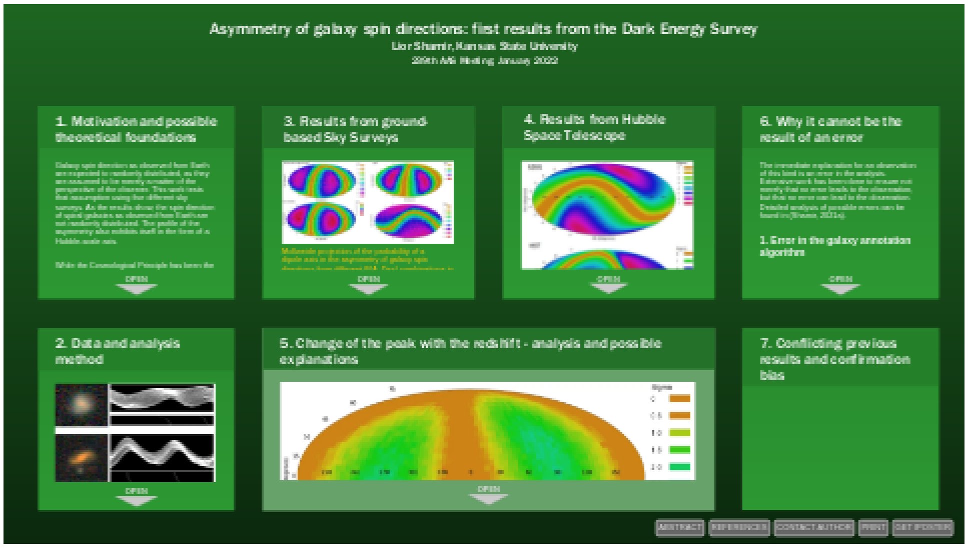
Asymmetry of galaxy spin directions: first results from the Dark Energy Survey



Asymmetry of galaxy spin directions: first results from the Dark Energy Survey
Lior Shamir, Kansas State University
239th AAS Meeting January 2022

1. Motivation and possible theoretical foundations

3. Results from ground-based Sky Surveys

4. Results from Hubble Space Telescope

6. Why it cannot be the result of an error

1. Error in the galaxy annotation algorithm

2. Data and analysis method

5. Change of the peak with the redshift - analysis and possible explanations

7. Conflicting previous results and confirmation bias

Lior Shamir, Kansas State University

239th AAS Meeting, January 2022

PRESENTED AT:

1. MOTIVATION AND POSSIBLE THEORETICAL FOUNDATIONS

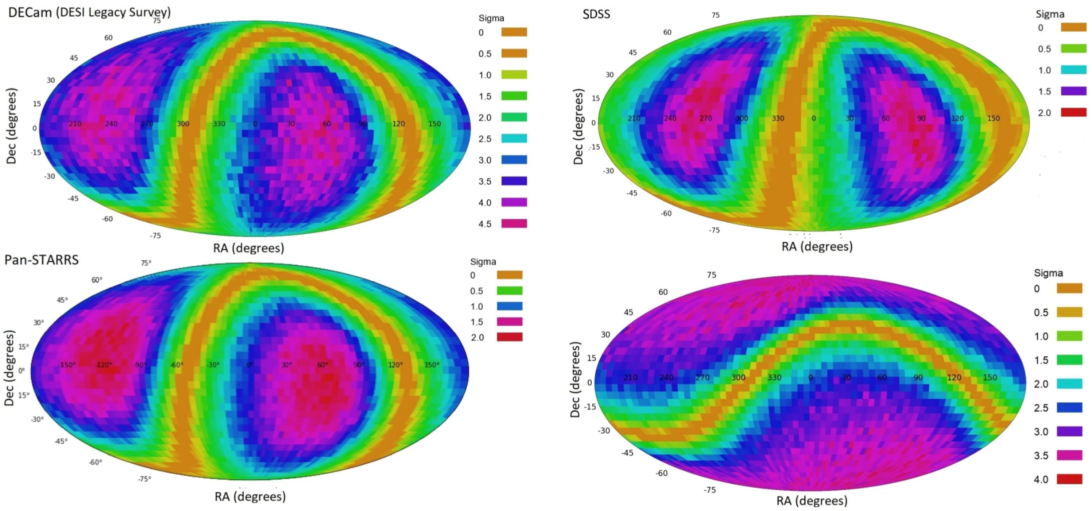
Galaxy spin direction as observed from Earth are expected to randomly distributed, as they are assumed to be merely a matter of the perspective of the observer. This work tests that assumption using five different sky surveys. As the results show, the spin direction of spiral galaxies as observed from Earth are not randomly distributed. The profile of the asymmetry also exhibits itsefl in the form of a Hubble-scale axis.

While the Cosmological Principle has been the common working assumption for most cosmological theories, accumulating evidence suggest that the Universe is not necessarily isotropic. Probes that show cosmological-scale anisotropy include the cosmic microwave background (Eriksen et al., 2004; Cline et al., 2003; Gordon & Hu, 2004; Campanelli et al., 2007; Zhe et al., 2015), short gamma ray bursts (Meszaros, 2019), radio sources (Ghosh et al., 2016; Tiwari & Jain, 2015; Tiwari & Nusser, 2016), LX-T scaling (Migkas et al., 2020), Ia supernova (Javanmardi et al., 2015; Lin et al., 2016), galaxy morphology types (Javanmardi & Kroupa, 2017), dark energy (Adhav et al., 2011; Adhav, 2011; Perivolaropoulos, 2014; Colin et al., 2019), polarization of quasars (Hutsem ´ekers et al., 2005; Secrest et al., 2021), and high-energy cosmic rays (Aab et al., 2017).

In particular, the anisotropy of the CMB shows certain evidence of a Hubble-scale axis, sometimes refered to as the "axis of evil".

Possible explanations can be related to the geometry of the Universe such as ellipsoidal Universe, or related to double inflation or rotating Universe. The contention of rotating Universe is also related to black hole cosmology, as a black hole is expected to inherit the spin of the star from which it was created.

3. RESULTS FROM GROUND-BASED SKY SURVEYS



Mollweide projection of the probability of a
dipole axis in the asymmetry of galaxy spin directions from different (RA, Dec) combinations in DES, SDSS, Pan-STARRS, and DECam (DESI Legacy Survey).

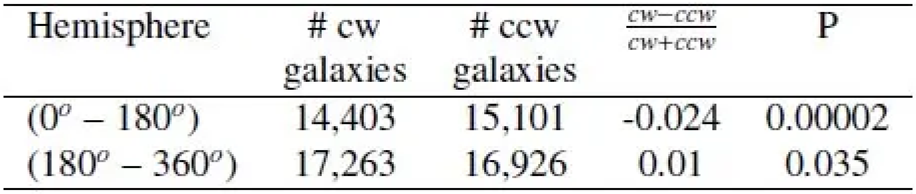
The figure shows the probability of a dipole axis in the distribution of galaxy spin direction in DES, DECam (DESI Legacy Survey), SDSS, and Pan-STARRS. The analysis shows the probability of a dipole axis in each part of the sky, based on the analysis described in Section 2.

The SDSS galaxies are normalized to have the same redshift range as the DECam galaxies. The most likely axes of all datasets is within 1 sigma. The RA is very close in all four datasets. The most likely declination is somewhat different, possibly due to the lower range of the declination, but still within one sigma.

A simpler analysis just counts the galaxies with different spin directions in opposite hemispheres. The tables below show the distribution in opposite hemispheres in DECam (mostly the Southern hemisphere) and SDSS (mostly the Northern hemisphere). The tables show the asymmetry in very simple binomial distribution.

Hemisphere	# cw galaxies	# ccw galaxies	$\frac{cw-ccw}{cw+ccw}$	P
$(0^o - 180^o)$	252,478	250,555	0.0038	0.0033
$(180^o - 360^o)$	151,948	152,917	-0.0033	0.039

Number of clockwise and counterclockwise galaxies in opposite hemispheres in DECam. The P values are the binomial distribution probability to have such difference or stronger by chance when assuming 0.5 probability for a galaxy to spin clockwise or counterclockwise.

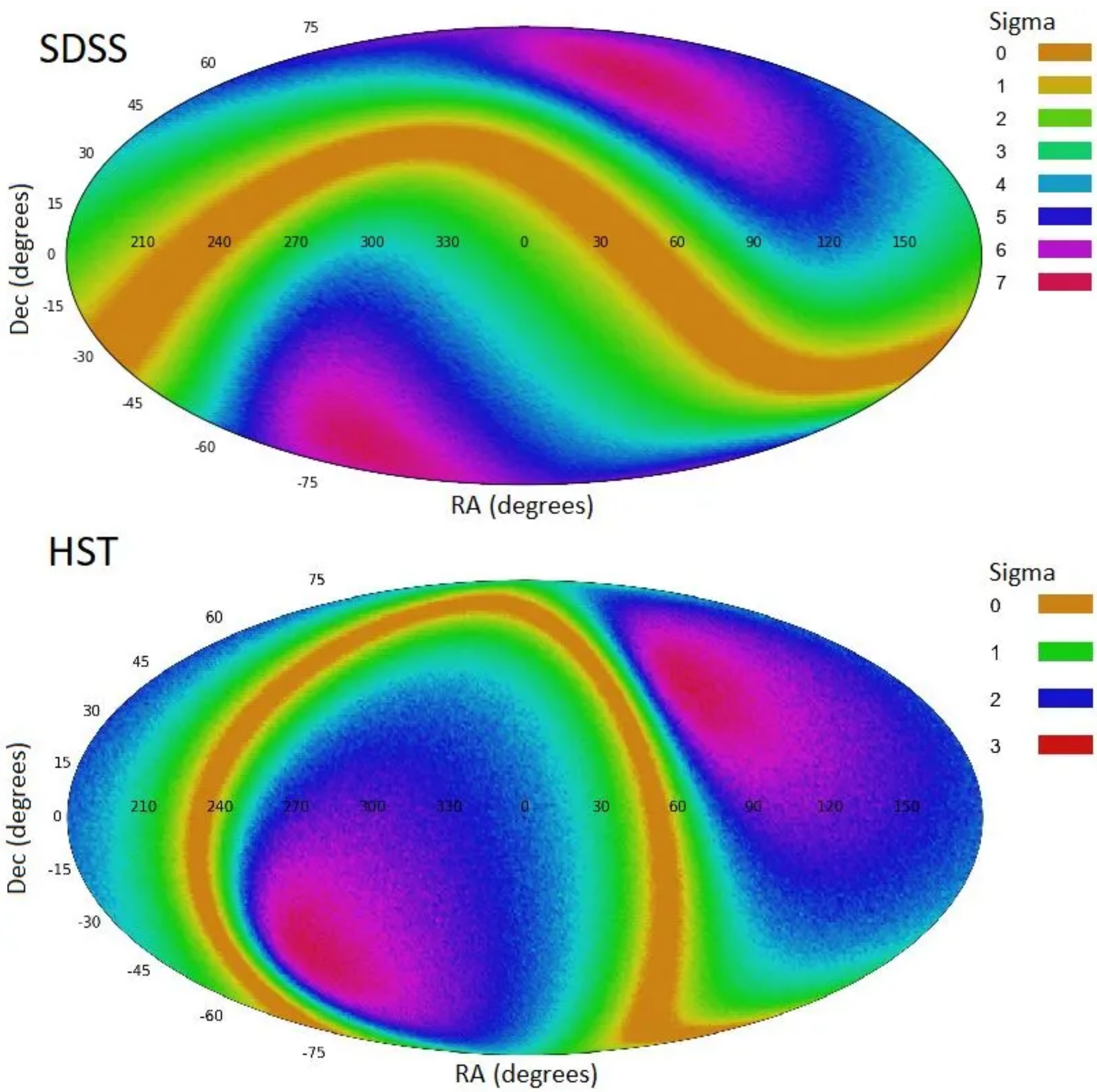


Hemisphere	# cw galaxies	# ccw galaxies	$\frac{cw-ccw}{cw+ccw}$	P
$(0^o - 180^o)$	14,403	15,101	-0.024	0.00002
$(180^o - 360^o)$	17,263	16,926	0.01	0.035

Number of clockwise and counterclockwise galaxies in opposite hemispheres in SDSS.

Another simple analysis shows that the DESI Legacy Survey footprint can be separated into two hemispheres such that one hemisphere has a higher number of clockwise galaxies, and the other hemisphere has a higher number of counterclockwise galaxies. The bias is exactly inverse between the opposite hemispheres: 0.004 (P=0.0015) in RA (0^0-150^0 V 330^0-360^0) and -0.004 (P=0.012) in the opposite hemisphere (150^0-330^o). The analysis is based on nearly 10^6 galaxies.

4. RESULTS FROM HUBBLE SPACE TELESCOPE



The probability of a dipole axis in the asymmetry between galaxy spin directions from different integer (RA, Dec) combinations in HST and SDSS. SDSS galaxies are limited to z>0.15.

Hubble Space Telescope cannot provide datasets nearly as large as the Earth-based sky surveys, but it has two major advantages: 1) The images are not subjected to atmosphereic effect, and 2) the galaxies are of a much higher redshift, allowing to analyze differences between redshift ranges.

The figure shows a comparison of the distribution of the spin directions of spiral galaxies in HST (the five CANDELS fields) and the distribution of SDSS galaxies with redshift >0.15. The profiles of distribution are not identical, but very close to each other, certainly well within one sigma (Shamir, 2021b). Additional analysis of the change with the redshift is provided in Section 5.

6. WHY IT CANNOT BE THE RESULT OF AN ERROR

The immediate explanation for an observation of this kind is an error in the analysis. Extensive work has been done to ensure not merely that no error leads to the observation, but that no error can lead to the observation. Detailed analysis of possible errors can be found in (Shamir, 2021a).

1. Error in the galaxy annotation algorithm

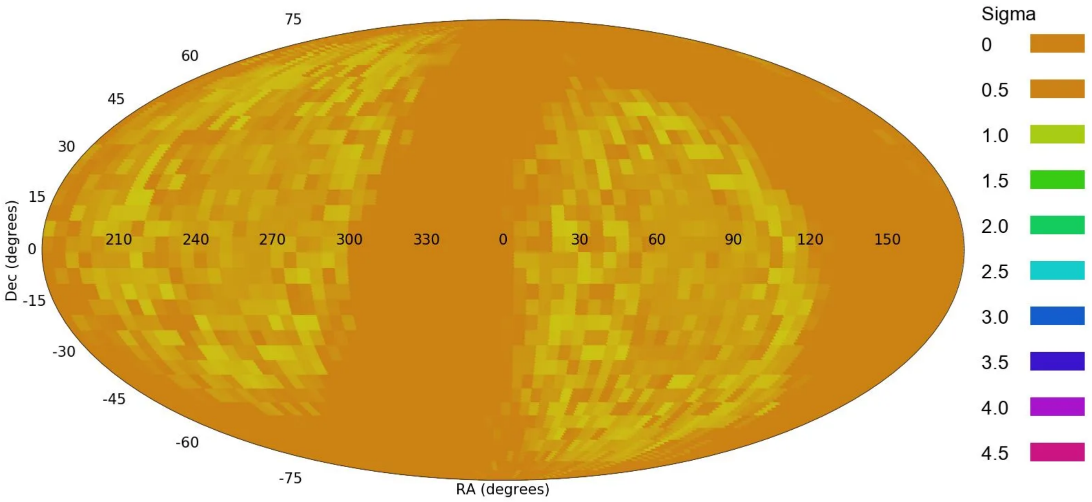
There are multiple indications showing that the galaxy annotation algorithm cannot lead to such observation.

The algorithm is completely symmetric, and it is based on defined intuitive rules. It is not based on pattern recognition, machine learning, deep learning, or any other forms of data-driven rules that tend to be complex and non-intuitive.

Mirroring of the galaxy images provides exactly inverse results to the results when using the original images. That is also expected as the algorithm of the galaxy annotation is fully symmetric.

In any case, because each galaxy is analyzed independently, even if the annotation algorithm was biased, an error in the annotation would have been expected to exhibit itself in the form of consistent assymetry in all parts of the sky. Such error is not expected to "flip" in opposite hemispheres. All galaxies were analyzed by the same computer system to eliminate the possibility that the algorithm runs dofferently on different machines.

Assigning the galaxies with random spin directions immediately eliminates the signal, as shown in the figures below. The two figures attempt to fit the same galaxies of the combined dataset, but with random spin directions., to dipole and quadrupole alignment. As expected, the signal immediately disappears.



Dipole analysis when the galaxies are assigned with random spin directions. The signal is lower than 1 sigma.

Even if the algorithm is fully symmetric, it might still make wrong annotations.

If the galaxy annotation algorithm has a certain error the asymmetry A in a certain part of the sky is defined by

$$A = \frac{(N_{cw}+E_{cw})-(N_{ccw}+E_{ccw})}{N_{cw}+E_{cw}+N_{ccw}+E_{ccw}}$$

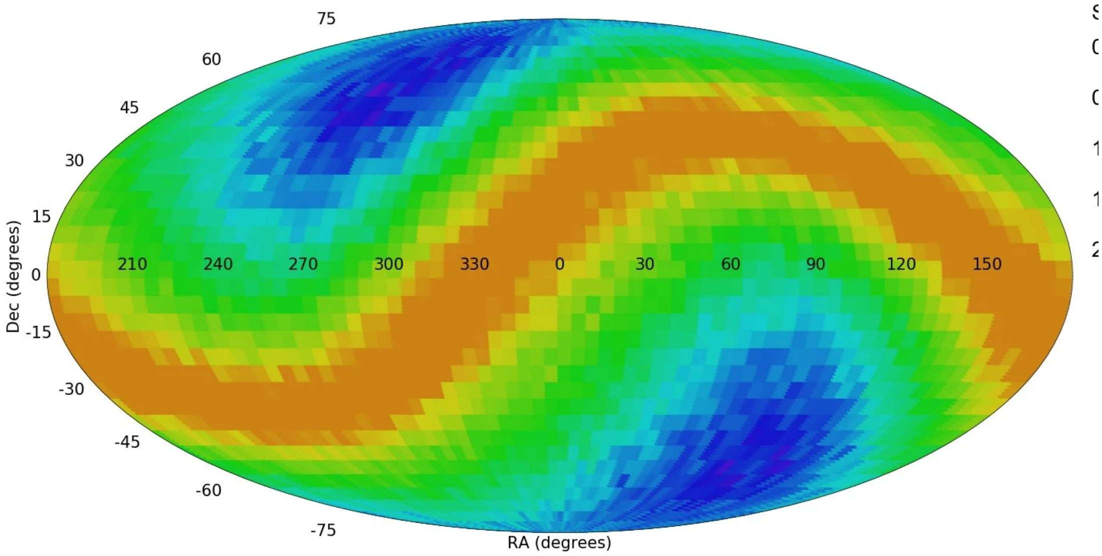
where E_{cw} is the number of counterclockwise galaxies annotated incorrectly as clockwise, and E_{ccw} is the number of clockwise galaxies classified incorrectly as counterclockwise.

The galaxy classification algorithm is symmetric, and therefore the number of counterclockwise galaxies misclassified as clockwise is roughly equal to the number of clockwise galaxies missclassified as counterclockwise. Assuming E_{cw}=E_{ccw}, the asymmetry A can be defined as

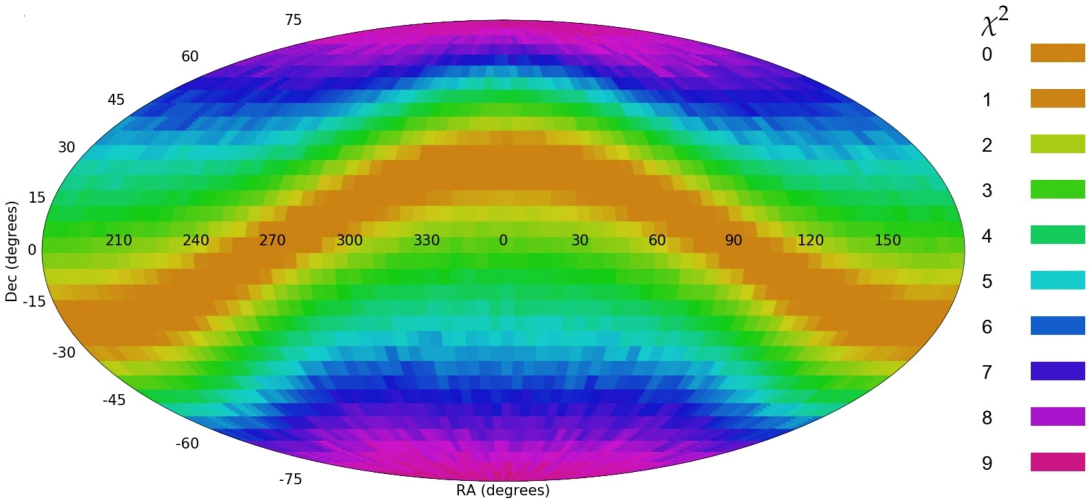
$$A = \frac{N_{cw}-N_{ccw}}{N_{cw}+E_{cw}+N_{ccw}+E_{ccw}}$$

Because E_{cw} and E_{ccw} cannot be negative, misclassified galaxies are expected to make the asymmetry lower. Therefore, misclassified galaxies are not expected to lead to the observed asymmetry.

Several experiments were used to test the impact of misclassified galaxies empirically. The figure below shows SDSS data such that 25% of the galaxies were assigned with random spin directions (Shamir, 2021a).



The figure shows that the error did not have substantial impact on the results, mainly because it is symmetric (Shamir, 2021a). However, when the error is not symmetric, even a small 1% error leads to very strong bias, and a dipole axis that peaks exactly at the celestial pole



Additionally, the analysis of some of the datasets was based on manual annotation of the galaxies, with no use of automation.

2. Bias in the sky survey hardware or photometric pipeline

Autonomous digital sky surveys are complex research instruments. It is difficult to think of an error in the hardware or software that can lead to asymmetry between the number of clockwise and counterclockwise galaxies, but due to the complexity of these systems it is also difficult to prove that such error does not exist.

However, while it is difficult to think of such error in one telescope, it is clearly difficult to think of such error that happen consistently in four telescopes.

3. Cosmic variance / Milky Way obstruction

The asymmetry is determined by the difference between two measurements made in the same field. Therefore, the asymmetry between the number of clockwise and counterclockwise galaxies observed from Earth is a relative measurement. That measurement is not be affected by cosmic variance. Any effect that impacts the number of clockwise galaxies observed from Earth is expected to have a similar effect on the number of counterclockwise galaxies in the same field.

4. Multiple photometric objects in the same galaxy

In some cases, digital sky survey can identify several photometric objects as independent galaxies, even in case they are part of one large extended object. 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 0.01o away.

Even if such objects existed in the dataset, they are expected to be evenly distributed between galaxies that spin clockwise and galaxies that spin counterclockwise. Experiments by using datasets of galaxies assigned with random spin directions and adding artificial objects to the galaxies showed that adding objects at exactly the same position of the original galaxies does not lead to signal of asymmetry (Shamir, 2021a).

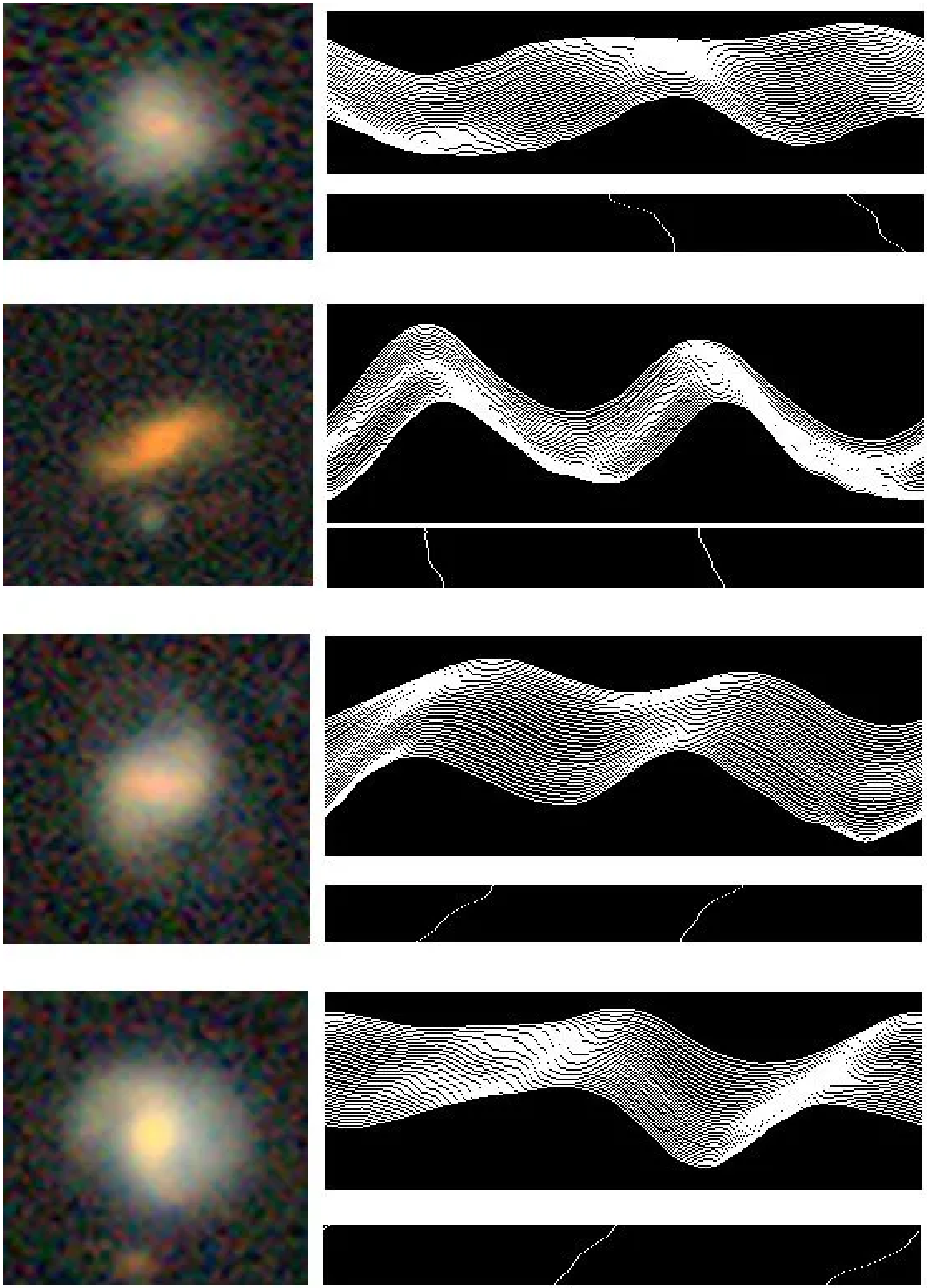
5. Atmospheric effect

There is no know atmospheric effect that can make a galaxy that spin clockwise appear as if it spin 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 Hubble Space Telescope, and are therefore not subjected to any kind of atmospheric effect.

6. Backward spiral galaxies

Backward spiral galaxies are relatively rare, and expected to be distributed equally between galaxies with different spin directions. Therefore, there is no reason to assume that the observations shown here are driven by backward spiral galaxies.

2. DATA AND ANALYSIS METHOD



Examples of DES galaxies, their radial intensity plots, and the detected peaks. Ganalyzer turns the galaxy image into its radial intensity plot, and then applies a linear regression on the peaks identified in it. The sign of the linear regression reflects the curve of the arm, and therefore the spin direction of the galaxy.

Automatic annotation of the galaxies is required not merely due to the large size of the datasets, but also to avoid human bias. The algorithm used for the annotation is Ganalyzer (Shamir, 2011).

Ganalyzer works by clear, defined, and symmetric rules that can identify the spin direction of a spiral galaxy, but can also identify when a galaxy does not have clear spin patterns. That is different from some supervised machine learning algorithms that tend to make a forced choice to assign a certain image into a predicted class.

Ganalyzer (Shamir, 2011, 2012, 2017, 2020a,b, 2021) works by first converting a galaxy image into its radial intensity plot. The radial intensity plot is a transfomation of the galaxy image such that each pixel (x,y) in the radial intensity plot is the median of the 5x5 pixels around

$$(O_x + \sin(\theta) \cdot r, O_y - \cos(\theta) \cdot r)$$

where θ is the polar angle and r is the radial distance from the center of the galaxy. Then the peaks in each line of the radial intensity plot are detected, and neghboring peaks are grouped to make lines. The sign of the linear regression of these lines indicate the curve of the arms, and therefore the direction towards which the galaxy rotates.

One of the most important features of Ganalyzer is that it is not based on machine learning or complex data-driven rules. It is clear how Ganalyzer works, and it does not rely on a training set or manually annotated ground truth that can capture human biases or other biases.

A detailed description of the method is available in (Shamir, 2011, 2012, 2017, 2020a,b, 2021).

Manual annotation

In addition to the automatic annotation, some of the datasets were annotated manually. To avoid bias driven by the human perception, random half of the galaxies were mirrored.

Size of the datasets

Datasets from five different sky surveys are used: DES, DECam (from the DESI Legacy Survey). SDSS, Pan-STARRS, and HST CANDELS. The number of annotated galaxies in each sky survey are as follows:

DES: 541,440

DECam: 807,898

SDSS: 63,693

Pan-STARRS: 33,028

HST: 8,690

The DES dataset is partial as galaxies are still being downloaded and processed. Downloading the datasets is done by a single computer to avoid any possible differences driven by the difference between the computers used to download the images. Downloading the DECam dataset took more than six months. The processing is also done using a single computer to avoid any possible differences between computer systems. The annotation therefore also lasts for several months.

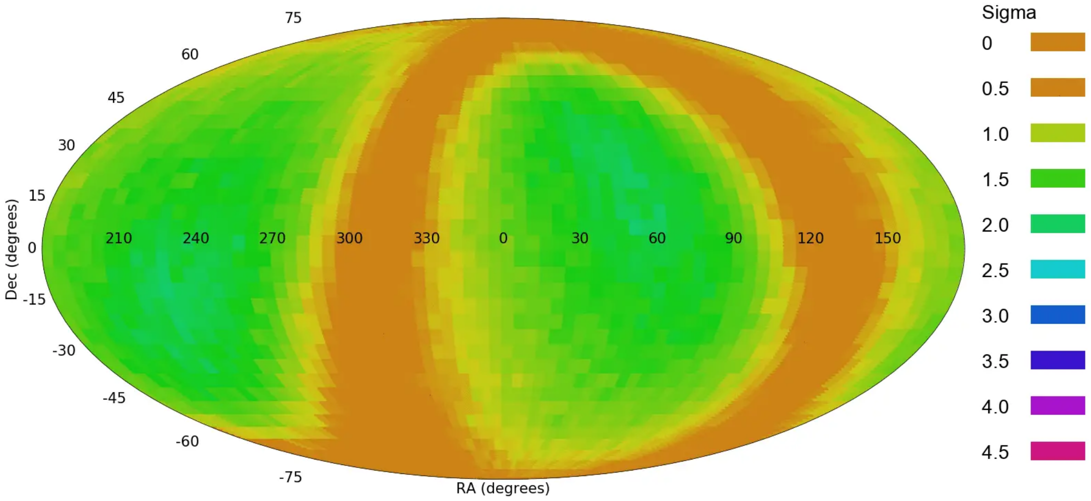
Analysis of dipole axis in the distribution of spin directions

The analysis of the distribution of the galaxies was done using X^2 statistics is computed for each integer coordinates by fitting the cosine of the angle between the galaxy and the axis to the absolute value of the cosine of the angle multipled by the spin direction, such that a clockwise spin direction is "1" and counterclockwise spin direction is "-1" (Shamir, 2012, 2020, 2021).

$$\chi^2_{\alpha,\delta} = \Sigma_i \frac{(d_i \cdot |\cos(\phi_i)| - \cos(\phi_i))^2}{\cos(\phi_i)}$$

That is done from each possible combination of integer RA and Dec. The X^2 computed with the actual spin directions of the galaxies is compared to the mean and standard deviation of the 1000 runs of X^2 computed when assigning the galaxies with random spin directions.

5. CHANGE OF THE PEAK WITH THE REDSHIFT - ANALYSIS AND POSSIBLE EXPLANATIONS



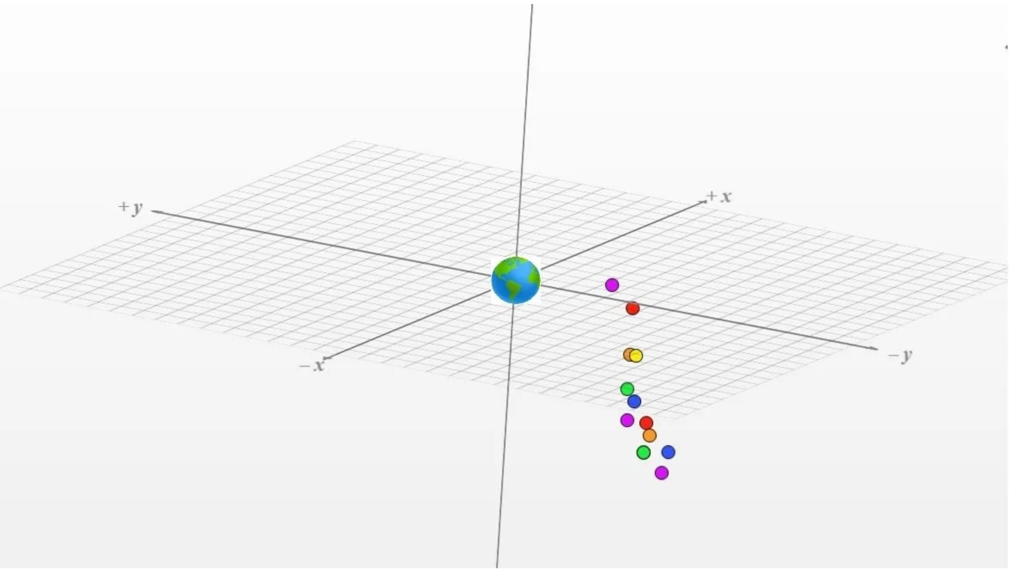
The profile of asymmetry axes when limiting the galaxies to different redshift ranges, from (0.01<z<0.11) to (0.16<z<0.26).

The most likely location of the dipole axis changes with the redshift. That change can be profiled with the SDSS dataset, where all galaxies in that dataset have redshift. The figure shows the profiles of the asymmetry when limiting the galaxies to different redshift ranges starting from (0.01<z<0.11) to (0.16<z<0.26). The location of the most likely axis changes consistently with the redshift. Another evidence is the agreement between HST and SDSS, where the SDSS galaxies are limited to z>0.15, as shown in Section 4. One immediate explanation to the change is that the axis does not necessarily go directly through Earth.

To approximate the 3D direction of the axis, a simple 3D analysis between two 3D points can be used:

$$\alpha = atan2(y_a - y_b, \sqrt{(x_a - x_b)^2 + (z_a - z_b)^2})$$
$$\delta = atan2(-(x_a - x_b), -(z_a - z_b))$$

The figure below shows that the most likely axes identified in different redshift ranges form a consistent 3D line.



Simple visualization of the 3D points computed when computing the msot likely axis using different redshift ranges. The points form a consistent 3D line.

The two points from which the direction of the axis can be determined are the two most distant points from each other, which are also to two points with the lowest and highest redshift used in the figure. The closet point to Earth is at (266°,10°), and 310 Mpc away. An observer in that point would see an axis in (268°,-29°). These number or merely a rough approximation, and are based on separating the galaxies into different redshift ranges of 0.1. The 0.1 range is definitely large, and therefore the numbers provided by the analysis are merely an approximation.

7. CONFLICTING PREVIOUS RESULTS AND CONFIRMATION BIAS

Since galaxy spin direction is expected to be merely a matter of the perception of the observer, the null hypothesis is that the distribution of galaxy spin direction is random. Several previous studies suggested random distribution, and showed conclusions that conflict with the results shown here.

One study was based on crowdsourcing done by unprofessional volunteers through Galaxy Zoo (Land et al., 2008). That approach had the advantage of using a large number of volunteers to increase the bandwidth of the annotation. Its main downside was that the annotations were subjected to a very substantial human bias. The main problem was not merely the inaccuracy if the annotations done by anonymous unprofessional volunteers, but mainly that the bias was systematic. Because the attempt to use crowdsourcing for that task was first of its kind, the presence and dominance of the perceptual bias was not known, and therefore the galaxies were not mirrored randomly to offset for the bias. After applying a process that involved multiple data corrections, the results show an asymmetry of 1%-2%, which agrees in magnitude and direction with the analysis shown with the SDSS galaxies used here or in (Shamir, 2020). Due to the corrections being applied, the number of galaxies used for the analysis shrunk, and the asymmetry was determined as statistically insignificant. However, the results also do not conflict with the results shown here. The magnitude and direction of the asymmetry observed with Galaxy Zoo data are aligned with the results observed with SDSS data used here, although there is no statistical significance to accept or reject that agreement.

A study that used computer annotation of the spin direction of spiral galaxies was done by (Hayes et al., 2017). The abstract suggests that “when viewed across the entire GZ1 sample (and by implication, the Sloan catalogue), the winding direction of arms in spiral galaxies as viewed from Earth is consistent with the flip of a fair coin”. Certainly, that conclusion conflicts with the results shown here. The explanation to the conflict can be explained by one sentence in Section 4.1: “We choose our attributes to include some photometric attributes that were disjoint with those that Shamir (2016) found to be correlated with chirality, in addition to several SPARCFIRE outputs with all chirality information removed.”

That is, to create a machine learning algorithm that can determine the spin direction of galaxies, attributes that correlate with spin direction asymmetry were removed. Naturally, when removing the attributes that correlate with the asymmetry in spin direction, the machine learning algorithm produced symmetric results. When not removing these attributes, the signal of the asymmetry is 2.52 sigma, which is not necessarily random.

Another study (Iye et al., AJ, 2021) used the dataset of (Shamir, 2017a), and argue that the asymmetry is the result of “duplicate objects” in the dataset. When removing the duplicate objects to create a “clean” dataset, the signal drops to 0.29 sigma. However, the dataset used in (Shamir, 2017a) was used for photometric analysis. It was not used to study the distribution of galaxies with opposite spin directions. The (Shamir, 2017a) paper did not make any claim for the presence or absence of a dipole axis, and no such claim about that dataset was made in any other paper. When using that dataset for analyzing the distribution of the galaxy population, photometric objects that are part of the same galaxy become “duplicate objects”, but as mentioned above, no such claim was made about that dataset.

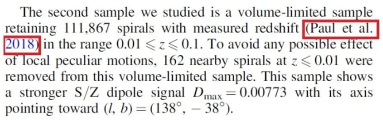
But the more interesting point is why a “clean” dataset showed random distribution. The answer can be found in the sentence “The second sample we studied is a volume-limited sample retaining 111,867 spirals with measured redshift (Paul et al. 2018) in the range 0.01<z<0.1”.

The 0.29 sigma signal was observed when using a dataset in which the redshift was limited to z<0.1. As shown in (Shamir, 2020b), the asymmetry signal increases as the redshift gets higher. When limiting the redshift to z<0.1, the distribution becomes statistically insignificant. Therefore, the random distribution in z<0.1 is completely expected, and in full agreement with previous work. The paper does not provide a motivation for limiting the redshift to 0.1, and that experimental design decision seems arbitrary.

More importantly, the “measured redshift” is in fact the photometric redshift from the catalog of (Paul et al., 2018). In the analysis shown here and in all previous publications, the position of each galaxy is determined by its RA and Dec, which are considered very accurate. In (Iye et al., 2021), however, the position of each galaxy is 3D, and determined by its RA, Dec, and redshift. Since the galaxies in (Shamir, 2017a) do not have redshift, the “measured redshift” used by Iye et al (2021) is in fact the photometric redshift. The photometric redshift is a highly inaccurate approximation of the redshift, and it is also systematically biased. Looking for ~1% signal in a dataset that has ~20% error is essentially a random number generator. Indeed, the results shown by (Iye et al., 2021) are completely different from everything published by me in the past. That shows, as expected, that the results are driven by the error and systematic bias of the photometric redshift. It is needles to mention that none of the analyses shown by me here or anywhere else were based on the photometric redshift, which is clearly a poor probe to study subtle asymmetries in the large-scale structure.

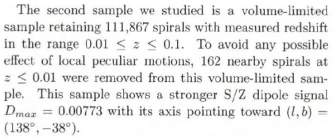
One might wonder how such a crude scientific error was not noticed in a peer-review process. According the AAS EiC, neither the reviewer nor the editors knew that the analysis of the dipole was based on the photometric redshift. Indeed, the photometric redshift is not discussed or mentioned anywhere in the paper. The only link to the photometric redshift is the reference to (Paul et al., 2018). However, the reference is not present in the accepted version of the paper, which means it was added only after the paper was already accepted for publication.

Journal version



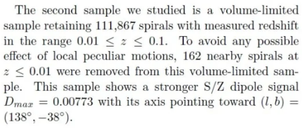
The second sample we studied is a volume-limited sample retaining 111,867 spirals with measured redshift (Paul et al. 2018) in the range $0.01 \leqslant z \leqslant 0.1$. To avoid any possible effect of local peculiar motions, 162 nearby spirals at $z \leqslant 0.01$ were removed from this volume-limited sample. This sample shows a stronger S/Z dipole signal $D_{\max} = 0.00773$ with its axis pointing toward $(l, b) = (138°, -38°)$.

"Accepted" author version



The second sample we studied is a volume-limited sample retaining 111,867 spirals with measured redshift in the range $0.01 \leq z \leq 0.1$. To avoid any possible effect of local peculiar motions, 162 nearby spirals at $z \leq 0.01$ were removed from this volume-limited sample. This sample shows a stronger S/Z dipole signal $D_{max} = 0.00773$ with its axis pointing toward $(l, b) = (138°, -38°)$.

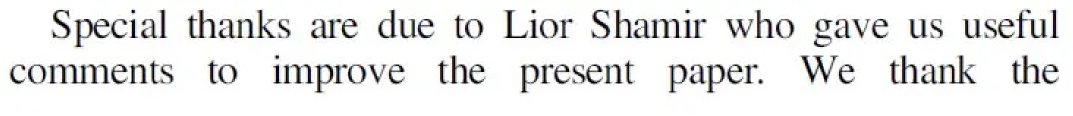
"Accepted" ArXiv version



The second sample we studied is a volume-limited sample retaining 111,867 spirals with measured redshift in the range $0.01 \leq z \leq 0.1$. To avoid any possible effect of local peculiar motions, 162 nearby spirals at $z \leq 0.01$ were removed from this volume-limited sample. This sample shows a stronger S/Z dipole signal $D_{max} = 0.00773$ with its axis pointing toward $(l, b) = (138°, -38°)$.

Due to the wording and the due to the fact that the term “measured redshift” is never used as a synonym to photometric redshift, even with the reference to (Paul et al., 2018) it is difficult to notice that the analysis is based on the photometric redshift. But the reference to the photometric redshift catalog was not even present in the accepted version of the paper, and therefore the reviewer had no way to know that the photometric redshift was used. Except for the reference to (Paul et al., 2018), the paper provides no information that discloses that the photometric redshift was used. The paper might be considered “peer-reviewed”, but that paper that was reviewed is not the same paper that was published.

One might also notice the acknowledgement in the end of the paper.



Special thanks are due to Lior Shamir who gave us useful comments to improve the present paper. We thank the

I state that these authors never asked for my comments, never asked me any other question, and at no point of time I even knew that the paper was being written. The first time I saw the paper was after it was already accepted for publication, and the authors refused to take any comments from me. The paper contains a very large number of scientific and factual errors. I claim zero responsibility for the content of that paper, and certainly no link to the conduct of its authors.

ABSTRACT

<p>Previous observations using SDSS, Pan-STARRS, HST, and DECam have shown substantial evidence of cosmological-scale patterns in the spin directions of galaxies. Here I show first results from the Dark Energy Survey (DES). As all other telescopes, DES galaxies show clear patterns in the spin directions of spiral galaxy. The profile of the spin directions of spiral galaxies is virtually identical to the profile observed by Pan-STARRS and DECam, and well within one sigma from SDSS and HST. All telescopes show that the spin directions of spiral galaxies exhibit a clear axis at a cosmological-scale. That axis agrees across eight additional datasets of sorted spiral galaxies. The spiral galaxies were separated by their spin directions either manually or by a mathematically symmetric algorithm that follows clear symmetric rules. In both cases the results are nearly identical, further demonstrating the consistency of the patterns. Limiting the data to different redshift ranges shows that the most likely position of the axis changes consistently with the redshift. A possible explanation could be that if such axis exists, it does not necessarily go directly through Earth. I explain why the observation cannot be the result of an error. I also survey previous studies and explain why they showed random distribution of the spin directions of spiral galaxies.</p>

REFERENCES

Aab, A., Abreu, P., Aglietta, M., et al. 2017, Science, 357, 1266

Adhav, K., Bansod, A., Wankhade, R., & Ajmire, H. 2011, Open Physics, 9, 919

Adhav, K. S. 2011, International Journal of Astronomy and Astrophysics, 1, 204

Campanelli, L. 2021, Foundations of Physics, 51, 56

Campanelli, L., Cea, P., Fogli, G., & Tedesco, L. 2011, Modern Physics Letters A, 26, 1169

Campanelli, L., Cea, P., & Tedesco, L. 2006, Physical Review Letters, 97, 131302

—. 2007, Physical Review D, 76, 063007

Cline, J. M., Crotty, P., & Lesgourgues, J. 2003, Journal of Cosmology and Astroparticle Physics, 2003, 010

Colin, J., Mohayaee, R., Rameez, M., & Sarkar, S. 2019, Astronomy & Astrophysics, 631, L13

Dojcsak, L., Shamir, L., Quantitative analysis of spirality in elliptical galaxies, New Astronomy, 28, 1-8, 2014.

Eriksen, H. K., Hansen, F. K., Banday, A. J., Gorski, K. M., & Lilje, P. B. 2004, Astrophysical Journal, 605, 14

Gordon, C., & Hu, W. 2004, Physical Review D, 70, 083003

Ghosh, S., Jain, P., Kashyap, G., et al. 2016, Journal of Astrophysics and Astronomy, 37, 1

Hutsemekers, D., Cabanac, R., Lamy, H., & Sluse, D. 2005, Astronomy & Astrophysics, 441, 915

Javanmardi, B., & Kroupa, P. 2017, Astronomy & Astrophysics, 597, A120

Javanmardi, B., Porciani, C., Kroupa, P., & Pflam- Altenburg, J. 2015, Astrophysical Journal, 810, 47

Longo, M., Physics Letters B, 699, 224, 2011.

Meszaros, A. 2019, Astronomical Notes, 340, 564

Migkas, K., Schellenberger, G., Reiprich, T., et al. 2020, Astronomy & Astrophysics, 636, A15

Perivolaropoulos, L. 2014, Galaxies, 2, 22

Secrest, N. J., von Hausegger, S., Rameez, M., et al. 2021, The Astrophysical Journal Letters, 908, L51

Shamir, L., Analysis of the alignment of non-random patterns of spin directions in populations of spiral galaxies, Particles, 4(1), 11-28, 2021a.

Shamir, L., Large-scale asymmetry in galaxy spin directions: evidence from the Southern hemisphere, 38, e037, Publications of the Astronomical Society of Australia, 2021b.

Shamir, L., Galaxy spin direction distribution in HST and SDSS show similar large-scale asymmetry, Publications of the Astronomical Society of Australia, 37, e053, 2020a.

Shamir, L., Patterns of galaxy spin directions in SDSS and Pan-STARRS show parity violation and multipoles, Astrophysics and Space Science, 365, 136, 2020b.

Shamir, L., Large-scale asymmetry between clockwise and counterclockwise galaxies revisited, Astronomical Notes, 341(3), 324-330, 2020c.

Shamir, L., Asymmetry between galaxies with different spin patterns: A comparison between COSMOS, SDSS, and Pan-STARRS, Open Astronomy, 29, 2020e.

Shamir, L., Large-scale photometric asymmetry in galaxy spin patterns, Publications of the Astronomical Society of Australia, 34, e044, 2017a.

Shamir, L., Colour asymmetry between galaxies with clockwise and counterclockwise handedness, Astrophysics and Space Science, 362, 33, 2017b.

Shamir, L., Handedness asymmetry of spiral galaxies with z<0.3 shows cosmic parity violation and a dipole axis, Physics Letters B, 715, 25-29, 2012.

Shamir, L., Color differences between clockwise and counterclockwise spiral galaxies, Galaxies, 3(1), 215-220, 2013.

Shamir, L., Ganalyzer: A tool for automatic galaxy image analysis, Astrophysical Journal, 736(2), 141, 2011.

Shamir, L., Asymmetry between galaxies with clockwise handedness and counterclockwise handedness, Astrophysical Journal, 823(1), 32, 2016.

Tiwari, P., Ghosh, S., & Jain, P. 2019, The Astrophysical Journal, 887, 175

Tiwari, P., & Jain, P. 2013, International Journal of Modern Physics D, 22, 1350089

—. 2015, Monthly Notices of the Royal Astronomical Society, 447, 2658

Tiwari, P., & Nusser, A. 2016, Journal of Cosmology and Astroparticle Physics, 2016, 062

Zhe, C., Xin, L., & Sai, W. 2015, Chinese Physics C, 39, 055101