Large-scale asymmetry in galaxy spin directions - analysis of galaxies with spectra in DES, SDSS, and DESI Legacy Survey

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Abstract

Multiple previous studies using several different probes have shown considerable evidence for the existence of cosmological-scale anisotropy and a Hubble-scale axis. One of the probes that show such evidence is the distribution of the directions toward which galaxies spin. The advantage of the analysis of the distribution of galaxy spin directions compared to the CMB anisotropy is that the ratio of galaxy spin directions is a relative measurement, and therefore less sensitive to background contamination such as Milky Way obstruction. Another advantage is that many spiral galaxies have spectra, and therefore allow to analyze the location of such axis relative to Earth. This paper shows an analysis of the distribution of the spin directions of over 90K galaxies with spectra. That analysis is also compared to previous analyses using the Earth-based SDSS, Pan-STARRS, and DESI Legacy Survey, as well as space-based data collected by HST. The results show very good agreement between the distribution patterns observed with the different telescopes. The dipole or quadrupole axes formed by the spin directions of the galaxies with spectra do not necessarily go directly through Earth.

1 Introduction

Recent observations with several different probes have shown accumulating evidence of cosmological-scale anisotropy, and the presence of a Hubble-scale axis. Perhaps the most notable and thoroughly studied probe showing evidence of cosmological-scale anisotropy and a cosmological-scale axis is the cosmic microwave background (Eriksen et al., 2004; Cline et al., 2003; Gordon and Hu, 2004; Campanelli et al., 2007; Zhe et al., 2015;Abramo et al., 2006; Mariano and Perivolaropoulos, 2013; Land and Magueijo, 2005; Ade et al., 2014; Santos et al., 2015; Dong et al., 2015; Gruppuso et al., 2018; Yeung and Chiu, 2022). Other messengers that show cosmological anisotropy and possible axes in the large-scale structure include radio sources (Ghosh et al., 2016; Tiwari and Jain, 2015; Tiwari and Nusser, 2016); LX-T scaling (Migkas et al., 2020), short gamma ray bursts (Mészáros, 2019); cosmological acceleration rates (Perivolaropoulos, 2014; Migkas et al., 2021; Krishnan et al., 2021), galaxy morphology types (Javanmardi and Kroupa, 2017); Ia supernova (Javanmardi et al., 2015; Lin et al., 2016); dark energy (Adhav et al., 2011; Adhav, 2011; Perivolaropoulos, 2014; Colin et al., 2019); fine structure constant (Webb et al., 2011); galaxy motion (Skeivalas et al., 2021); H0; (Luongo et al., 2021); polarization of quasars (Hutsemekers et al., 2009; Secrest et al., 2021; Zhao and Xia, 2021; Semenait et al., 2021); and high-energy cosmic rays (Aab et al., 2017).

Other studies showed that the large-scale distribution of galaxies in the Universe is not random, as discussed by De Lapparent et al. (1986); Hawkins et al. (2003); Colless et al. (2003); Jones et al. (2005); Deng et al. (2006); Adelman-McCarthy (2008) and others. Data-driven observations based on large datasets revealed the existence of very large structures (Gott III et al., 2005; Lietzen et al., 2016; Horváth et al., 2015) that could be beyond astrophysical scale, and therefore challenge the cosmological principle.

These observations can be viewed as a certain tension with the standard cosmological models (Pecker, 1997; Perivolaropoulos, 2014; Bull et al., 2016; Velten and Gomes, 2020; Krishnan et al., 2021; Luongo et al., 2021), and triggered several expansions to the standard models, as well as other cosmological theories that shift from the standard models. Possible explanations and theories include double inflation (Feng and Zhang, 2003); primordial anisotropic vacuum pressure (Rodrigues, 2008); contraction prior to inflation (Piao et al., 2004); flat space cosmology (Tatum et al., 2018a,b; Azarnia et al., 2021); multiple vacua (Piao, 2005); spinor-driven inflation (Bolmer and Mota, 2008); and moving dark energy (Beltran Jimenez and Maroto, 2007).

Other proposed theories can be related to the geometry of the Universe such as ellipsoidal universe (Campanelli et al., 2006; 2007; 2011; Gruppuso, 2007; Cea, 2014); geometric inflation (Arciniegas et al., 2020a; Edelstein et al., 2020; Arciniegas et al., 2020b; Jaime, 2021); supersymmetric flows (Rajpoot and Vacaru, 2017); and rotating universe (Gödel, 1949). Early rotating universe theories were based on a non-expanding universe (Gödel, 1949), and therefore conflict with the observation that the Universe is expanding. More recent models of rotating Universe were modified to support cosmological expansion (Ozsváth and
The existence of a cosmological-scale axis can also be associated with the theory of black hole cosmology, and can explain cosmic accelerated inflation without the assumption of dark energy (Patricia, 1972; Stuckey, 1994; Easson and Brandenberger, 2001; Chakraborty et al., 2020). Black holes spin (Gammie et al., 2004; Takahashi, 2004; Volonteri et al., 2005; McClintock et al., 2006; Mudambi et al., 2020; Reynolds, 2021), and their spin is inherited from the spin of the star from which the black hole was created (McClintock et al., 2006). Due to the spin of the black hole, it has been proposed that a universe hosted in a black hole should have an axis and a preferred direction (Poplawski, 2010a; Seshavatharam and Lakshminarayana, 2014; Christillin, 2013; Seshavatharam and Lakshminarayana, 2020b,a). Black hole cosmology is also associated with the theory of holographic universe (Susskind, 1995; Bak and Rey, 2000; Bousso, 2002; Myung, 2005; Hu and Ling, 2006; Rinaldi et al., 2022), which can also represent the large-scale structure of the Universe in a hierarchical manner (Sivaram and Arun, 2013; Shor et al., 2021).

In addition to the messengers discussed above, multiple previous studies showed substantial evidence that the distribution of the spin directions of spiral galaxies is anisotropic, and forms a cosmological-scale axis (MacGillivray and Dodd, 1985; Longo, 2011; Shamir, 2012; 2013; 2016; 2017a,b; 2019; 2020a,b,c,d; Lee et al., 2019a,b; Shamir, 2021a,b). These observations include different telescopes such as SDSS (Shamir, 2012; 2020d; 2021a; 2022), Pan-STARRS (Shamir, 2020d), HST (Shamir, 2020b), and DECam (Shamir, 2021b,c). These telescopes show consistent patterns of the asymmetry, regardless of the telescope being used or the method of annotation of the galaxies (Shamir, 2021b; 2022).

The alignment of the spin directions of galaxies was observed within cosmic web filaments, as discussed in (Tempel et al., 2013; Tempel and Libeskind, 2013; Tempel et al., 2014; Dubois et al., 2014; Kralic et al., 2021) among other studies, but also between galaxies too far from each other to interact gravitationally (Lee et al., 2019b,a). That alignment is difficult to explain with the standard gravity models, and was defined as “mysterious” (Lee et al., 2019b,a). It has also been proposed that the galaxy spin direction is a probe for studying the early Universe (Motloch et al., 2021).

As a relative measurement, the probe of the large-scale distribution of galaxy spin directions has the advantage of being less sensitive to background contamination such as Milky Way obstruction. The reason is that the asymmetry in galaxy spin directions in a certain field is determined by the difference between the number of galaxies spinning clockwise and the number of galaxies spinning counterclockwise in the same field. Since all galaxies are observed in the exact same field, any background contamination or other effect that affects galaxies spinning clockwise is naturally expected to affect galaxies spinning counterclockwise in the same manner. Because the background contamination affects all galaxies in the field, its existence is not expected to affect the asymmetry. That might be different from other probes such as CMB, where the measurement is absolute, and background contamination that affects a certain field can lead to the observation of anisotropy.

Another advantage of using spin direction asymmetry is that spiral galaxies are very common in the Universe, and are present in a broad redshift range. That important advantage allows to identify not merely the existence of a cosmological-scale axis, but also to determine its approximated location relative to Earth. This paper uses a dataset of ~100K spiral galaxies with spectra to identify the location of the axis formed by the distribution of these galaxies.

## 2 Data

The dataset used in this study is made of galaxies imaged by three different telescopes: the Sloan Digital Sky Survey (SDSS), the Dark Energy Survey (DES), and the Dark Energy Spectroscopic Instrument (DESI) Legacy Survey. That datasets is compared to the distribution of the spin directions of galaxies in datasets used in previous studies.

The directions of the curves of the spiral arm of a galaxy is a reliable indication on the spin direction of the galaxy. For instance, De Vaucouleurs (1958) used dust silhouette and Doppler shift to determine that in all tested cases the spiral arms were trailing, and therefore allow to determine the spin direction of the galaxy. While in some rare cases galaxies can have leading arms, such as NGC 4622 (Freeman et al., 1991), the vast majority of spiral galaxies have trailing arms, and therefore the curve of the galaxy arms can in most cases determine the direction towards which it spins.

The primary task related to the data used in this study is the annotation of galaxies by their spin direction. Although one of the datasets used here was annotated manually (Shamir, 2020d), the scale of databases acquired by modern digital sky surveys is far too large for manual annotation. The practical approach to the annotation of very large datasets of galaxy images is by automatic annotation. It should be mentioned that while pattern recognition, and specifically deep neural networks, have become the common solution to automatic annotation of galaxy images, these approaches might not be suitable for studying subtle cosmological-scale anisotropies (Dhar and Shamir, 2022). Pattern recognition, and specifically deep neural networks, are based on complex data-driven rules, and are therefore subjected to subtle biases that are very difficult to identify (Carter et al., 2020; Dhar and Shamir, 2021), and have also been detected in galaxy images (Dhar and Shamir, 2022). Such biases might skew the results. A more thorough discussion about the possible impact of bias in the annotation...
2.1 Automatic annotation of clockwise and counterclockwise galaxies

The galaxies were annotated automatically from the 2D galaxy images by using the Ganalyzer algorithm (Shamir, 2011). Ganalyzer is a model-driven algorithm that uses fully symmetric clear mathematical rules to determine the spin direction of a spiral galaxy. The algorithm is described in detail in (Shamir, 2011), and brief description is also available in (Dojcsak and Shamir, 2014; Hoehn and Shamir, 2014; Shamir, 2017c,b, 2020d, 2021a,b, 2022).

In summary, Ganalyzer first transforms each galaxy image into its radial intensity plot. The radial intensity plot transformation of a galaxy image is a $35 \times 360$ image, such that the pixel $(x, y)$ in the radial intensity plot is the median value of the $5 \times 5$ pixels around coordinates $(O_x + \sin(\theta) \cdot r, O_y - \cos(\theta) \cdot r)$ in the original galaxy image, where $r$ is the radial distance in percentage of the galaxy radius, $\theta$ is the polar angle measured in degrees, and $(O_x, O_y)$ are the pixel coordinates of the galaxy center.

Pixels on the galaxy arms are expected to be brighter than pixels that are not on the galaxy arm at the same radial distance from the center. Therefore, peaks in the radial intensity plot are expected to correspond to pixels on the arms of the galaxy at different radial distances from the center. To identify the arms, a peak detection algorithm (Morháč et al., 2000) is applied to the lines in the radial intensity plot.

Figure 1 shows examples of the radial intensity plots and the peaks detected in them in four DES galaxies. The figure also shows the radial intensity plot of each galaxy, and the lines formed by the detected peaks. Each line in the radial intensity plot shows the brightness of the pixels around the center of the galaxy. That is, the first value in the line is the brightness of the pixel at $0^\circ$ compared to the galaxy center, and the last value in the line is the brightness of the pixel at $359^\circ$. Since each line is at a different radius from the center, each radial intensity plot has multiple lines. Below each radial intensity plot shown in Figure 1, the figure displays the peaks identified in the lines. That is, if a pixel in the radial intensity plot is identified as a peak in its line, the corresponding pixel in the image below the radial intensity plot is white. Otherwise, the pixel is black. More information about Ganalyzer can be found in (Shamir, 2011; Dojcsak and Shamir, 2014; Shamir, 2017c,b, 2019, 2020d, 2021a,b, 2022).

As Figure 1 shows, the lines formed by the peaks identified in the radial intensity plots form lines in different directions. A linear regression is applied to the peaks in adjunct lines formed by the peaks, and the slope of the linear regression reflects the curve of the arm. As Figure 1 shows, if the galaxy spin clockwise the slope of the regression is positive, while if the galaxy spins counterclockwise the slope is negative. Therefore, the slope of the regression can be used to determine the spin direction of the galaxy.

Naturally, many galaxies are elliptical galaxies, irregular galaxies, or spiral galaxies that do not have an identifiable spin direction. To avoid galaxies that do not have an identifiable spin direction, only galaxies with 30 or more peaks that form curved lines in the radial intensity plots are used. If that criteria is not met, the galaxy is determined to have an unidentifiable spin direction. As mentioned above, the main advantage of the algorithm is that it follows defined and fully symmetric rules. Analysis of different situations when applying the algorithm to populations of galaxies are described in Shamir (2021a), and also more briefly in Section 4.

2.2 Galaxy images and digital sky surveys

The dataset of galaxies with spectra used in this study is based on data collected by three different digital sky sur-
veys: SDSS, DES, and the DESI Legacy Survey. The SDSS galaxies are 63,693 galaxies with spectra used in (Shamir 2019, 2020d). The preparation of that dataset is described in detail in (Shamir 2020d). The galaxies from the DESI Legacy Survey are the subset of galaxies used by Shamir (2021b) that had spectroscopic redshift through the catalog of Zhou et al. (2021). The entire DESI Legacy Survey dataset contained 807,898 galaxies (Shamir 2021b), but only 23,715 of these galaxies had spectroscopic redshift through the catalog of Zhou et al. (2021). The Zhou et al. (2021) catalog contains mostly the photometric redshift of the DESI Legacy Survey galaxies. As also discussed in Section 4, since the inaccuracy of photometric redshift is greater than the expected signal, the photometric redshift cannot be used for this study, and therefore only galaxies that had spectroscopic redshift are used.

Similarly to the DESI dataset, galaxies from DES data release (DR) 1 were also used. The initial list of DES objects included all objects identified as exponential disks, de Vaucouleurs $r^{1/4}$ profiles, or round exponential galaxies, and were brighter than 20.5 magnitude in one or more of the g, r or z bands. That list contained an initial set of 18,869,713 objects. The galaxy images were downloaded using the cutout API of the DESI Legacy Survey server, which also provide access to DES data. The size of each image was 256×256, and retrieved in the JPEG format. Each image was scaled using the Petrosian radius to ensure that the galaxy fits in the image. The process of downloading the images started on April 25th 2021, and ended about six months later on November 1st 2021.

Once the image files were downloaded, they were annotated by their spin direction using the Ganalyzer method described above and in (Shamir 2011, Dojcisk and Shamir 2014, Shamir 2017c,d,b, 2019, 2020d, 2021b, 2022). The annotation of the galaxies lasted 73 days of operation using a single Intel Xeon processor. Then, the images were mirrored using ImageMagick and annotated again to allow repeating the experiments with mirrored images. That provided a dataset of 773,068 galaxies annotated by their spin directions. To remove satellite galaxies or stars positioned inside a galaxy, objects that had another object in the dataset within 0.01° or less were removed from the dataset. That provided a dataset of 739,286 galaxies imaged by DES, and 14,365 of these galaxies had redshift through the 2dF redshift survey (Colless et al., 2003, Cole et al. 2005).

Combining all three datasets and removing objects that appeared in more than one dataset provided a dataset of 90,023 galaxies with spectra. Figure 3 shows the distribution of the redshift in the dataset, and Figure 2 shows the distribution of the galaxies by their RA. Figure 4 shows the galaxy population density in each 5°×5° field of the sky. The density is determined by the number of galaxies in each 5°×5° field divided by the total number of galaxies.

An important property of the dataset used in this study is that the data are retrieved and analyzed without any prior assumptions, and are not based on any existing catalog of galaxy morphology. Because the dataset is made of data from several telescopes covering both the Northern and Southern hemispheres, there is no existing catalog of galaxy morphology that includes all galaxies used in this study. More importantly, using an existing catalog of galaxy morphology might expose the analysis to bias of a catalog that was not prepared with the normalization of spin direction in mind. For instance, morphology catalogs that were prepared manually can be biased by the human perception (Land et al., 2008, Hayes et al., 2017). Due to the complex nature of the human perception, these subtle but consistent biases are very difficult to quantify and correct.

In the past two decades, catalogs of galaxy morphology were prepared by using machine learning algorithms, and specifically deep neural networks such as (Gravet et al., 2015, Pérez-González et al., 2015, Goddard and Shamir 2020, Cheng et al. 2021). While these catalogs are prepared by using a computer software, the rules used to make the annotation are determined automatically by using training sets of galaxies that were annotated manually. Therefore, the machine learning systems can still capture the perceptual biases of the humans who annotated the
data that was used to train the machine learning system. Also, the rules used by these machine learning systems are complex non-intuitive rules generated automatically from the data by which the machine learning system is trained. Due to their complexity, it is very difficult to verify theoretically or empirically that these rules are fully symmetric, and do not lead to certain biases.

It might be reasonable to assume that if such bias existed, it would have been expected to be consistent throughout the sky, and would not exhibit inverse asymmetry in opposite hemispheres. However, due to the complex nature of these algorithms it is very difficult to prove such claim. For instance, it has been shown that by selecting a different training set, a deep neural network produces a slightly but consistently different catalog (Dhar and Shamir, 2022). Therefore, using catalogs that were prepared for other purposes, and do not necessarily ensure that the algorithm is fully symmetric in terms of the spin directions of the galaxies, can introduce an additional source of bias that depends on the way the catalog was prepared, and might be carried on to the rest of the analysis.

As discussed in Section 2.1, the algorithm used to determine the spin direction of the galaxies can also perform the broad morphological classification of elliptical and spiral galaxies (Shamir, 2011), and identify just galaxies with identifiable spin direction. Elliptical galaxies or other galaxies that their spin direction cannot be determined are not included in the analysis, and the removal of the galaxies is done by the same model-driven symmetric algorithm described in Section 2.1. Further discussion on the use of catalogs of galaxy morphology can be found in Section 4.7.

### 3 Results

A very simple way of observing the distribution of galaxy spin directions in a certain field in the sky is by comparing the number of galaxies spinning clockwise to the number of galaxies spinning counterclockwise. The statistical significance of the difference can be determined by using binomial distribution, such that the probability of a galaxy to spin clockwise or counterclockwise is assumed to be 0.5. The asymmetry A can be defined by $A = \frac{cw - ccw}{cw + ccw}$, where cw is the number of galaxies spinning clockwise, and ccw is the number of galaxies spinning counterclockwise.

A galaxy that seems to spin clockwise to an observer on Earth would seem to spin counterclockwise if the observer was in the opposite side of the galaxy. Therefore, the asymmetry of the distribution of galaxy spin directions in one hemisphere is expected to be inverse in the opposite hemisphere. Perhaps the most simple way of separating the sky into two hemispheres is such that one hemisphere is $(0^\circ < \alpha < 180^\circ)$, and the other hemisphere is $(180^\circ < \alpha < 360^\circ)$. That separation is clearly very simple, and used in this case for the sake of simplicity. Table 1 shows the number of clockwise and counterclockwise galaxies in each hemisphere, and the binomial probability to have such difference by chance.

As the table shows, the hemisphere $(0^\circ < \alpha < 180^\circ)$ has a higher number of galaxies spinning clockwise, while the opposite hemisphere has a higher number of galaxies spinning counterclockwise. While the sign of the asymmetry is inverse in the opposite hemisphere, the asymmetry in the hemisphere $(180^\circ < \alpha < 360^\circ)$ is not necessarily statistically significant. However, even if assuming no asymmetry in that hemisphere, after applying a Bonferroni correction the the Bonferroni-corrected P value of the asymmetry in $(0^\circ < \alpha < 180^\circ)$ is ~0.014, which is statistically significant. When repeating the analysis by using the mirrored images the results inverse, as expected due to the symmetric nature of the GAnalyzer algorithm that was used to annotate the images.

The inverse asymmetry of galaxy spin direction between opposite hemispheres has been done in the past with several telescopes such as SDSS (Shamir, 2020a,b), DECam (Shamir, 2021a, 2022), and Pan-STARRS (Shamir, 2020c, 2021b, 2022). For instance, as shown in (Shamir, 2022), separating the entire dataset of galaxies imaged by DECam, mostly in the Southern hemisphere, into two hemispheres provided significant difference between the number of galaxies spinning in opposite directions in the two opposite hemispheres.

| Hemisphere             | # cw galaxies | # ccw galaxies | $\frac{cw - ccw}{cw + ccw}$ | P         |
|------------------------|--------------|---------------|-----------------------------|-----------|
| $(0^\circ < \alpha < 180^\circ)$ | 23,070       | 23,606        | -0.0115                     | 0.007     |
| $(180^\circ < \alpha < 360^\circ)$ | 21,808       | 21,539        | 0.0062                      | 0.09      |

Table 1: Distribution of clockwise and counterclockwise galaxies in opposite hemispheres. The P values are the binomial distribution probability to have such difference or stronger by chance when assuming mere chance 0.5 probability for a galaxy to spin clockwise or counterclockwise.
magnitude of the difference and the redshift. Table 2 shows the same analysis shown in Table 1 for the hemisphere (0° < α < 180°), but after separating the galaxies into galaxies with redshift of z < 0.15 and galaxies with redshift of z > 0.15.

As the table shows, in the higher redshift ranges the asymmetry becomes significantly stronger than when limiting the redshift to lower redshift ranges. The observation is in agreement with previous results using smaller datasets of galaxies with spectra [Shamir, 2020d]. A more detailed analysis that shows the consistent increase of the difference and the statistical signal with the redshift is described in [Shamir, 2020d].

### 3.1 Analysis of a dipole axis in different redshift ranges

The analysis by separating the sky into two simple hemispheres has the advantage of simplicity, but might not provide a full accurate analysis of the location of the most probable axis around which the galaxies are aligned. The separation into two simple hemispheres is arbitrary, and while it shows evidence of asymmetry by using very simple statistics, it does not allow to profile or identify the location of the most likely axis. A more comprehensive analysis of the presence of a dipole axis can be done by fitting the cosine of the angular distances of the galaxies from each possible (α, δ) combination to their spin directions.

That analysis can be done by assigning the galaxies with their spin direction d, which is 1 for galaxies spinning clockwise, and -1 for galaxies spinning counterclockwise. The cosines of the angular distances φ is then χ² fitted into d · |cos(φ)|. From each possible (α, δ) integer combination, the angular distance φᵢ between (α, δ) and each galaxy i in the dataset is computed. The χ² from each (α, δ) is determined by Equation 1

\[
\chi^2_{α,δ} = \sum_i \left( \frac{d_i \cdot |\cos(φ_i)| - \cos(φ_i))^2}{\cos(φ_i)} \right), \quad (1)
\]

where dᵢ is the spin direction of galaxy i, and φᵢ is the angular distance between galaxy i and (α, δ).

For each (α, δ) combination, the χ² is computed with the real spin directions of the galaxies, and then computed 1000 times when dᵢ is assigned with a random spin direction. Using the χ² from 1000 runs, the mean and standard deviation of the χ² when the spin directions are random is computed. Then, the σ difference between the χ² computed with the real spin directions and the mean χ² computed with the random spin directions is used to determine the σ of the χ² fitness to occur by chance. That is done for each (α, δ) integer combination in the sky to determine the probability of each (α, δ) to be the center of the dipole axis [Shamir, 2012, 2019, 2020b, d, 2021a, b, 2022].

Figure 5 shows the computed probabilities of a dipole axis in different (α, δ) combinations. The most probable axis is at (α = 65°, δ = 52°), with probability of 4.7σ to occur by chance. The 1σ error of the location of that axis is (0°, 122°) for the RA, and (42°, -77°) for the declination.

When assigning the galaxies with random spin directions, the asymmetry becomes insignificant [Shamir, 2012, 2019, 2020b, d, 2021a, b, 2022]. Figure 6 shows the probabilities of a dipole axis in different (α, δ) combinations when using the same galaxies used in Figure 5, but when assigning these galaxies with random spin directions. The most likely axis has statistical strength of 0.91σ.

Figure 6: The probability of a dipole axis at different (α, δ) combinations when the galaxies are assigned with random spin directions.

Figure 7 shows the profile when fitting the galaxy spin directions into a dipole axis alignment using galaxies at different redshift ranges. The figure shows that the location of the most likely axis changes with the redshift, until around the redshift range of 0.12 < z < 0.22, after which it stays constant. One immediate explanation to the change in the position of the most likely location of the axis when the redshift increases is that the axis does not necessarily...
The profiles of asymmetry observed with the low redshift galaxies can be compared to previous analyses of galaxy spin directions using Pan-STARRS (Shamir, 2020d) and DECam (Shamir, 2021b). The Pan-STARRS dataset used in Shamir (2020d) includes 33,028 galaxies, and the DECam dataset contains 807,898 galaxies (Shamir, 2021b). The vast majority of the galaxies in these datasets do not have redshift, but because the magnitude of all galaxies is limited to 19.5, the redshift is also expected to be relatively low. Figure 8 shows the profile of asymmetry observed with Pan-STARRS and DECam as reported in Shamir (2021b, 2022). These results are compared to the results with the dataset described in Section 2 when the redshift of the galaxies is limited to 14,785.

The asymmetry in the distribution of galaxy spin directions observed when the redshift of the galaxies is relatively high can be compared to the asymmetry profile observed by galaxies imaged by the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (Grogin et al., 2011) of the Hubble Space Telescope (HST). The HST dataset contains 8,690 galaxies annotated manually by their spin direction, as explained in Shamir (2020b). During that process of annotation, a random half of the galaxies were mirrored for the first cycle of annotation, and then all galaxies were mirrored for a second cycle of annotation as described in Shamir (2020b) to offset possible effect of human perceptual bias. That provided a complete dataset that is also not subjected to atmospheric effects. A full description of the dataset and the analysis of the distribution of galaxy spin direction is described in Shamir (2020b). These galaxies do not have spectra, but due to the nature of the Hubble Space Telescope it is clear that the galaxies imaged by HST are of much higher redshift than the galaxies imaged by the Earth-based sky surveys. Figure 9 shows the profile observed using the HST galaxies as described in Shamir (2020b), and the profile of asymmetry when using the dataset described in Section 2 when the redshift of the galaxies is limited to 0.16 < z < 0.26. The most likely axis observed with HST galaxies is at (α = 78°, δ = 47°), with probability of 2.8σ to have such distribution by chance. As the figure shows, although the two datasets do not share any galaxies, they show similar positions of the most likely axes observed in the distribution of galaxy spin directions. The most likely axis observed with the dataset described in Section 2 peaks at (α = 48°, δ = 67°).

Table 3 shows the location of the most likely axis when the dataset described in Section 2 is separated into different redshift ranges. As the table shows, the declination of the galaxies changes consistently as the redshift gets higher, while the change in the right ascension is milder.

The change in the location of the peak of the most likely axis when the redshift of the galaxies changes can be viewed as an indication that the axis does not necessarily go directly through Earth. In such case, the location of the most likely axis is expected to change at low redshifts, and then to remain nearly constant at the higher redshifts. Figure 10 displays a simple two-dimensional illustration of a possible axis compared to Earth. The angle α is measured between two points determined using two different redshifts, but the two redshifts are relatively low. That angle is much larger than β, which is the difference in the position of the dipole axis as seen from Earth when using two higher redshifts. Therefore, an axis that does not go directly through Earth is expected to change its location as seen from Earth in lower redshifts, but remain nearly at the same location when observed in higher redshift ranges.

Figure 11 visualizes the most likely axis points in a 3D space such that the distance d is determined by converting the mean redshift of the galaxies in each redshift range to the distance, measured in Mpc. The 3D transformation is then performed by Equation 2. As expected, the points are aligned in a manner that forms a three-dimensional axis.

\[
x = \cos(\alpha) \cdot d \cdot \cos(\delta)
\]
\[
y = \sin(\alpha) \cdot d \cdot \cos(\delta)
\]
\[
z = d \cdot \sin(\delta)
\]

To estimate the three dimensional direction of the axis, a simple analysis between two points η and ξ in a three-dimensional space can be used as shown by Equation 3.

Since the points in Table 3 as visualized in Figure 10 are aligned in an axis, the direction of the axis can be determined by the two most distant points from each other. These two points are also the two points with the lowest and highest redshift as shown in Table 3.
The closet point to Earth shown in Table 3 is at \((\alpha = 61^\circ, \delta = 10^\circ)\), and \(~283\) Mpc away, based on the average 0.064 mean redshift of the galaxies in that redshift range. An observer in that point would see an axis in \((\alpha = 262^\circ, \delta = 85^\circ)\), and the other end of that axis in \((\alpha = 82^\circ, \delta = -85^\circ)\).

\[
\begin{align*}
\alpha &= \text{atan}2(y_\eta - y_\xi, \sqrt{(x_\eta - x_\xi)^2 + (z_\eta - z_\xi)^2}) \\
\delta &= \text{atan}2(-(x_\eta - x_\xi), -(z_\eta - z_\xi))
\end{align*}
\]  

(3)

3.2 Quadrupole axis analysis

Analysis of the distribution of the CMB provided consistent evidence of a quadrupole axis alignment of the CMB anisotropy (Efstathiou, 2003; Feng and Zhang, 2003; Cline et al., 2003; Weeks et al., 2004; Gordon and Hu, 2004; Piao et al., 2004; Piao, 2005; Campanelli et al., 2006; 2007; Gruppuso, 2007; Beltran Jimenez and Maroto, 2007; Rodriguez, 2008; Zhe et al., 2015; Santos et al., 2015). Fitting the galaxy spin directions into quadrupole axis alignment can be done as described in Section 3.1 but instead of \(\chi^2\) fitting \(\cos(\phi)\) into \(d \cdot |\cos(\phi)|\) as was done for identifying a dipole axis, the quadrupole alignment is identified by \(\chi^2\) fitting \(\cos(2\phi)\) into \(d \cdot |\cos(2\phi)|\), as described in Shamir (2019, 2020d, 2021b).

Figure 12 shows the likelihood of a quadrupole axis in different \((\alpha, \delta)\) combinations. One axis peaks at \((\alpha = 52^\circ, \delta = -8^\circ)\), with statistical signal of 4.3\(\sigma\). The 1\(\sigma\) error range for that axis is \((34^\circ, 87^\circ)\) for the RA, and \((-42^\circ, 36^\circ)\) for the declination. The other axis peaks at \((\alpha = 151^\circ, \delta = 31^\circ)\) with statistical signal of 3.1\(\sigma\). The 1\(\sigma\) error of that axis is \((118^\circ, 191^\circ)\) for the RA, and \((-5^\circ, 66^\circ)\) for the declination. Figure 13 shows the same analysis when the galaxies are assigned random spin directions, showing that the
Figure 8: The profile of galaxy spin direction distribution in the dataset described in Section 2 (top), compared to the profiles observed in Pan-STARRS (bottom) and DECam (middle) as reported in (Shamir, 2021b). The graphs show similar profiles of galaxy spin direction distribution observed in the different telescopes.

axes disappear when the galaxy spin directions are random.

As with the analysis of the dipole alignment, the analysis shown in Figure 12 can be compared to previous analyses (Shamir, 2020d, 2021b). Figure 14 displays the same analysis with Pan-STARRS and DECam as shown in (Shamir, 2021b), compared to the analysis of the dataset described in Section 2 using the 43,566 that have the same redshift distribution as the subset of DECam galaxies with redshift. The figure shows that the profile of galaxy spin direction distribution observed with the dataset described in Section 2 is similar to the previous results using Pan-STARRS and DECam shown in (Shamir, 2021b).

Figure 15 shows the analysis when fitting the distribution of galaxy spin direction to quadrupole axis alignment as observed when separating the redshift of the galaxies to certain different redshift ranges. As with the dipole alignment, the statistical signal of the quadrupole alignment becomes stronger as the redshift gets higher. The locations of the most likely axes change at the relatively lower redshifts, indicating that the axis is not necessarily Earth-centered. Table 4 shows the most likely position of the two axes in each redshift range.

Figure 16 displays the points in Table 4 in a three-dimensional space. The figure shows that the two axes form two lines that can be considered straight lines. Figure 17 shows the two-dimensional projections of the x,y plane and the x,z plane. The directions of the two axes can be determined by applying a linear regression to the points of each axis. According to the alignment of the points in Table 4, the two axes meet at RA 313° and declination of 65° from Earth, and at distance of 1736 Mpc.

3.3 Analysis of differences in galaxy morphology

Another analysis was focused on differentiating the morphological differences between galaxies. For that purpose, the galaxies were separated by their $rS$, where $r$ is the radius (in pixels), and $S$ is the galaxy surface size, also measured in pixels as described in (Shamir, 2011). The surface size of the galaxy is measured by the number of foreground pixels, which can be counted after separating the foreground and background pixels of the galaxy as described in (Shamir, 2011). That allowed to separate the galaxies by their mass distribution. A smaller $rS$ value indicates that the surface size of the galaxy is large compared to its radius, and there-
| z    | # galaxies | RA (Axis 1) | Dec (Axis 1) | Statistical significance | RA (Axis 2) | Dec (Axis 2) | Statistical significance |
|------|------------|-------------|--------------|--------------------------|-------------|--------------|--------------------------|
| 0.0-0.1 | 41,218   | 347         | 26           | 1.2σ                     | 63          | -12          | 0.8σ                     |
| 0.01-0.11 | 45,618   | 344         | 23           | 1.2σ                     | 61          | -12          | 0.8σ                     |
| 0.02-0.12 | 49,693   | 342         | 21           | 1.2σ                     | 61          | -14          | 0.9σ                     |
| 0.03-0.13 | 51,027   | 345         | 20           | 1.3σ                     | 65          | -15          | 1.1σ                     |
| 0.04-0.14 | 51,243   | 341         | 18           | 1.6σ                     | 63          | -17          | 1.2σ                     |
| 0.05-0.15 | 50,446   | 348         | 15           | 1.4σ                     | 68          | -17          | 1.2σ                     |
| 0.06-0.16 | 48,362   | 348         | -27          | 1.5σ                     | 71          | -20          | 1.5σ                     |
| 0.07-0.17 | 44,739   | 350         | -36          | 1.6σ                     | 66          | -25          | 1.5σ                     |
| 0.08-0.18 | 40,101   | 353         | -40          | 1.5σ                     | 67          | -33          | 1.7σ                     |
| 0.09-0.19 | 35,565   | 344         | -38          | 1.8σ                     | 70          | -34          | 2.1σ                     |
| 0.1-0.2   | 32,206   | 349         | -35          | 2.2σ                     | 64          | -37          | 2.6σ                     |
| 0.11-0.21 | 28,486   | 351         | -37          | 2.7σ                     | 64          | -36          | 2.9σ                     |
| 0.12-0.22 | 24,462   | 347         | -34          | 2.9σ                     | 62          | -34          | 3.4σ                     |
| 0.13-0.23 | 21,001   | 350         | -36          | 3.2σ                     | 60          | -37          | 3.7σ                     |
| 0.14-0.24 | 17,497   | 345         | -35          | 3.5σ                     | 61          | -35          | 3.9σ                     |
| 0.15-0.25 | 14,785   | 341         | -32          | 3.9σ                     | 57          | -37          | 4.1σ                     |
| 0.16-0.26 | 12,664   | 338         | -36          | 3.1σ                     | 65          | -36          | 3.9σ                     |

Table 4: The most likely quadrupole axis when the galaxies are limited to different redshift ranges.

Figure 10: Changes in the position of a non-Earth centered axis as seen from Earth when its peaks are identified at different redshifts. The change in the location of the axis in lower redshift range $\alpha$ is far larger than the change in the location in higher redshift range $\beta$.

Figure 11: Three-dimensional visualization of the points in Table 3. The points form an axis that might not go directly through Earth.

4 Analysis of reasons that can lead to asymmetry not originated from the real sky

While several messengers have shown evidence of violation of the cosmological-scale isotropy assumption as discussed in Section 1, the null hypothesis would be that the spin directions of spiral galaxies are distributed randomly. This section discusses several possible reasons that could have led to the observation of asymmetry that does not reflect an asymmetry in the local Universe.

4.1 Error in the galaxy annotation algorithm

An error in the annotation algorithm can lead to any form of distribution, depends on the nature of the error. However, multiple indications show that the asymmetry cannot be the result of an error in the classification algorithm. The algorithm is a model-driven symmetric method that is based on clear rules. It is not based on complex data-driven...
rules used by pattern recognition systems. Such systems are complex and non-intuitive, rely on the data they are trained by and even by the order of the samples in the training set, making it virtually impossible to verify their symmetricity. The algorithm used here is fully symmetric, and follows clear defined rules as discussed in Section 2.

Another evidence that the asymmetry is not driven by an error in the annotation algorithm is that the asymmetry changes between different parts of the sky, and inverse between opposite hemispheres. Since each galaxy is analyzed independently, a bias in the annotation algorithm is expected to be consistent throughout the sky, and it is not expected to flip in opposite hemispheres. The downloading of the images and the automatic analysis of the images were all done by the same computer, to avoid unknown differences between computers that can lead to bias or unknown differences in the way galaxy images are analyzed.

Due to the theoretical and empirical evidence that the algorithm is symmetric, an error in the galaxy annotation is expected to impact clockwise and counterclockwise galaxies in a similar manner. If the galaxy annotation algorithm had a certain error in the annotation of the galaxies, the asymmetry \( A \) can be defined by Equation 4.

\[
A = \frac{(N_{cw} + E_{cw}) - (N_{ccw} + E_{ccw})}{N_{cw} + E_{cw} + N_{ccw} + E_{ccw}},
\]

where \( E_{cw} \) is the number of galaxies spinning clockwise incorrectly annotated as counterclockwise, and \( E_{ccw} \) is the number of galaxies spinning counterclockwise incorrectly annotated as spinning clockwise. Because the algorithm is symmetric, the number of counterclockwise galaxies incorrectly annotated as clockwise is expected to be roughly the same as the number of clockwise galaxies misclassified as counterclockwise, and therefore \( E_{cw} \approx E_{ccw} \) \cite{Shamir2021a}. Therefore, the asymmetry \( A \) can be defined by Equation 5.

\[
A = \frac{N_{cw} - N_{ccw}}{N_{cw} + E_{cw} + N_{ccw} + E_{ccw}}
\]

Since \( E_{cw} \) and \( E_{ccw} \) cannot be negative, a higher rate of incorrectly annotated galaxies is expected to make \( A \) lower. Therefore, incorrect annotation of galaxies is not expected to lead to asymmetry, and can only make the asymmetry lower rather than higher.

An experiment \cite{Shamir2021a} of intentionally annotating some of the galaxies incorrectly showed that even when an error is added intentionally, the results do not change significantly even when as many as 25% of the galaxies are
Figure 15: The probability of a quadrupole axes at different \((\alpha, \delta)\) combinations in different redshift ranges.
assigned with incorrect spin directions, as long as the error is added to both clockwise and counterclockwise galaxies [Shamir 2021a]. But if the error is added in an asymmetric manner, even a small asymmetry of 2% leads to a very strong asymmetry, and a dipole axis that peaks exactly at the celestial pole [Shamir 2021a].

It should be mentioned that in one of the datasets shown here, which is the dataset acquired by HST, the annotation was done manually, and without using any automatic classification. The galaxies imaged by HST were annotated manually, and the results are in agreement with the automatic annotation of galaxies imaged by the other telescopes and annotated automatically.

4.2 Bias in the sky survey hardware or photometric pipelines

Autonomous digital sky surveys are some of the more complex research instruments, and involve sophisticated hardware and software to enable the collection, storage, analysis, and accessibility of the data. It is difficult to think of an error in the hardware or software that could lead to asymmetry between the number of galaxies spinning in opposite directions, but due to the complexity of these systems it is also difficult to prove that such error does not exist. That possible error is addressed here by comparing the results using data from several different telescopes. The instruments used in this study are independent from each other, and have different hardware and different photometric pipelines. As it is unlikely to have such bias in one instrument, it is very difficult to assume that all of these different instruments have such bias, and the profile created by that bias is consistent across all of them.

4.3 Cosmic variance

The distribution of galaxies in the universe is not completely uniform. These subtle fluctuations in the density of galaxy population can lead to “cosmic variance” [Driver and Robotham 2010, Moster et al. 2011], which can impact measurements at a cosmological scale [Kamionkowski and Loeb 1997, Camarena and Marra 2018, Keenan et al. 2020].

The probe of asymmetry between galaxies spinning in opposite directions is a relative measurement rather than an absolute measurement. That is, the asymmetry is determined by the difference between two measurements made in the same field, and therefore should not be affected by cosmic variance. Any cosmic variance or other effects that impacts the number of clockwise galaxies observed from Earth is expected to have a similar effect on the number of counterclockwise galaxies.

4.4 Multiple objects at the same galaxy

In some cases, digital sky surveys can identify several photometric objects as independent galaxies, even in cases they are part of one larger galaxy. In the datasets used here all photometric objects that are part of the same galaxy were removed by removing all objects that had another object within 0.01°.

Even if such objects existed in the datasets, they are expected to be distributed evenly between galaxies that spin clockwise and galaxies that spin counterclockwise, and therefore should not introduce an asymmetry. Experiments by using datasets of galaxies assigned with random spin di-
Figure 18: $r_s$ of different galaxies. Higher $r_s$ indicates that the galaxy is less dense. The galaxies on the left have a relatively low $r_s$ of 0.0068 and 0.0065, indicating that the galaxies are more dense. The more sparse galaxies on the right have a higher $r_s$ of 0.0185 and 0.0176.

The experiments were made by using $\sim 7.7 \cdot 10^4$ SDSS galaxies, and assigning the galaxies with random spin directions. Then, gradually adding more objects with the same location and spin directions as the galaxies in the original dataset, and the new artificial galaxies were assigned with the same spin direction as the galaxies in the original dataset (Shamir, 2021a). Adding such artificial galaxies did not lead to statistically significant signal.

### 4.5 Differences in inclination

The axis shown in Section 3.1 is profiled by computing the most likely axis when limiting the galaxies to different redshift ranges. In each redshift range, the axis is computed by the cosine dependence of all galaxies in the dataset that fit the redshift range, regardless of their location in the sky. By applying simple geometry, the change in the location of the most likely axis in different redshift ranges can be used to deduce the location of an axis that does not necessarily go directly through Earth.

That analysis can also be affected by differences in the inclination of galaxies. The inclination of the galaxies can impact the ability to identify its spin direction, as a sharper inclination makes it more difficult to identify the spin patterns. As mentioned above, the axis is computed for each redshift range by fitting all galaxies in that redshift range, regardless of their position in the sky, and therefore it is expected that the impact of the inclination would be statistically the same among clockwise and counterclockwise galaxies.

To test that assumption, the inclination of galaxies that spin clockwise was compared to the inclination of galaxies that spin counterclockwise. The inclination of each galaxy was computed by $\cos^{-1}\left(\frac{\text{short axis}}{\text{long axis}}\right)$, and the short and long axis of all galaxies were determined by Ganalyzer.

As expected, the table shows that the difference in inclination between clockwise and counterclockwise galaxies is not statistically significant, and well below the standard error. The inclination in higher redshifts is somewhat higher than the lower redshift, and that difference can be attributed to the smaller size of the galaxies. But also in the higher redshifts, there are no statistically significant differences between the inclination of clockwise galaxies and the inclination of counterclockwise galaxies. As also expected, no differences in the inclination were observed in opposite hemispheres.

Table 5: Average inclination (in radians) of clockwise galaxies and counterclockwise galaxies in different redshift and RA ranges. The errors are the standard errors of the means.

| $z$ range | RA range | Average inclination cw (rad) | Average inclination ccw (rad) |
|----------|----------|-----------------------------|-----------------------------|
| $< 0.15$ | all      | $1.14372 \pm 0.001$         | $1.14426 \pm 0.001$         |
| $0.15$   | all      | $1.18472 \pm 0.002$         | $1.18529 \pm 0.002$         |
| $< 0.15$ | ($0^\circ < \alpha < 180^\circ$) | $1.14387 \pm 0.002$         | $1.14459 \pm 0.002$         |
| $0.15$   | ($0^\circ < \alpha < 180^\circ$) | $1.18488 \pm 0.003$         | $1.18564 \pm 0.003$         |
| $< 0.15$ | ($180^\circ < \alpha < 360^\circ$) | $1.14357 \pm 0.002$         | $1.14371 \pm 0.002$         |
| $0.15$   | ($180^\circ < \alpha < 360^\circ$) | $1.18451 \pm 0.002$         | $1.18464 \pm 0.002$         |

Table 5 shows the average inclination of the galaxies in different redshift ranges and different RA ranges.

As expected, the table shows that the difference in inclination between clockwise and counterclockwise galaxies is not statistically significant, and well below the standard error. The inclination in higher redshifts is somewhat higher than the lower redshift, and that difference can be attributed to the smaller size of the galaxies. But also in the higher redshifts, there are no statistically significant differences between the inclination of clockwise galaxies and the inclination of counterclockwise galaxies. As also expected, no differences in the inclination were observed in opposite hemispheres.

### 4.6 Photometric redshift

Some of the analysis shown here is based on the redshift of the galaxies. Obtaining the spectra of a galaxy is a relatively long process, and therefore the vast majority of the
galaxies do not have spectra. To estimate the redshift of galaxies that do not have spectra, the redshift can be estimated computationally from the photometric information in an approach called “photometric redshift”. While the photometric redshift is very quick to compute, it is also highly inaccurate, ambiguous (meaning that one galaxy can have several different photometric redshifts), and systematically biased.

In this study the asymmetry is of magnitude smaller than 1%. The error of the state-of-the-art photometric redshift methods is 10% to 20%. Since it is normally determined by complex data-driven rules of machine learning systems, it is also systematically biased in a manner that is difficult to quantify and profile. Therefore, the photometric redshift is not a suitable probe that can be used in this study. All redshifts used in the paper are the spectroscopic redshifts, and the photometric redshifts are not used in any part of this study. Some of the analyses are done with no redshift information at all, showing that the signal is not originated from an error or systematic bias in the redshift.

4.7 Bias carried over from previous catalogs

Catalogs of galaxy morphology can be prepared by either manual annotation of the galaxies (Land et al. 2008; Nair and Abraham 2010; Baillard et al. 2011), or by automatic annotation (Gravet et al. 2015; Pérez-González et al. 2015; Goddard and Shamir 2020; Cheng et al. 2021). When not prepared specifically for the purpose of analysis of galaxy spin directions, such catalogs can be biased in some way by the process through which the galaxies were annotated. For instance, Land et al. (2008) found very substantial bias in the annotation of galaxies by their spin direction when the annotation was done by anonymous volunteers. Such bias driven by the human perception is difficult to quantify and correct, and even a small but consistent bias can lead to strong signal in the analysis Shamir (2021a). Such bias can also affect the separation of galaxies into elliptical and spiral galaxies, and therefore using a catalog that was prepared manually could lead to unexpected patterns that might be driven by the human perception rather than the real sky.

Some catalogs of galaxy morphology were prepared by using certain algorithms. Examples of such catalogs include Gravet et al. 2015; Pérez-González et al. 2015; Goddard and Shamir 2020; Cheng et al. 2021. However, these catalogs rely in most cases on machine learning algorithms, which work by complex data-driven rules. Due to their complexity and non-intuitive nature, it is very difficult to verify that these algorithms are fully symmetric. More importantly, these machine learning systems are based on manual annotation of the galaxies, and therefore any bias in the manual annotation would be carried on to the catalog. For instance, Goddard and Shamir 2020; Cheng et al. 2021 are two catalogs that made use of crowdsourcing annotations that are known to be biased (Land et al. 2008; Hayes et al. 2017), and therefore are not safe for the task shown in this study, any other task related to an analysis of anisotropy in the large-scale structure. Moreover, algorithms based on deep neural networks use any discriminative information they can find in the classes of images, and therefore also learn the background of the images, leading to unusual and unexpected biases that are difficult to profile, as explained in detail in Dhar and Shamir (2022).

An important aspect of the experimental design of this study is that no catalog of galaxy morphology was used. The entire process of annotation was done by the model-driven symmetric algorithm explained in Section 2.1, and no assumptions are made about the distribution of the galaxies in any existing catalog of galaxy morphology. The only selection of the galaxies is by the object detection algorithms and the magnitude of the objects in HST, DESI Legacy Survey, SDSS, and Pan-STARRS photometric pipelines. It is difficult to think of a bias in these algorithms that would prefer one spin direction over another, and would also inverse that preference in the opposite hemisphere. While it is difficult to think of such bias in one sky survey, it is highly unlikely that such bias would appear in several sky surveys, with consistent profiles such that the profile of the bias in one sky survey matches the profile of the bias in the other surveys.

4.8 Atmospheric effect

There is no known atmospheric effect that can make a galaxy that spin clockwise appear as if it spins counterclockwise. Also, because the asymmetry is always measured with galaxies imaged in the same field, any kind of atmospheric effect that affects galaxies the spin clockwise will also affect galaxies that spin counterclockwise. Therefore, it is unlikely that a certain atmospheric effect would impact the number of clockwise galaxies at a certain field, but would have different impact on galaxies spinning counterclockwise. In any case, one of the datasets used here is made of galaxies imaged by the space-based HST, and are therefore not subjected to any kind of atmospheric effect.

4.9 Backward spiral galaxies

In rare cases, the shape of the arms of a spiral galaxy is not an indication of the spin direction of the galaxy. An example is NGC 4622. Freeman et al. 1991; Buta et al. 2003. A prevalent and systematically uneven distribution of backward spiral galaxies might indeed lead to asymmetry between the number of galaxies spinning clockwise and the number of galaxies spinning counterclockwise. For instance, if a relatively high percentage of galaxies that actually spin clockwise are backward spiral galaxies, it would have led to an excessive number of galaxies that seem to be spinning counterclockwise.
However, backward spiral galaxies are relatively rare. Also, these backward spirals are expected to be distributed equally between galaxies that spin clockwise and galaxies that spin counterclockwise, and there is no indication of asymmetry between backwards spiral galaxies. Therefore, according to the known evidence, there is no reason to assume that the observations shown here are driven by backward spiral galaxies.

5 Conclusion

Autonomous digital sky surveys powered by robotic telescopes have allowed the collection of unprecedented amounts of astronomical data, enabling to address research questions that their studying was not feasible in the pre-information era. For instance, very large structures such as the Great Wall of Sloan were not discovered until robotic telescopes that can collect very large databases were introduced.

The question addressed here is the large-scale distribution of the spin directions of spiral galaxies. Multiple previous experiments have shown that the distribution of spin directions of spiral galaxies as observed from Earth might not be random (Longo 2011; Shamir 2012, 2013; Lee et al. 2019a,b; Shamir 2021a,b). This study uses a large dataset of galaxies with spectra from several different telescopes. The analysis shows that the asymmetry in the spin directions of spiral galaxies increases with the redshift. The peak of the most likely axis changes consistently with the redshift, which can imply on an axis that does not go directly through Earth. The analysis uses several telescopes, covering the both the Northern and Southern hemispheres. The findings are in agreement with previous results, including space-based data acquired by the Hubble Space Telescope. Another noted observation is that the asymmetry becomes stronger as the redshift gets higher. Although the redshift range of the galaxies used in this study is naturally limited by the imaging capabilities of the telescopes, that correlation can be interpreted as higher asymmetry in the earlier Universe. If that trend is consistent also in higher redshifts not observed in this study, it can be viewed as an indication that the asymmetry patterns are primordial, and were stronger in the young Universe, but gradually becomes weaker as the Universe gets older. That can be explained by gravitational interaction between galaxies and galaxy mergers that can change the spin direction of the galaxies. Future sky surveys such as the Vera Rubin Observatory will have far greater depth, and will allow to test whether the trend continues also in higher redshifts.

Studies with smaller datasets of galaxies showed non-random spin directions of galaxies in filaments of the cosmic web, as described in (Tempel et al. 2013; Tempel and Libeskind 2013; Tempel et al. 2014; Dubois et al. 2014; Kraljic et al. 2021) and others. Other studies showed alignment in the spin directions even when the galaxies are too far from each other to interact gravitationally (Lee et al. 2019a,b), unless assuming modified Newtonian dynamics (MOND) gravity models that explain longer gravitational span (Sanders 2003; Darabi 2014; Amendola et al. 2020).

Other observations of large-scale alignment in spin directions focused on quasars such as (Hutsemékers 1998; Hutsemékers et al. 2005; Agarwal et al. 2011; Hutsemékers et al. 2014). Position angle of radio galaxies also showed large-scale consistency of angular momentum (Taylor and Jagannathan 2011). These observations agree with observations made with datasets such as the Faint Images of the Radio Sky at Twenty-centimetres (FIRST) and the TIFR GMRT Sky Survey (TGSS), showing large-scale alignment of radio galaxies (Contigiani et al. 2017; Panwar et al. 2020).

These observational studies are also supported by simulations of dark matter (Aragón-Calvo et al. 2007; Zhang et al. 2009; Codis et al. 2012; Libeskind et al. 2013, 2014; Ganeshaiah Veena et al. 2018; Kraljic et al. 2020) and galaxies (Dubois et al. 2014; Codis et al. 2018; Ganeshaiah Veena et al. 2019; Kraljic et al. 2020), showing links between spin directions and the large-scale structure. That correlation was associated with the stellar mass and color of the galaxies (Wang et al. 2018), and it has been proposed that the association was also linked to halo formation (Wang and Kang 2017). That led to the contention that the spin direction in the halo progenitors is linked to the large-scale structure of the Universe (Wang and Kang 2018). It should be mentioned that the spin direction of a galaxy might not be necessarily the same as the spin direction of the dark matter halo, as it has been proposed that in some cases a galaxy might spin in a different direction than its host dark matter halo (Wang et al. 2018).

The analysis of spin directions done in this study provides evidence of large-scale dipole and quadrupole alignment. The observation of a large-scale axis has been proposed in the past by analyzing the cosmic microwave background (CMB), with consistent data from the Cosmic Background Explorer (COBE), Wilkinson Microwave Anisotropy Probe (WMAP) and Planck, as described in (Abramo et al. 2006; Mariano and Perivolaropoulos 2013; Land and Magueijo 2005; Ade et al. 2014; Santos et al. 2015; Gruppupo et al. 2018) and other studies. Observations also showed that the axis formed by the CMB temperature is aligned with other cosmic asymmetry axes such as dark energy and dark flow (Mariano and Perivolaropoulos 2013). Other notable statistical anomalies in the CMB are the quadrupole-octopole alignment (Schwarz et al. 2004; Ralston and Jain 2004; Copi et al. 2007, 2010, 2015), the asymmetry between hemispheres (Eriksen et al. 2004; Land and Magueijo 2005; Akrami et al. 2014), point-purity asymmetry (Kim and Naselsky 2010a, b), and the CMB Cold Spot. If these anomalies are not statistical fluctuations (Bennett et al. 2011), they can be viewed as ob-
servations that disagree with ΛCDM, as proposed by Bull et al. (2016), Yeung and Chu (2022) and others.

As described in Section 1, the possible axis observed in the CMB is aligned with theories related to the geometry of the Universe such as ellipsoidal universe (Campanelli et al. 2006, 2007; Gruppuso 2007; Rodrigues 2008; Campanelli et al. 2011; Cea, 2014), rotating universe (Gödel 1946, Godel 1949; Ozsváth and Schücking 1962; Ozsváth and Schücking 2001; Su and Chu 2009; Sivaram and Arum 2012; Chechin 2016, 2017; Campanelli 2021), holographic big bang (Pourhasan et al. 2014; Altamirano et al. 2017), negative gravitational mass (Le Corre 2021), and Black hole cosmology (Pathria 1972; Stuckey 1994; Easson and Brandenberger 2001; Seshavatharam 2010; Poplawski 2010b,a; Chakrabarty et al. 2020; Seshavatharam and Lakshminarayana 2020b; Rinaldi et al. 2022).

The availability of robotic telescopes provides the ability to analyze a possible non-random distribution of the spin directions of spiral galaxies, and that research question was not approachable in the pre-information era. As evidence for such non-random distribution are accumulating, additional research will be needed to fully understand its nature, and match it with other messengers in addition to CMB.

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