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Gravitational multipolar structure of the local universe

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Abstract. Understanding the matter distribution in the Local Universe is crucial for comprehending the process of structure formation and for studying overdensities and underdensities regions. With this goal, we analyze the galaxy distribution from the 2MASS Redshift Survey catalog within the redshift range $0.015 \leq z \leq 0.060$, that represents the cut sample. In this region, interesting structures are found, such as the underdensity known as the Dipole Repeller (DR) and the overdense region constituted by the Shapley Supercluster, which together form the Shapley-DR system acting as a gravitational dipole. We study this matter distribution by calculating its angular power spectrum and evaluating the signatures at different scales, comparing them with 1000 simulated maps (mocks) generated with the GLASS code under a fiducial cosmology. From this comparison, we identify the relevant signatures observed in the angular power spectrum and investigate the matter structures that produce them.

Resumo. Entender a distribuição de matéria no Universo Local é importante para compreender o processo de formção de estruturas e estudar as regiões de sobredensidades e vazios. Com este objetivo, estudamos a distribuição de galáxias do catálogo 2MASS Redshift Survey para o intervalo de redshift $0.015 \leq z \leq 0.060$. Nesta região encontram-se estruturas interessantes como a subdensidade denominada Dipole Repeller (DR) e a região de sobredensidade constituida pelo aglomerado de Shapley, que juntas constituem o sistem Shapley-DR que atua como um dipolo gravitacional. Estudamos esta distribuição de matéria calculando seu espectro de potência angular e avaliamos as assinaturas em diferentes escalas, comparando-as com 1000 mapas simulados (Mocks) gerados com o código GLASS, assumindo uma cosmologia fiducial. A partir dessa comparação identificamos as assinaturas relevantes observadas no espectro de potência angular, e procuramos pelas estruturas de matéria ou vazios que as produzem.

Keywords. large-scale structure of the Universe – data analysis – observational

1. Introduction

Characterizing overdensities and voids in the Local Universe is essential for understanding the formation of cosmic structures and how these regions influence velocity flows and large-scale gravitational dynamics. Our objective in this work is to use data from the 2MASS Redshift Survey (2MRS), together with statistical analysis techniques, to describe the angular distribution of galaxies in the Local Universe and to study its gravitational multipolar structure through the power spectrum of the galaxy density field. The analysis is performed using 2MRS galaxies as tracers, filtered within the redshift range $0.015 \leq z \leq 0.060$. In this interval lies the system formed by a large underdensity termed the Dipole Repeller (DR) and the largest supercluster of galaxies, the Shapley Supercluster, which together form a gravitational dipole system that produces the bulk flow motion of matter in the Local Universe Lopes et al. (2024).

The Generator for Large Scale Structure (GLASS) (Tessore et al. 2023) is a scientific tool used to model the non-linear power spectrum with the desired level of detail. It is applied here to generate 1000 accurate galaxy mock catalogues, assuming a fiducial cosmology, in order to estimate the power-spectrum uncertainties and to investigate how their magnitude varies as a function of the angular multipole (ℓ).

HEALPix (Hierarchical Equal Area iso-Latitude Pixelization) is a spherical pixelization framework that generates discretized sky maps from very large astronomical datasets through its hierarchical structure, equal-area pixel partitioning, and iso-latitude pixel distribution Górski et al. (2005). In this work, it is used to visualize the 2MRS data maps and to perform mathematical operations between them in order to obtain the density contrast map and its corresponding power spectrum.

2. Observational Data

The Two Micron All Sky Survey (2MASS) was an effort conducted from two 1.3 m diameter telescopes at Mount Hopkins, Arizona, and Cerro Tololo, Chile, operating between 1997 and 2003 to obtain a uniform map of the whole sky in the near-infrared. Near-infrared wavelengths are sensitive to old stellar populations that dominate galaxy masses, making 2MASS an excelent starting point to study the distribution of matter in the nearby Universe. Huchra et al. (2012)

The Survey covered 99.998%, producing 4.1 million compressed FITS images and identifying 471 million point sources of the celestial sphere, at J(1.25 μ m), H (1.65 μ m) and K_s (2.16 μ m) photometric bands. (Skrutskie et al. 2006)

The 2MASS Redshift Survey (2MRS) is an extended catalog from 2MASS containing 43,533 brightest galaxies with $K_s < 11.75$, interstellar extinction E(B-V) ≤ 1 mag, and galactic latitude $|b| \geq 5^\circ$ for $30^\circ \leq l \leq 330^\circ$ ($|b| \geq 8^\circ$ towards the Galactic Bulge) to avoid the Milky Way's zone. The sample has 11,000 spectroscopic observations and 32,533 used velocities from literature to generate a redshift catalog that covers 91% of the sky, concentrated within 300 Mpc. (Huchra et al. 2012)

For the purposes of this work, the analysis is restricted to the Local Universe, within the redshift range $0.015 \leq z \leq 0.060$.

3. Methodology

The following steps outline the full analysis pipeline, starting from the 2MRS data processing and ending with the APS computed from the density contrast map.

The dataset is first imported and filtered to retain only the galaxies within the desired redshift range. Next, the equatorial coordinates (RA, DEC) are transformed into Galactic coordinates

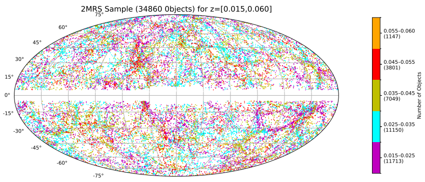

Figure 1: Mollweide galaxy projection using Matplotlib.

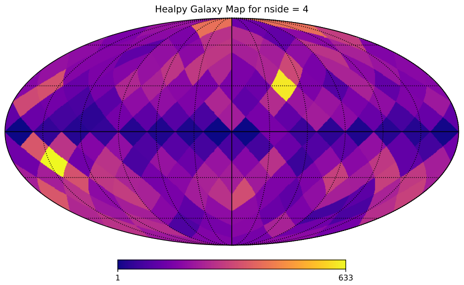

Figure 2: Mollweide galaxy projection using HEALPix.

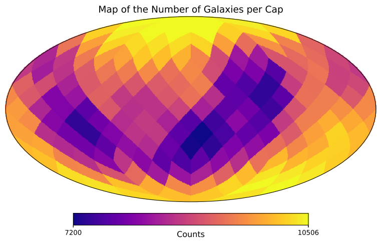

Figure 3: Galaxy Counts Map.

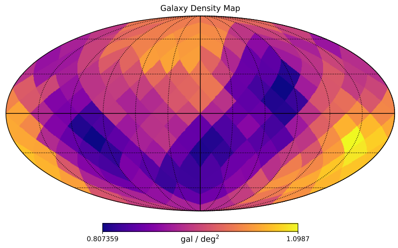

Figure 4: Galaxy Density Map.

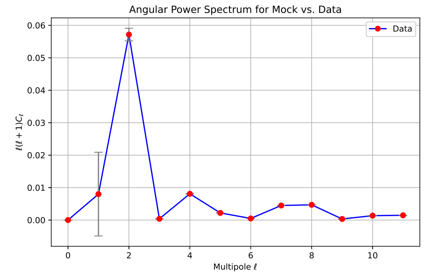

Figure 5: Angular power spectrum for 2MRS filtered data (green line) and mocks (blue line).

(l,b) in order to visualize the full-sky distribution of galaxies in a Mollweide projection. They are produced using Matplotlib for Fig. 1), and HEALPix (Górski et al. 2005) for Fig. 2, providing a visual representation of the data.

The celestial sphere is pixelized at a resolution of nside=4, corresponding to 192 pixels, using the HEALPix framework to analyze the galaxy density map. We first obtain the valid area map, excluding the avoidance zone around the *Via Lactea* disk. Then obtain the number of galaxies map (Fig. 3) defining the data points inside a circular region of 60° radius around each pixel. The number of galaxies in each pixel is then divided by the corresponding effective area, producing the spatial density map (Fig. 4). From this, we obtain the density contrast map, which represents fluctuations in the galaxy density relative to the mean and helps to visualize the regions with the greatest deviations relative to the mean:

$$\delta(\hat{n}) = \frac{\rho(\hat{n}) - \bar{\rho}}{\bar{\rho}} \,. \tag{1}$$

We decompose this map in sperical harmonics using the anafast function from Górski et al. (2005), which performs a spherical harmonic analysis and estimates the power spectrum from the derived $a_{\ell m}$ coefficients:

$$\delta(\hat{n}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\hat{n}) \,, \tag{2}$$

and then obtain the angular power spectrum (APS):

$$C_\ell = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2 \,. \tag{3}$$

The APS (C_ℓ) is a statistical measure that quantifies how the matter distribution varies across different angular scales on the sky. For different angular sizes (θ) we have the corresponding multipoles (ℓ), following the relation:

$$\theta \sim \frac{180^\circ}{\ell} \tag{4}$$

The APS derived from the density contrast map, used to quantify the matter distribution across different angular scales for the filtered 2MRS sample, is shown in Fig. 5 as the green curve.

Using GLASS code, we produced 1000 mock catalogs with a lognormal distribution in RA, DEC, and redshift, following the same procedure applied to the 2MRS data to construct the density contrast map. We then computed the APS for each mock catalog and calculated the mean and standard deviation (shown as the red error-bar region in Fig. 5) to estimate the uncertainties in the observational data.

This approach enables the identification of underdensities and overdensities (Novaes et al. 2016; Dias et al. 2023; Franco et al. 2024, 2025), that is, the multipolar gravitational patterns that influence velocity flows in the Local Universe.

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