0.104   | 0.068   |
| BengalySVM | 0.581 | 0.336     | -          | 0.023      | 0.047    | 0.067 | 0.151     | 0.536   | 0.44    |
| BengalyW2M | 0.457 | 0.289     | 0.023      | -          | 0.01     | 0.02  | 0.095     | 0.553   | 0.457   |
| Alonso15 | 0.369 | 0.206     | 0.047      | 0.01       | -        | 0.041 | 0.045     | 0.472   | 0.38    |
| Yoon14  | 0.455 | 0.374     | 0.067      | 0.02       | 0.041    | -     | 0.148     | 0.67    | 0.581   |
| Appleby14 | 0.21  | 0.068     | 0.151      | 0.095      | 0.045    | 0.148 | -         | 0.296   | 0.223   |
| LowzFid | 0.264 | 0.104     | 0.536      | 0.553      | 0.472    | 0.67  | 0.296     | -       | 0.009   |
| LowzSVM | 0.269 | 0.068     | 0.44       | 0.457      | 0.38     | 0.581 | 0.223     | -       | 0.009   |

Table 2. The probability that randomly picked directions are closer than the distance between the corresponding dipoles, in which 'BengalyFid' and 'BengalySVM' corresponds to the full Fiducial and SVM samples analysed here, respectively, while both 'Lowz' cases consists of their 0.10 < z < 0.15 results. The remaining directions were obtained in Aghanim et al. (2014); Yoon et al. (2014); Appleby & Shafieloo (2014); Alonso et al. (2015); Bengaly et al. (2017), respectively.

Huterer 2015), we were able to show that the dipole amplitude indeed decreases on deeper scales, and that there is consistency between the SVM dipole direction with similar datasets. However, the Fiducial one shows much better agreement with simulations than the SVM, which we credit to a more rigorous criterion to eliminate stars from the original catalogue. Still, this procedure cannot explain the large A values obtained in the 0.10 < z ≤ 0.15 redshift shell, a result whose origin is unclear. According to Rubart et al. (2014), the presence of local LSS underdensities can increase the dipole anisotropy in the number counts, being thus a possible explanation for this signal. A more thorough investigation of this hypothesis will be pursued in the future.

This work presents the first contribution of the WIXSC catalogue to Cosmology in the form of an updated test of the large-scale isotropy of the Universe, in which we found no significant departure from this fundamental hypothesis, yet we are still very limited by the completeness and systematics of the available data. Nonetheless, the WIXSC data set can be considered a testbed for forthcoming surveys, especially LSST (Abell et al. 2009) and SKA (Schwarz et al. 2015), as they will reach much deeper scales on large sky areas and, therefore, will enable much more precise tests of the CP in the years to come (Itoh et al. 2010; Schwarz et al. 2015; Yoon & Huterer 2015).

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