The influence of the Zone of Avoidance on the measurement of the clustering dipole of galaxies

Magdalena Krupa[1], Maciej Bilicki[2] and Agnieszka Pollo[3,1]

1. Astronomical Observatory of the Jagiellonian University, Orla 171, 30–244 Kraków, Poland
2. Center for Theoretical Physics PAS, Al. Lotników 32/46, 02–668 Warszawa, Poland
3. National Centre for Nuclear Research, Pasteura 7, 02–093 Warszawa, Poland

Our own Galaxy obscures a large (approximately 20%) portion of the sky, creating the so-called Zone of Avoidance (ZoA), which poses problems for observations of the extragalactic universe. Because of that, all cosmological measurements based on all-sky statistics of the large scale structure of the Universe need to compensate for the lack of information from the sky areas hidden behind the ZoA. Among such cosmological measurements there are tests of the validity of the Cosmological Principle via calculation of the clustering dipole of galaxies, for which a full sky coverage is absolutely vital. In this paper we review different methods of filling the ZoA and discuss their effectiveness tested on simulated galaxy catalogs. In particular we re-estimate the expected accuracy of recovery of the amplitude and the direction of the estimated acceleration of the Local Group. Finally, we present the results of the clustering dipole measurements in the 2MASS catalog obtained with the best selected method and with a realistic error estimation.

1 Introduction

The calculation of the so-called clustering dipole of galaxies is a popular method to study the motion of the Local Group of galaxies (which our Milky Way is a part of) since the first all-sky galaxy surveys (e.g. Strauss et al., 1992; Erdoğdu et al., 2006; Lavaux et al., 2010; Bilicki et al., 2011; Carrick et al., 2015). As the dipole observed in the Cosmic Microwave Background (CMB) radiation distribution is interpreted as the result of the same motion, both measurements are expected to provide consistent results, and their comparison provides an important cosmological test of the Cosmological Principle.

However, as all the estimators of the clustering dipole in use are very sensitive to the distribution of sources, full coverage of the sky is of vital importance. At the same time, stars and interstellar dust in the plane of the Milky Way obscure a large part (∼20%; e.g. Schröder et al. 2019) of the extragalactic sky, creating the so-called Zone of Avoidance (ZoA). To correct for this effect, this part of the sky is usually artificially filled in some manner before the measurement is made. In this work we measure and compare errors associated with the most popularly used methods to remove and refill the ZoA, with the aim of finding the optimal method for reliable calculation of the clustering dipole of galaxies.

2 Method

We calculate the clustering dipole of galaxies based on all-sky catalogs under the assumption that the visible matter is a good tracer of the underlying density field. As the estimator, we use the so-called *flux dipole*, defined as:

$$\widetilde{\mathbf{d}} = C \sum_{m_{min}}^{m_{max}} 10^{-0.4 m_i} \hat{\mathbf{r}}_i \quad (1)$$

where C is a normalization constant characteristic of a catalog, m_i is the apparent magnitude of the i-th source and r_i is the direction of the i-th source on the sky.

We calculate the clustering dipole first in the Millennium XXL (MXXL; Smith et al. 2017) simulated galaxy catalog and then in the 2MASS catalog, as a function of limiting magnitude. Our aim is to determine how a dipole measurement depends on the definition and the method of reconstructing the ZoA, as well as to establish which of the tested methods results in the approximation of the calculated clustering dipole closest to its true value. We consider three definitions of the ZoA:

- **I**: $|b| < 10°$; $|b| < 15°$ for $l < 30° \vee l > 330°$
- **II**: $|b| < 5°$ for $l < 135° \vee l > 225°$; $|b| < 10°$ for $l < 75° \vee l > 285°$; $|b| < 15°$ for $l < 30° \vee l > 330°$
- **III**: $|b| < 5°$; $|b| < 10°$ for $l < 75° \vee l > 285°$; $|b| < 15°$ for $l < 30° \vee l > 330°$

We also use three methods to populate the ZoA: (1) cloning the strips adjacent to the ZoA with mirror–like reflections; (2) similarly as above: cloning every second galaxy from twice as wide adjacent strips; (3) random filling.

We want to find the optimal method of dealing with the ZoA problem when calculating the clustering dipole based on all-sky galaxy catalogs. In order to do so, we employ the following algorithm: 1. ZoA reconstruction according to a combination of its removal and refilling methods described above; 2. calculation of the clustering dipole, which gives us an estimate of the amplitude and direction of the acceleration of the Local Group of galaxies; 3. calculation of the misalignment angle (an angle between the CMB and galaxy clustering dipole which appears due to a combination of various effects, such as stochasticity in the nonlinear relation between the velocity and acceleration of the Local Group); 4. comparison of the results obtained with different methods.

We perform this analysis first for the MXXL simulated galaxy catalog. It allows us to compare the results obtained for the datasets with the ZoA modified in 12 different ways against the clustering dipole calculated for the unaltered, original dataset. Based on this comparison we are able to establish which method of the ZoA reconstruction provides the results closest to the ones obtained for the original dataset. Then, we use this method to calculate the clustering dipole in a real catalog: 2MASS (Skrutskie et al., 2006).

3 Data

For our work we used two datasets: MXXL simulated galaxy catalog and 2MASS galaxy catalog. MXXL is an N-body simulation consisting of more than 58 mln

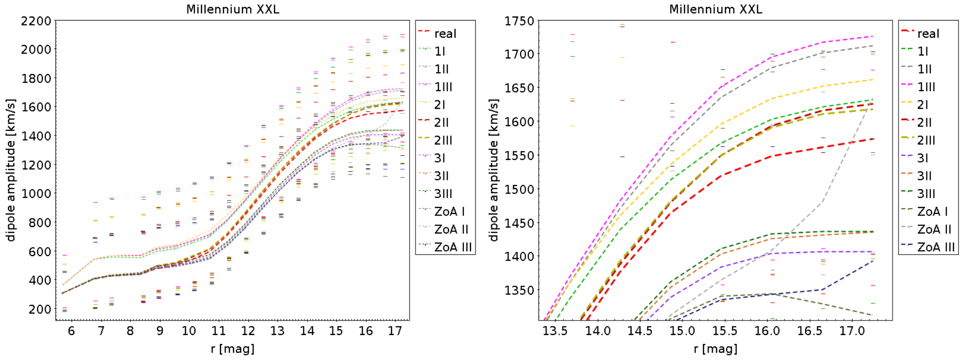

Fig. 1: The clustering dipole amplitude obtained for MXXL simulated galaxy catalog with the use of different methods of the ZoA treatment; *right:* the close-up of the dipole centered on the highest values of the limiting magnitude; the results obtained for the unaltered simulated catalogs denoted as REAL and marked by bold red curves; results 2II and 2III – the closest to the REAL one – also marked as bold curves; errors marked by horizontal dashes.

sources, out of which we found 2 772 185 useful for our purpose. The magnitudes in this simulated catalog reach $r \approx 20$ mag. However, we introduced a cutoff at $r = 17.5$ mag in order to obtain a galaxy sample comparable with the 2MASS galaxy catalog.

Two Micron All-Sky Survey (2MASS) catalog is the first near-infrared all-sky survey, and it covers 99.998% of the sky. It contains more than 1 million galaxies and is complete for sources brighter than $K \approx 13.5$ mag.

4 Results

Fig. 1 presents the growth of the dipole amplitude as a function of an increasing magnitude limit, calculated for the MXXL simulated galaxy catalog, modified in 12 different ways. The errors were estimated via a bootstrap method and in Fig. 1 they are marked by horizontal dashes. In the legend REAL denotes the original, unmodified MXXL simulated galaxy catalog and is marked as a bold red curve, reaching $\sim$1550 km s^{-1} for the limiting magnitude of the catalog. Colored curves (1I – 3III) mark the results obtained for the MXXL simulated galaxy catalog modified according to the 9 tested methods of filling the ZoA (3 shapes of the ZoA filled in 3 ways, as described in Sec. 2). All of them also reach, within the error bars, values close to $\sim$1550 km s^{-1}. The right panel of Fig. 1 presents a close-up for the largest limiting magnitude values. It is clearly visible that the optimal results (curves closest to the REAL one) are obtained for the method 2II, followed closely by 2III (indicated by bold curves in Fig. 1). The 3 remaining bold curves in Fig. 1, described as ZoA II – III, mark the results obtained for three versions of a *removed and not filled in* ZoA. In this case the removal of the simulated galaxies in the ZoA underestimates the calculated values of the dipole amplitude for all 3 shapes of the ZoA. The shape I has the least influence on the results. Moreover, the dipole amplitude for this definition of the ZoA reaches its maximum value at $\sim$16 mag and starts decreasing. The curves, representing the results obtained with the use of the two remaining definitions of the ZoA (II and III), rise sharply for the largest limiting magnitudes.

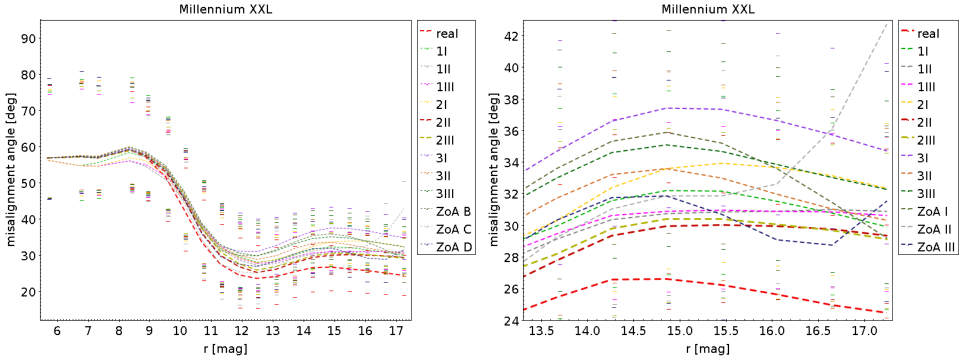

Fig. 2: The misalignment angle obtained for MXXL simulated galaxy catalog with the use of different methods the ZoA treatment; *right:* the close-up of the misalignment angle centered on the highest values of the limiting magnitude; the results obtained for the unaltered simulated catalogs denoted as REAL and marked by bold red curves; results 2II and 2III – the closest to the REAL one – also marked as bold curves; errors marked by horizontal dashes.

Finally, it is also clearly visible that the error bars for these 3 curves decrease with the increasing limiting magnitude.

Fig. 2 presents the misalignment angle as a function of the limiting magnitude. Similarly as above, the errors were estimated via a bootstrap method (in Fig. 2 marked by horizontal dashes). REAL indicates the misalignment angle calculated for the unmodified MXXL simulated galaxy catalog. Curves denoted by 1I – 3III represent the results calculated with the use of the catalog with the ZoA removed and filled according to the 9 tested methods (see Sect 2). Finally, ZoA I – III depict the misalignment angle calculated for data with the ZoA left empty. It is significant, that any of the modifications of the MXXL simulated galaxy catalog results in the sustained overestimation of the misalignment angle with comparison to the REAL result. The right panel of Fig. 2 presents a close-up of the results for the largest magnitudes. Similarly to the case of the dipole amplitude, the removal of the ZoA defined by I results in the shape of the misalignment angle's curve similar to the referential, REAL one, while the definitions II and III cause the misalignment angle to rise sharply for the largest magnitudes. Also, it is visible, that once more filling the ZoA according to the methods 2II and 2III results in the values of the misalignment angle, still overestimated, but the closest to the one obtained for the original MXXL simulated galaxy catalog.

Fig. 3 presents the juxtaposition of the statistical errors for each method of dealing with the ZoA problem, both for the dipole amplitude and the misalignment angle. From Fig. 3 we conclude:

- all the tested methods overestimate the amplitude (5% – 35%) and underestimate the misalignment angle (20% – 40%);
- all the methods from the 3rd group (random filling) overpredict the misalignment angle significantly while the dipole amplitude to the lesser degree;
- all the methods from the 1st group (cloning adjacent areas) overpredict the amplitude significantly, while the misalignment angle only slightly less than

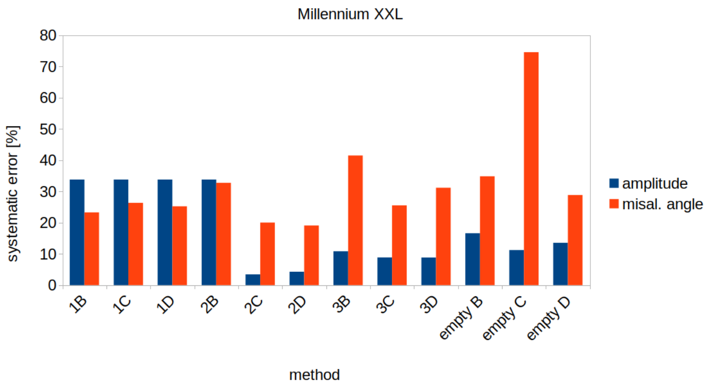

Fig. 3: The systematic errors of the amplitude and misalignment angle measurement for MXXL simulated galaxy catalog with the use of different methods of the ZoA treatment.

the methods from the 3rd group;

- the methods from the 2nd group can be considered the best, however only with the most conservative removal of the ZoA; otherwise they fare no better than the methods from the 1st group;
- the systematic errors of the amplitude are in some cases (mainly for the methods from the 1st group) larger with the ZoA filled than left empty; filling the ZoA improves mainly the misalignment angle;

Fig. 4 presents the comparison of the results for the MXXL simulated catalog and the 2MASS catalog, both obtained via the method of filling the ZoA we deem optimal, that is 2II. r magnitudes in the MXXL simulated galaxy catalog were rescaled to match the K_{s} band of 2MASS.

The left panel of Fig. 4 presents the growth of the amplitude as a function of the limiting magnitude, for Millennium and 2MASS galaxy catalogs. In both cases the amplitude increases, reaching its peak at $\sim$1550 km/s for the limit of $\sim$13.5 mag. While for the MXXL simulated galaxy catalog the amplitude seems to converge at that value, for the 2MASS catalog that is not the case.

The right panel of Fig. 4 presents the misalignment angle as a function of the limiting magnitude of the galaxy sample. It is visible that the misalignment angle for the 2MASS catalog reaches significantly lower values ($\sim 10^\circ$ than for the MXXL catalog ($\sim 30^\circ$). Similarly to the amplitude, here also the misalignment angle for the 2MASS catalog does not converge, contrary to what is visible for the MXXL.

5 Conclusions

In our work we tested methods of dealing with the ZoA problem for the calculation of the clustering dipole of galaxies. First, we performed our analysis using the MXXL simulated galaxy catalog, which provided us with the possibility of comparing the results obtained with the artificially filled ZoA vs. the idealized ones, enabling us to establish which of the tested methods is optimal for our purpose. We found that filling the ZoA, defined according to our definition II (see Sect. 2), by cloning

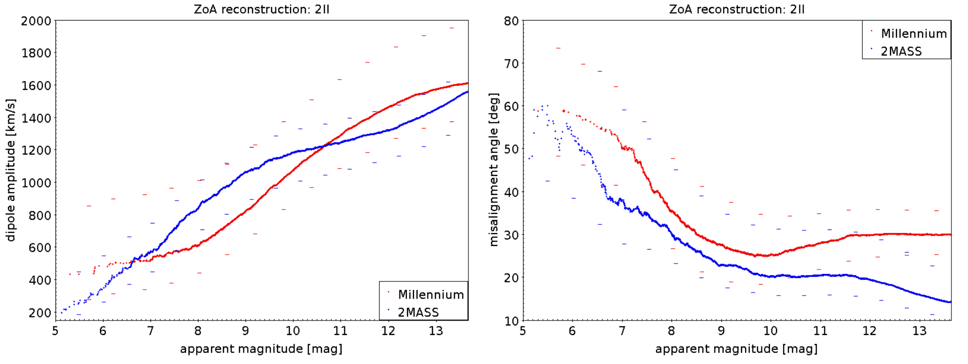

Fig. 4: The clustering dipole amplitude and the misalignment angle obtained for MXXL simulated galaxy catalog and 2MASS galaxy catalog with the use of the optimal method of filling the ZoA.

every second source from large areas adjacent to the ZoA results in both the dipole amplitude and the misalignment angle closest to the idealized ones (Fig. 1 and 2).

Then, we wanted to use this method to find the value and direction of the clustering dipole for a real all-sky galaxy catalog – 2MASS. As shown in Fig. 4, both the dipole amplitude and the misalignment angle reach similar values for the MXXL simulated data and the 2MASS. They are also in agreement with previous estimates of the clustering dipole, presented in Bilicki et al. (2011), where the dipole amplitude at the limiting magnitude of the catalog was found to be: $V \approx 1500 \pm 260$ km s^{-1} and the misalignment angle: $\zeta \approx 17° \pm 5°$.

It is important to note, however, that neither for the MXXL nor for 2MASS, the clustering dipole converges. This indicates the need for a deeper all-sky galaxy catalog and points out the direction of further studies.

Acknowledgements. This work is supported by Polish National Science Centre grants UMO-2018/30/M/ST9/00757, UMO-2018/30/E/ST9/00698 and grant of Polish Ministry of Science and Higher Education DIR/WK/2018/12

References

Bilicki, M., Chodorowski, M., Jarrett, T., Mamon, G. A., *ApJ* **741**, 1, 31 (2011)

Carrick, J., Turnbull, S. J., Lavaux, G., Hudson, M. J., *MNRAS* **450**, 1, 317 (2015)

Erdoğdu, P., et al., *MNRAS* **368**, 4, 1515 (2006)

Lavaux, G., Tully, R. B., Mohayaee, R., Colombi, S., *ApJ* **709**, 1, 483 (2010)

Schröder, A. C., van Driel, W., Kraan-Korteweg, R. C., *MNRAS* **482**, 4, 5167 (2019)

Skrutskie, M. F., et al., *AJ* **131**, 1163 (2006)

Smith, A., et al., *MNRAS* **470**, 4646 (2017)

Strauss, M. A., et al., *ApJ* **397**, 395 (1992)