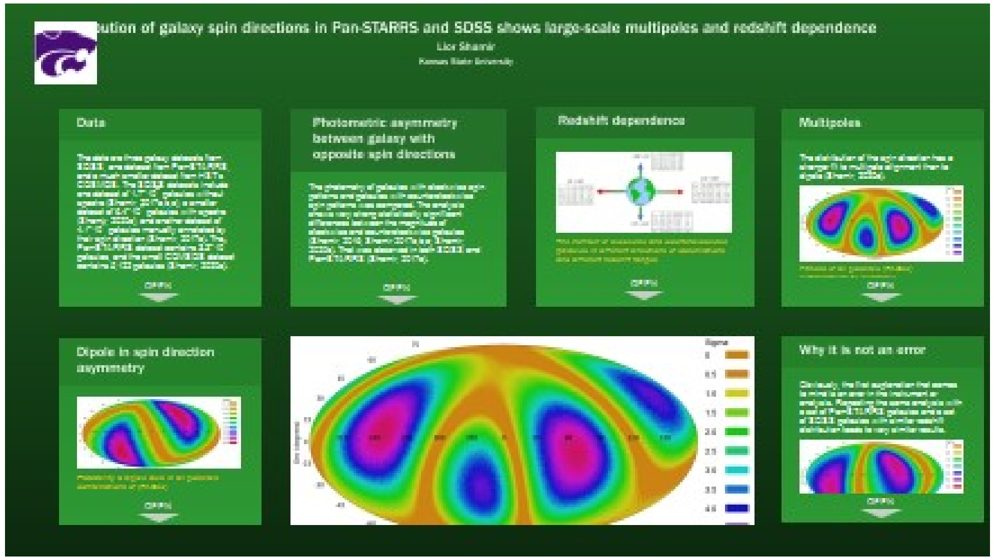
Distribution of galaxy spin directions in Pan-STARRS and SDSS shows large-scale multipoles and redshift dependence



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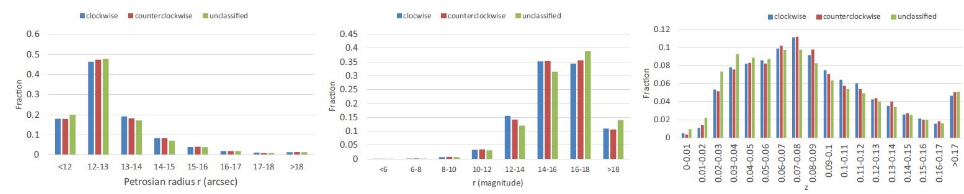
PRESENTED AT:

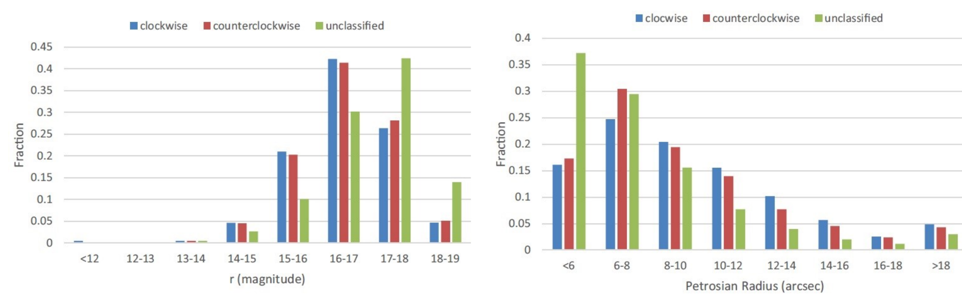
DATA

The data are three galaxy datasets from SDSS, one dataset from Pan-STARRS, and a much smaller dataset from HST's COSMOS. The SDSS datasets include one dataset of $1.7*10^5$ galaxies without spectra (Shamir, 2017a,b,c), a smaller dataset of $6.4*10^4$ galaxies with spectra (Shamir, 2020c), and another dataset of $4.1*10^4$ galaxies manually annotated by their spin direction (Shamir, 2017c). The Pan-STARRS dataset contains $3.3*10^4$ galaxies, and the small COMSOS dataset contains 5,122 galaxies (Shamir, 2020a).



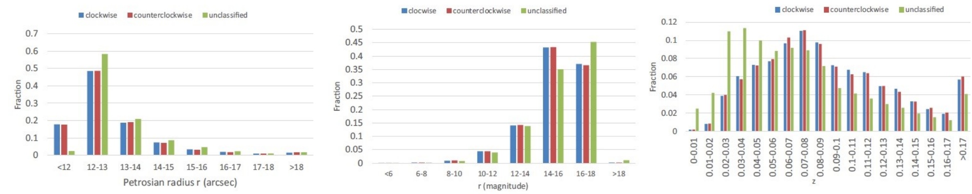
Magnitude, redshift, and size distribution of the galaxies in the SDSS dataset (Shamir, 2017a,b,c).

The Pan-STARRS dataset contains ~$3.3*10^4$ galaxies without spectra,



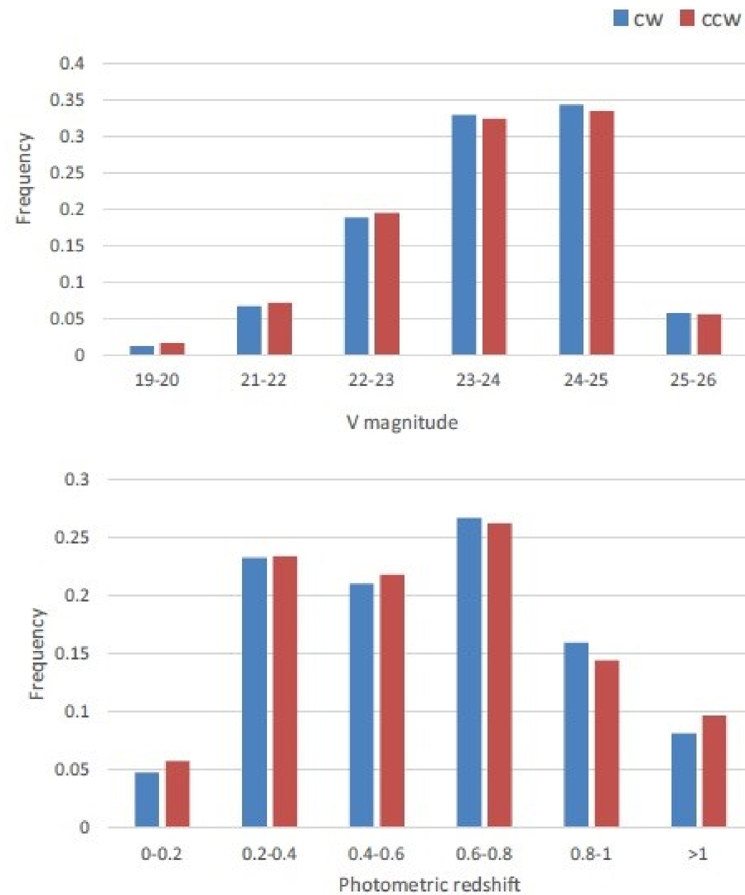
Magnitude and size distribution of the galaxies in the Pan-STARRS dataset (Shamir, 2017c).

A dataset of SDSS galaxies with spectra contains ~$4.1*10^4$ galaxies manually classified into clockwise and counterclockwise galaxies.



Magnitude, redshift, and size distribution of the manually annotated galaxies in the SDSS dataset (Shamir, 2017a).

The dataset of COSMOS galaxies contains 5,122 galaxies.

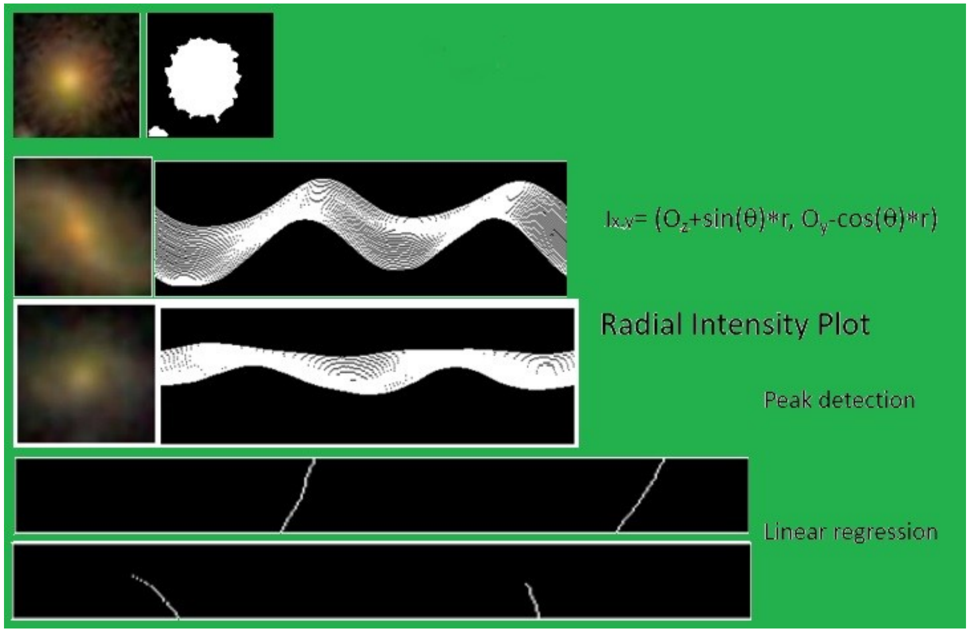


Magnitude and photometric redshift of the dataset of galaxies from COSMOS (Shamir, 2020a).

Galaxy annotation method

Ganalyzer is a galaxy annotation method that is completely automatic, and does not involve manual intervention to avoid any bias driven by the human perception. It also does not invlove machine learning or deep learning, that can capture human biases, background biases, or use complex rules that are difficult to understand. There is no "training" step as in machine learning, and all rules are clear and defined with simple mathematics. The method is fully symmetric, and works according to clear and defined rules (Shamir, 2011a,b).

Ganalyzer first separates foreground pixels from backgroun pixels using the Otsu binary threshold, and then transforms the galaxy image into its radial intensity plot. Then, it applies peak detection to identify the peaks on the radial intensity plot in different distances from the galaxy center. The collection of neighboring peaks makes an arm. The sign of the linear regression of the x position of the peaks determines whether the galaxy is clockwise or counterclockwise (Shamir, 2011a).



The Ganalyzer process of galaxy annotation (Shamir, 2011a).

PHOTOMETRIC ASYMMETRY BETWEEN GALAXY WITH OPPOSITE SPIN DIRECTIONS

The photometry of galaxies with clockwise spin patterns and galaxies with counterclockwise spin patterns was compared. The analysis shows very strong statistically significant differences between the magnitude of clockwise and counterclockwise galaxies (Shamir, 2016; Shamir 2017a,b,c; Shamir, 2020b). That was observed in both SDSS and Pan-STARRS (Shamir, 2017c).

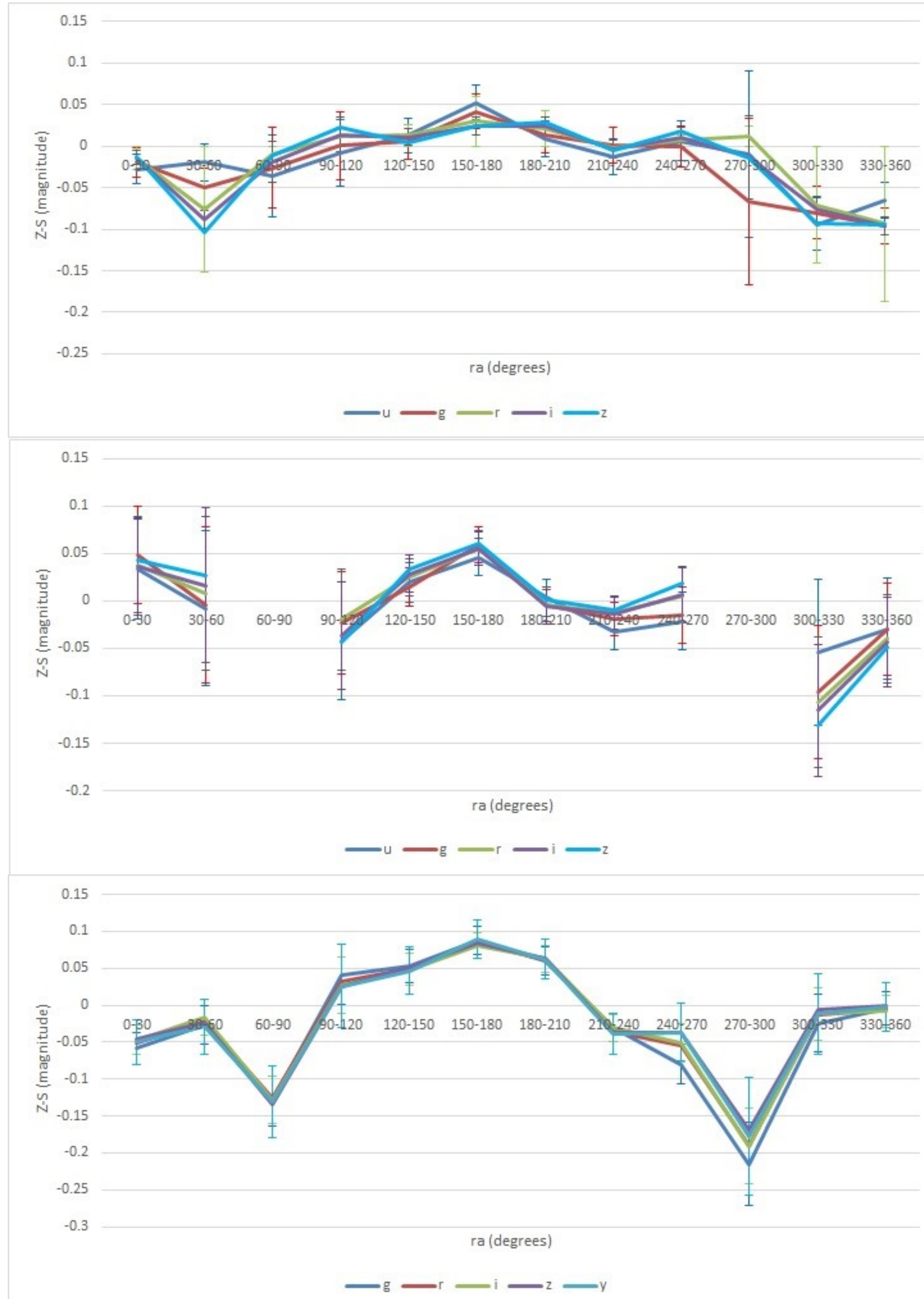
Dataset	Band	Mean clockwise	Mean counterclockwise	t-test P
SDSS automatically annotated	u	18.782±0.006	18.757±0.006	0.004
SDSS automatically annotated	g	17.503±0.006	17.482±0.006	0.016
SDSS automatically annotated	r	16.913±0.006	16.892±0.006	0.008
SDSS automatically annotated	i	16.597±0.006	16.578±0.006	0.021
SDSS automatically annotated	z	16.435±0.006	16.416±0.006	0.033
SDSS manually annotated	u	18.551±0.008	18.526±0.008	0.033
SDSS manually annotated	g	17.273±0.007	17.247±0.008	0.022
SDSS manually annotated	r	16.683±0.007	16.657±0.008	0.013
SDSS manually annotated	i	16.359±0.007	16.333±0.008	0.014
SDSS manually annotated	z	16.193±0.008	16.161±0.008	0.003
Pan-STARRS	g	17.054±0.01	16.986±0.01	$2.8 \cdot 10^{-5}$
Pan-STARRS	r	16.538±0.01	16.471±0.01	$1.5 \cdot 10^{-5}$
Pan-STARRS	i	16.236±0.01	16.171±0.01	$1.2 \cdot 10^{-5}$
Pan-STARRS	z	16.106±0.01	16.038±0.01	$4.6 \cdot 10^{-6}$
Pan-STARRS	y	15.931±0.01	15.897±0.01	$7.3 \cdot 10^{-6}$

Exponential magnitude mean, standard error, and t-test of the difference between clockwise and counterclockwise galaxies in the RA range (120^o, 210^o). Galaxies are from SDSS and Pan-STARRS show similar difference (Shamir, 2017c).

Dataset	Band	Mean clockwise	Mean counterclockwise	t-test P (two tails)
SDSS automatically annotated	u	18.830±0.007	18.883±0.007	$3.3 \cdot 10^{-8}$
SDSS automatically annotated	g	17.508±0.006	17.564±0.006	$1.3 \cdot 10^{-10}$
SDSS automatically annotated	r	16.886±0.006	16.937±0.006	$2.1 \cdot 10^{-9}$
SDSS automatically annotated	i	16.549±0.006	16.601±0.006	$2 \cdot 10^{-9}$
SDSS automatically annotated	z	16.360±0.006	16.415±0.006	$2.43 \cdot 10^{-9}$
SDSS manually annotated	u	18.639±0.02	18.648±0.02	0.80
SDSS manually annotated	g	17.338±0.02	17.347±0.02	0.76
SDSS manually annotated	r	16.718±0.02	16.738±0.02	0.52
SDSS manually annotated	i	16.374±0.02	16.398±0.02	0.44
SDSS manually annotated	z	16.193±0.02	16.219±0.02	0.43
Pan-STARRS	g	17.039±0.01	17.072±0.01	0.085
Pan-STARRS	r	16.521±0.01	16.550±0.01	0.092
Pan-STARRS	i	16.195±0.01	16.222±0.01	0.097
Pan-STARRS	z	16.058±0.01	16.081±0.01	0.187
Pan-STARRS	y	15.870±0.01	15.896±0.01	0.125

Exponential magnitude mean, standard error, and t-test of the difference between clockwise and counterclockwise galaxies in the RA range of ($< 30^o \vee > 300^o$).

The asymmetry changes based on the direction of observation, and is also inversed, showing that it cannot be due to a software error (a software error is expeted to be consistent throughout the sky). An experiment with manually classified galaxies also showed the same asymmetry, providing another evidence that the asymmetry cannot be driven by a computer error.



Asymmetry between the exponential magnitude of clockwise and counterclockwise
galaxies in different directions of observations. The datasets are SDSS automatically annotated galaxies (top), SDSS manually

annotated galaxies (middle), and automatically annotated Pan-STARRS galaxies (Shamir, 2017c).

Photometric Asymmetry in HST

A smaller scale experiment was done with 5,122 galaxies from HST's COSMOS survey. The results show asymmetry between clockwise and counterclockwise galaxies in that agrees with the asymmetry identified in SDSS and Pan-STARRS in that specific part of the sky. That shows that the effect might span over higher redshift than the depth of SDSS and Pan-STARRS.

Band	mean clockwise	mean counterclockwise	P (t-test)
B	23.052±0.018	23±0.018	0.024
V	22.603±0.020	22.553±0.02	0.042
g	23.131±0.019	23.077±0.019	0.023
r	22.266±0.019	22.218±0.02	0.045
i	21.719±0.018	21.680±0.018	0.065
z	21.358±0.017	21.323±0.018	0.087

Mean, standard error of the mean, and the one-tail statistical significance of the differences between the magnitude of clockwise galaxies and counterclockwise galaxies in COSMOS.

Color asymmetry

The clockwise and counterclockwise galaxies are not different just by their magnitude, but also their color. That difference also changes based on the direction of observation (Shamir, 2017b).

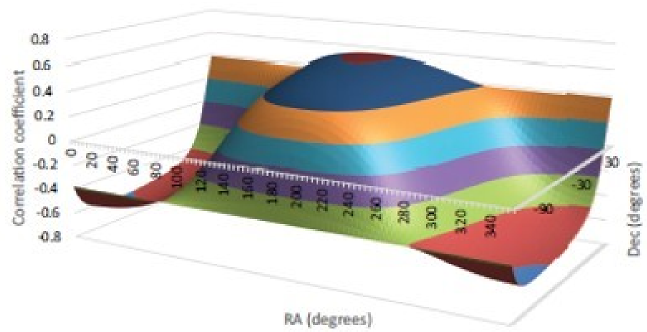
Colour	Mean clockwise	Mean counterclockwise	t-test P	Bonferroni-corrected t-test P
u-g	1.219±0.006	1.2±0.007	0.1	0.39
g-r	0.659±0.003	0.629±0.003	$< 10^{-5}$	$< 10^{-5}$
r-i	0.351±0.002	0.335±0.002	$< 10^{-5}$	$< 10^{-5}$
i-z	0.24±0.003	0.214±0.004	$< 10^{-5}$	$< 10^{-5}$

Mean, standard error of the mean, and two-tailed t-test P values of De Vaucouleurs model magnitude u-g, g-r, r-i, and i-z of clockwise and counterclockwise galaxies in the RA range of 30º-60º.

Relativistic beaming

Due to relativistic beaming, a galaxy rotating in the same direction as the Milky Way is expected to have different photometry than an identical galaxy rotating in the opposite direction of the Milky Way.

The photometric asymmetry peaks at around (172º,50º). The proximity to the galactic pole is aligned with a potential explanation of relativistic beaming (Shamir, 2017c).



Axis of maximum photometric asymmetry. The asymmetry peaks at (172º,50º).

The expected photometric asymmetry can be predicted using the following equation (Loeb & Gaudi, 2003):

$$F = F_0(1 + 4\frac{V_r}{c})$$

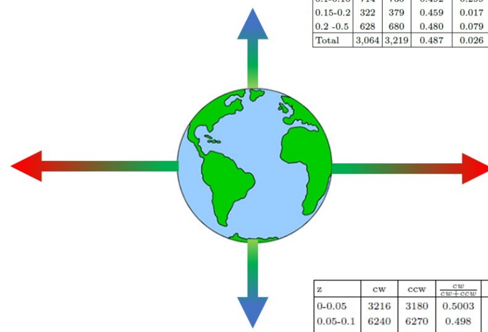
Assuming Vr of about 220km/s, the maximum expected difference is ~0.009 magnitude. However, the observed difference is already ~0.05. Therefore, to explain the asymmetry with relativistic beaming, the physics of galaxy rotation should correspond to rotation in velocity that is at least 10 times faster than their actual velocity.

Another observation that is not aligned with the relativistic beaming explanation is that the photometric difference is observed in the apparent magnitude, but the absolute magnitude does not show statistically significant difference between clocckwise and counterclockwise galaxies (Shamir, 2020c).

REDSHIFT DEPENDENCE

>300° < 30°

z	cw	ccw	$\frac{cw}{cw+ccw}$	P value
0-0.05	360	402	0.472	0.068
0.05-0.1	1040	1023	0.504	0.362
0.1-0.15	714	735	0.492	0.299
0.15-0.2	322	379	0.459	0.017
0.2 -0.5	628	680	0.480	0.079
Total	3,064	3,219	0.487	0.026



30° < 120°

z	cw	ccw	$\frac{cw}{cw+ccw}$	P value
0-0.05	245	260	0.485	0.266
0.05-0.1	442	429	0.507	0.34
0.1-0.15	370	384	0.491	0.32
0.15-0.2	229	185	0.553	0.017
0.2 - 0.5	379	302	0.556	0.0018
Total	1,665	1,560	0.516	0.034

210° < 300°

z	cw	ccw	$\frac{cw}{cw+ccw}$	P value
0-0.05	1643	1635	0.501	0.451
0.05-0.1	3351	3162	0.514	0.01
0.1-0.15	2105	2115	0.499	0.445
0.15-0.2	797	782	0.500	0.362
0.2 - 0.5	1165	1163	0.500	0.492
Total	9,061	8,857	0.505	0.07

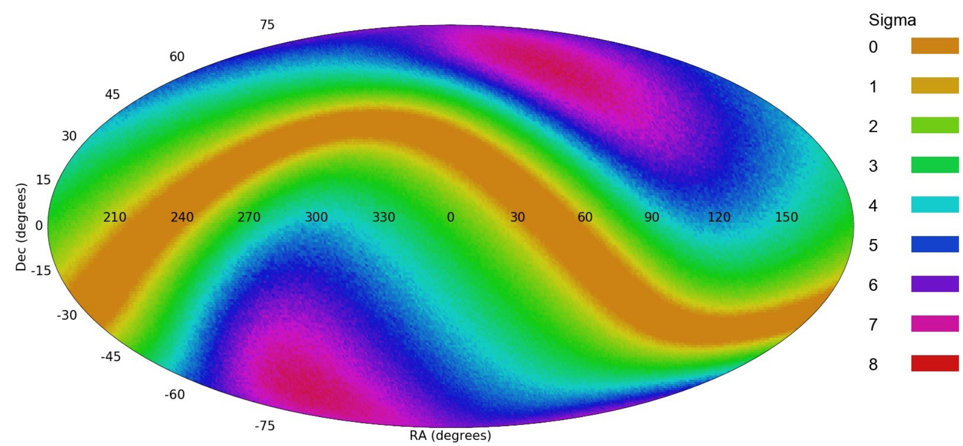
120° < 210°

z	cw	ccw	$\frac{cw}{cw+ccw}$	P value
0-0.05	3216	3180	0.5003	0.698
0.05-0.1	6240	6270	0.498	0.4
0.1-0.15	4236	4273	0.496	0.285
0.15-0.2	1586	1716	0.479	0.008
0.2 - 0.5	2598	2952	0.469	$1.07 \cdot 10^{-6}$
Total	17,876	18,391	0.493	0.0034

The number of clockwise and counterclockwise galaxies in different directions of observations and different redshift ranges.

Analysis of $6.4*10^4$ SDSS galaxies with spectra shows that the difference between the number of clockwise and counterclockwise galaxies grows with the redshift. The magnitude of the difference grows, although the sign of the difference changes based on the direction of observation (Shamit, 2020c).

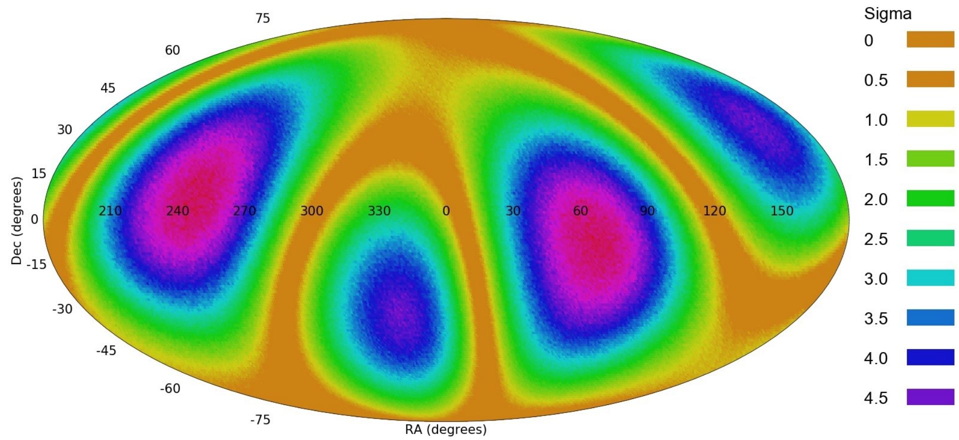
Because the asymmetry grows with the redshift, when using galaxies with (z>0.15), the dipole fittness is significantly stronger. The position of the most likely axis shifts, which could indicate that if the galaxy spin directions indeed form an axis of cosmological scale, it might have a certain drift.



Dipole fitness when using just galaxies with ($z>0.15$).

MULTIPOLES

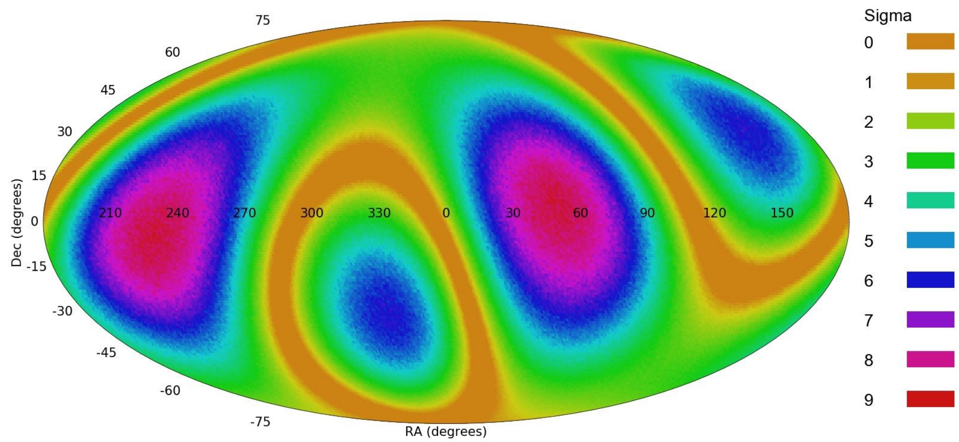
The distribution of the spin direction has a stronger fit to multipole alignment than to dipole (Shamir, 2020d).



Fitness of all possible (RA,Dec) combinations to quadrople.

Although likely a coincidence, it is interesting to note that the most likley axis at (52°,-7°) is close to the CMB cold spot. Statistical strength of the pole is 5.13 sigma.

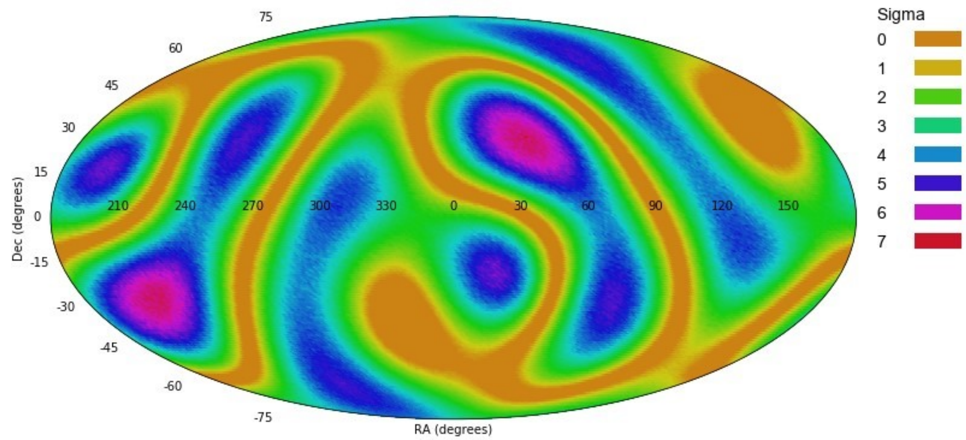
Because the asymmetry gets stronger with the redshift, quadrpole fitness gets stronger when the redshift increases.



Fitness of all possible (RA,Dec) combinations to quadrople such that all galaxies have z>0.15.

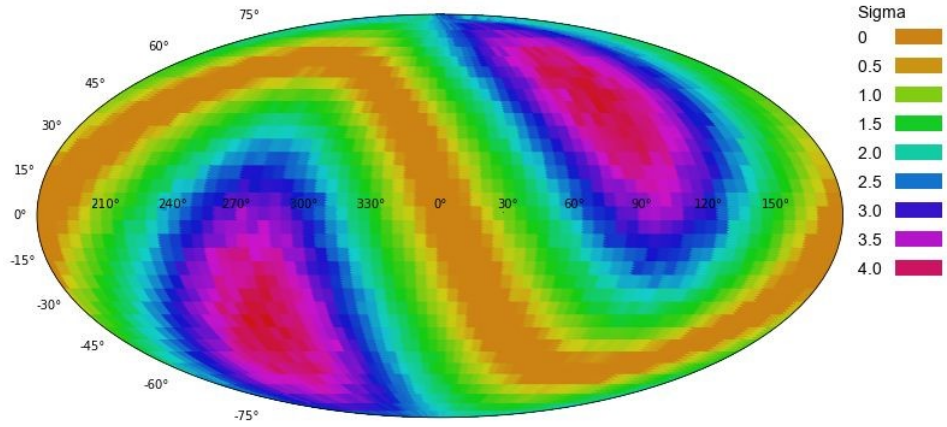
The most likely axes are at (232º,7º) and (153º,34º), roughly at the same location as when using the entire dataset, but the statistical signal of the most likely axes is much higher, with 5.94 sigma and 8.67 sigma, respectively.

Fitting to octopole alignment also shows good fitness when (z>0.15).



Octopole fitness when all galaxies have (z>0.15).

DIPOLE IN SPIN DIRECTION ASYMMETRY



Probability a dipole axis in all possible combinations of (RA,Dec).

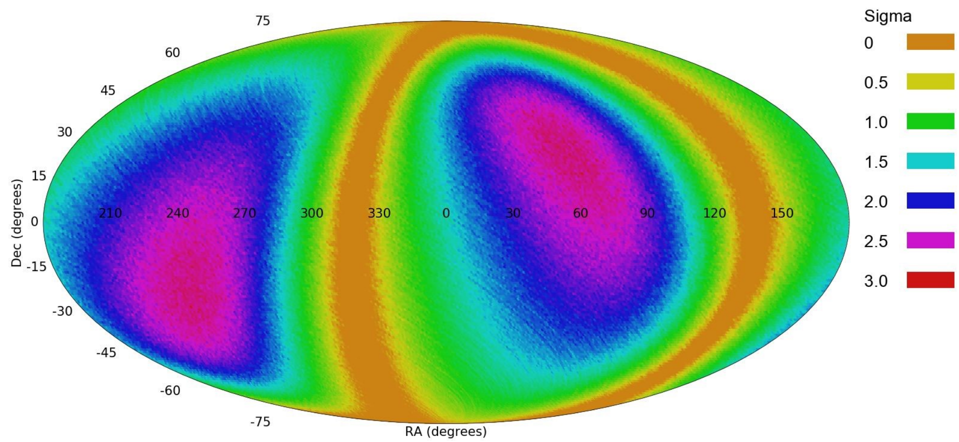
The annotation of the galaxies shows that in the dataset of SDSS galaxies without spectra, which is the largest dataset, 88,273 galaxies were annotated as clockwise, and 86,075 as counterclockwise. Assuming the probaility of a galaxy to be assigned with a certain spin direction of 0.5, the probability to have such distribution by chance is ($P<10^{-8}$).

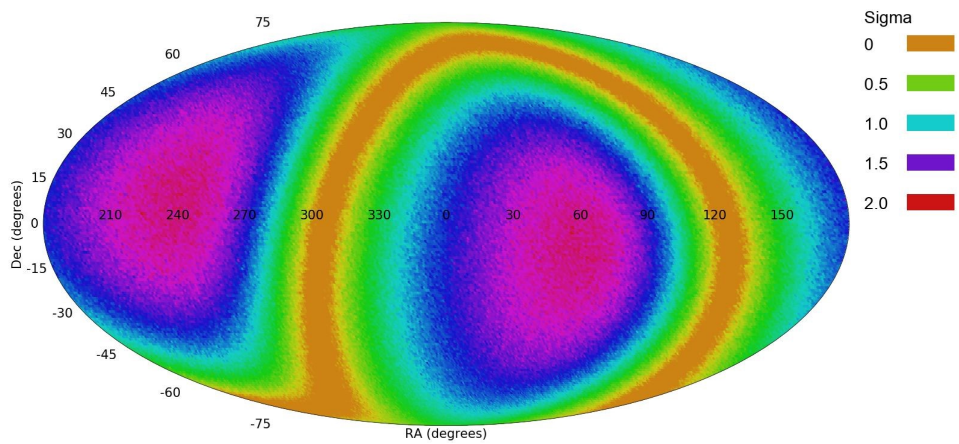
Dipole axis is determined by X^2 fitting of d*cos(p) to cos(p), such that d is the rotation direction of the galaxy {1,-1}, and p is the angular distance between the possible axis and the galaxy. That was done for each integer combination of RA, Dec (Shamir, 2012; Shamir, 2020a,c,d).

The most likely axis was identifed at (88º,36º), with of 4.34 sigma (P < 0:000014). The 1 sigma error of the right ascension of the axis is (62º, 124º), and the error range of the declination is (7º,69º).

WHY IT IS NOT AN ERROR

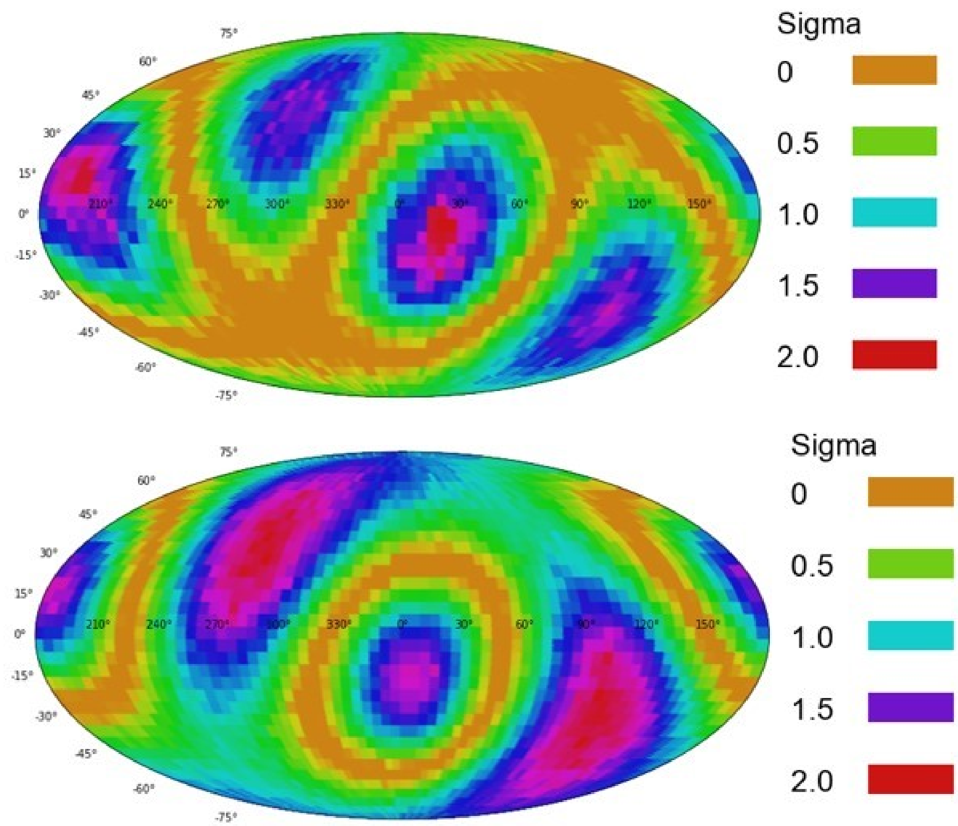
Obviously, the first explanation that comes to mind is an error in the instrument or analysis. Repeating the same analysis with a set of Pan-STARRS galaxies and a set of SDSS galaxies with similar redshift distribution leads to very similar results.





Most probable dipole in SDSS (top) and Pan-STARRS (bottom) such that the redshift distribution of the galaxies in both datasets is similar. While the redshift distribution is similar, the galaxies in the two datasets are different (Shamir, 2020c).

The same can also be attempted for quadropole alignment.

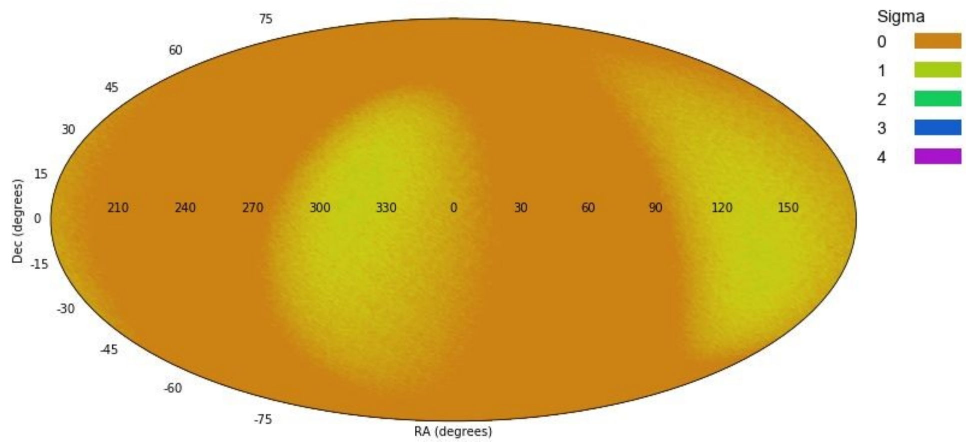


Most probable quadropole alignment in SDSS (top) and Pan-STARRS (bottom) such that the redshift distribution of the galaxies in both datasets is similar (Shamir, 2020c).

That is, two different datasets of galaxies imaged by two different instruments show the same patterns. It is difficult to think of an error that would exhibit itself in such form in even one instrument. Since two different instruments show the same results, it is unlikely that a flaw in the instrument or photometric pipeline is the reason for the asymmetry.

Error in the analysis

Another option for an error is an error in the analysis process. However, the analysis is very consistent in the sense that when assigning the galaxies random spin directions, the asymmetry immediately disappears.



Attempt to identify the most likely dipole axis such that the galaxies are assigned with random spin directions.

Error in the galaxy annotation

Another option for things to go wrong is the automatic galaxy annotation method. The algorithm is fully automatic and does not involve any human intervention that can lead to perceptional bias. It is also a deterministic, model-driven algorithm that works by clear and defined rules. It is not based on machine learning, deep learning, or any other method that uses complex and unintuitive rules that are determined automatically from training data. Such algorithms could capture the sky background or bias in the training set, and are difficult to analyze formally due to their complexity and "black box" nature.

Every experiment was repeated with mirrored galaxies. Expectedly, mirroring the galaxies provided inverse results compared to the original galaxies. That is expected because the image analysis software is compketely symmetric.

But even if the software did have a flaw in it, that cannot explain the results. If the software was flawed, it would be expected that the bias would be consistent throughout the sky. Instead, the bias changes gradually with the direction of observation, to form a consistent pattern. The software does not know the location of the galaxy in the sky when it is analyzed, and therefore no such pattern can be caused by a software error. If the software was biased, the same bias would have been expected in all parts of the sky. Surely, it is not expected to inverse in different directions of observation.

Another indication that the annotation method is not the source of the asymmetry is that a separate dataset of galaxies annotated manually led to the same results as using the automatic method. In that experiment, no software of any kind was used in any step of the galaxy annotation process.

Foreground contamination

Absolute measurements such as CMB might be sensitive to foreground contamination such as the obstruction of the Milky Way. However, the difference between clockwise and counterclockwise galaxies is a relative measurement, made by comparing two different measurements made in the same field. It is very difficult to think of an atmospheric or other effect that can impact clockwise galaxies differently than it impacts counterclockwise galaxies in the same field and same exposure. Any kind of obstruction that affects clockwise galaxies is also expected to effect counterclockwise galaxies in a similar manner.

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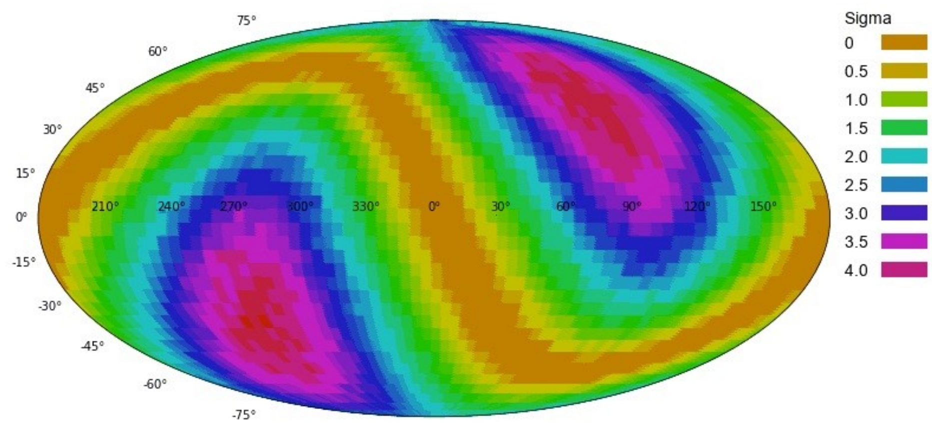
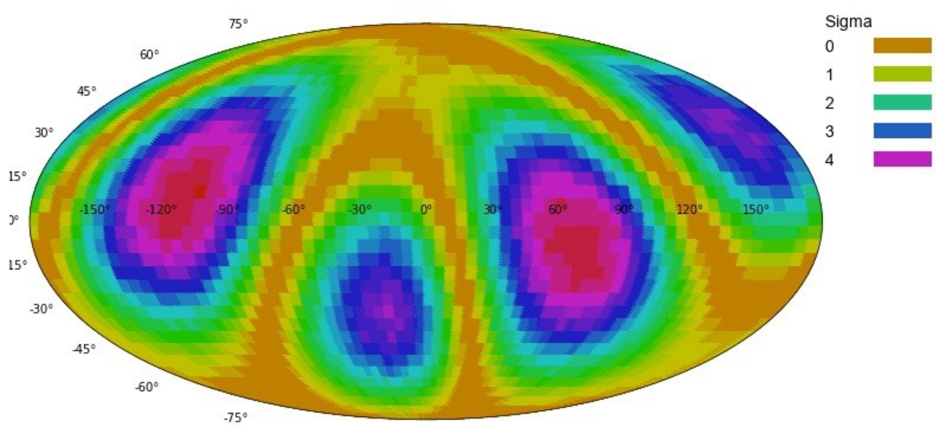
ABSTRACT

The apparent spin direction of a spiral galaxy changes based on the location of the observer relative to the galaxy, and therefore it can be assumed that the spin directions of spiral galaxies as observed from Earth are randomly distributed. Here I use large datasets of spiral galaxies from SDSS and Pan-STARRS to show that the distribution of the spin directions of spiral galaxies is not symmetric, and changes based on the direction of observation. The parity violation in spin directions exhibits multipoles, and has a best fit to a quadrupole with probability <6 sigma to have such distribution by chance. Comparison of SDSS and Pan-STARRS shows that the two sky surveys exhibit nearly identical patterns of the distribution of spiral galaxies, even when the datasets are completely orthogonal. Analysis of galaxies with spectra shows that the parity violation increases with the redshift in all tested directions of observation. The mean redshift of the galaxies is ~0.12, making the dataset far larger than any known astrophysical structure. The data analysis process is fully automatic, and is based on deterministic model-driven algorithms that follow defined rules, and are not sensitive to the size of the galaxies in the dataset. It does not involve manual analysis, and therefore the analysis is not subjected to a possible human bias. It also does not involve machine learning or deep neural networks that rely on complex unintuitive rules that can capture instrumental or atmospheric biases.





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