Observational search for primordial chirality violations using galaxy angular momenta

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We search for evidence of primordial chirality violation in the galaxy data from the Sloan Digital Sky Survey by comparing how strongly directions of galaxy angular momenta correlate with left and right helical components of a spin vector field constructed from the initial density perturbations. Within uncertainties, galaxy spins correlate with these two helical components identically, which is consistent with Universe without primordial chirality violation. Given current data, it is not yet possible to rule out maximal chiral violation, although the case of vanishing correlation with the right helical component is ruled out at about 3.8σ.

I. INTRODUCTION

As is well known, interactions of left- and right-handed fermions differ and chiral symmetry is broken on the microscopic scales (e.g. [1]). It is then conceivable that chiral symmetry is also broken in the early Universe, for example by helical couplings between various fields of a multi-field model of inflation. Other possible parity breaking mechanisms include addition of the Chern-Simons term to the gravitational Lagrangian [2], gravity at a Lifshitz point [3] or a chiral gravity with different Newton’s constant for the left- and right-handed gravitational waves [4]. If such violations were present, they might be manifest at late times and on large scales, for example in the cosmic microwave background [2–5].

In [6] we argued that vectors of galaxy angular momenta can also serve as a useful probe of such a violation. While amplitudes of galaxy momenta are generally affected by late time evolution and hard to predict (e.g. [7]), their directions41 are rather closely related to the initial conditions. Indeed, in [6] we proposed a vector field $J^{IC}$ quadratic in the initial density and gravitational potential (see Eq. (1) below) that correlates well with spins of dark matter haloes in numerical simulations and can thus serve as a proxy for halo spins. While our simulations focused on dark matter haloes, studies [7, 8] suggest that spins of galaxies are tracing spins of their underlying dark matter haloes sufficiently well to be practically useful as probes of initial conditions. Currently available galaxy survey data confirms, with statistical significance of about 3σ, that galaxy spins indeed correlate with the vector field $J^{IC}$ [9]. It is thus timely to start searching for the primordial chirality violations in the galaxy spin data.

With spins of galaxies serving as test probes, in this work we search for signs of such violation by comparing correlation strengths of the galaxy spins with the left and right helical components of $J^{IC}$, respectively. We define these components below. In some sense this is analogous to comparing interaction strengths of the left- and right-handed fermions.

From initial conditions obtained by the ELUCID collaboration in part of the Sloan Digital Sky Survey (SDSS) volume [10, 11], we calculate the predicted galactic spin field $J^{IC}$ and decompose it into its left and right helical components. We then compare whether the measured galaxy spins correlate with these two components with identical strength. Nonzero difference would signal either a parity violation in the early Universe, or a systematic in our measurement.

With sufficient number of galaxy spin measurements, it will be also possible to search for chirality violations in the galaxy spin field $J^g$ directly, without a need to correlate with $J^{IC}$ or another similar proxy. For example, one can compare the power spectra of the left and right helical components of $J^g$ [6]. An alternative strategy to search for chirality violation in galaxy data is comparing statistical properties of $J^{IC}_L$ and $J^{IC}_R$ directly, without any reference to the galaxy angular momenta (see Appendix A for an example). However, one expects that the optimal way how to search for these novel effects in the large scale structure data is by cross-correlating two different observables, as we do here. Unlike searches based on a single observable, cross-correlations remove the uncorrelated systematics and noise, which typically leads to favorable detection prospects. This can be seen on numerous historical examples, such as detection of gravitational lensing of the cosmic microwave background [12] and detection of cosmic structure in the 21 cm signal [13].

This paper is organized as follows: In § II we explain how to construct the vector field $J^{IC}$ used to predict the galaxy spins, explain how to separate it into its left and right helical components and present the correlation

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41 For brevity, in what follows we use “spin” to reference only the direction of the angular momentum of a galaxy / halo.
measures and error bar calculation. In § III we introduce the data used in our analysis. In § IV we present our results and conclude with a discussion in § V. Finally, in Appendix A we present an alternative search for a primordial chirality violation that uses only the statistics of the chiral components of $J^{IC}$ and does not require any galaxy angular momenta data.

We denote vectors with bold face letters, their Euclidean norm as $|v|$ and label their components with lower case letters $v_i$. $\epsilon_{ijk}$ and $\delta_{ij}$ represent components of the three-dimensional Levi-Civita tensor and Kronecker delta, respectively.

II. THEORY

In this section we explain how to predict directions of galaxy angular momenta from initial conditions, introduce the statistics we use to study chiral symmetry breaking and explain how we quantify uncertainties of our measurements.

A. Predicting galaxy spins

In our current understanding, the dark matter haloes acquire angular momenta from the inhomogeneous tidal field that torques the non-spherical protohalo early on [14–18]. At late times, interactions with the nearby large scale structure notably complicate the picture [17–38].

In [6] we showed that the vector field $J^{IC}$ constructed from the initial density field $\rho$ and the initial gravitational potential field $\phi$ according to

$$J^{IC}_a = \sum_{bck} \epsilon_{abc} \partial_b \phi \partial_c \rho$$

(1)

can be used to predict the directions of final angular momenta of dark matter halos in simulations. To suppress fluctuations on scales too small to affect the halo angular momentum, the initial fields $\rho, \phi$ are smoothed with a Gaussian kernel with a suitably chosen smoothing scale $r$. This is indicated by the superscript $r$. With perfectly known initial conditions, the optimal smoothing scale for a particular halo depends on its mass and for a $10^{13} M_\odot$ halo corresponds to about $2 h^{-1}$ Mpc. For each halo, the vector field $J^{IC}$ should be evaluated at its Lagrangian centre of mass.

B. Quantifying the chiral violation

In practice, measurements of halo angular momenta are unavailable and we have to work with angular momenta of galaxies $J^g$. Given $J^g$ and values of $J^{IC}$ at galaxy Lagrangian positions, we can define the correlation strength

$$\mu = \left\langle \frac{J^g}{|J^g|}, \frac{J^{IC}}{|J^{IC}|} \right\rangle,$$

(2)

with the average taken over the galaxies. In case of no relationship between the directions of $J^g$ and $J^{IC}$, the correlation between these two sets of vectors vanishes.

As explained in greater detail in [6], it is straightforward to split the divergence-free vector field $J^{IC}$ into its two helical components $J^{IC}_L, J^{IC}_R$. This decomposition can be achieved in the Fourier domain, where the components of the transformed field $J^{IC}_a$ are combined using two projection operators $P^{L/R}$,

$$J^{IC}_{L/R,a}(k) \equiv \sum_b P^{L/R}_{ab}(k) J^{IC}_b(k).$$

(3)

These projection operators explicitly read

$$P^{L/R}_{ab} = \frac{1}{2} \left( \delta_{ab} - \hat{k}_a \hat{k}_b \right) \pm i \epsilon_{abc} \hat{k}_c$$

(4)

and we defined the unit vector $\hat{k} = k/|k|$. The real space components of $J^{IC}_L/R$ are then obtained through a backward Fourier transform. Under the parity transformation the two helical components swap,

$$J^{IC}_L \leftrightarrow J^{IC}_R.$$  

(5)

Analogously to $\mu$, we can define the correlations with the left- and right-handed helical components of $J^{IC}$ as

$$\mu_X = \left\langle \frac{J^g}{|J^g|}, \frac{J^{IC}_X}{|J^{IC}_X|} \right\rangle, \quad X \in \{L, R\}$$

(6)

and their difference,

$$\mu_- = \mu_L - \mu_R.$$  

(7)

Because of the swap of $J^{IC}_L$ and $J^{IC}_R$ under parity transformation, $\mu_-$ flips sign. In a universe where the chiral symmetry is broken at high redshifts and this violation propagates into galaxy spins, we would detect nonzero $\mu_-$. On the other hand, in standard model we expect to find $\mu_-$ consistent with zero.

At present, it is possible to obtain the full direction vector of angular momentum $J^g$ for only a limited number of galaxies as it is necessary to perform an integral field spectroscopy and provide additional information. Measurements of $\mu_-$ would thus be too noisy. Fortunately, for our purposes of searching for the primordial chirality violation, we do not need to know the full direction vector $J^g/|J^g|$. By focusing only on the components of $J^g$ along the line of sight $\hat{r}$, we can significantly increase the number of galaxies in our sample.

When we restrict our attention to only the line of sight component of the galaxy spin,

$$J^g \rightarrow (J^g \cdot \hat{r}) \hat{r},$$

(8)

the vector $J^g/|J^g|$ in Eq. (2) and (6) is replaced with

$$\frac{J^g}{|J^g|} \rightarrow \hat{r} \text{ sign}(J^g \cdot \hat{r}) = \pm \hat{r}. $$

(9)
Rotational state of each galaxy is thus represented by a single bit of information, instead of a unit vector. For a later notational convenience we introduce a shorthand

\[ S \equiv \text{sign}(J^\theta \cdot \hat{r}). \]  

(10)

Analogously to above, we can define correlation strength with the reconstructed spin field

\[ \mu_X^\parallel = \left( S\hat{r} \cdot \frac{J^\IC_X}{|J^\IC_X|} \right), \quad X \in \{L, R\} \]  

(11)

Using SDSS data, we experimentally verified that \( J^\IC \) defined in Eq. (1) leads to nonzero \( \mu^\parallel \) with a statistical significance of about 3\( \sigma \) [9].

For the purposes of searching for the primordial chirality violation we also define correlations with the chiral components of \( J^\IC \)

\[ \mu_X^\perp = \left( S\hat{r} \cdot \frac{J^\IC_X}{|J^\IC_X|} \right), \quad X \in \{L, R\} \]  

(12)

and finally also

\[ \mu_L^\perp = \mu_L^\parallel - \mu_R^\parallel. \]  

(13)

Notice that even after the restriction to radial components, \( \mu_L^\parallel \) remains sensitive to chirality violations. Measurement of \( \mu_L^\perp \), thus amounts to indirectly probing chiral symmetry in the early Universe and will be the main result of this work.

C. Error bars

Our measurement of \( \mu_L^\perp \) are based on the vector fields \( J^\IC, J^\IC_L, J^\IC_R \) built up from the reconstructed initial conditions and a set of measured galaxy positions \( \{r_1, r_2, ..., r_N\} \) and signs of the radial components of their angular momenta \( \{S_1, S_2, ..., S_N\} \). Here \( N \) is the number of galaxies in our sample.

To estimate the uncertainties of our measurements, we repeat the calculations with the same vector fields \( J^\IC, J^\IC_L, J^\IC_R \) and galaxy positions \( \{r_1, r_2, ..., r_N\} \) but randomly shuffled signs of the radial component of the angular momenta,

\[ \{S_1, S_2, ..., S_N\} \rightarrow \{S_{\sigma_1}, S_{\sigma_2}, ..., S_{\sigma_N}\}, \]  

(14)

where \( \sigma_i \) is some permutation of \( \{1, 2, ..., N\} \). We repeat the calculations 40,000 times with independent random \( \sigma_i \) and as uncertainties of our results then take the standard deviations of these randomized results.

We estimate the error bars similarly for \( \mu^\parallel, \mu_L^\parallel \) and \( \mu_R^\parallel \).

III. DATA

In this section we present the observational data used in this work. We start by describing the initial density field \( \rho \) as reconstructed by the ELUCID collaboration. We then introduce the data used to determine angular momenta of galaxies and their positions.

A. Initial conditions

The initial density field \( \rho \) used in this work was obtained by the ELUCID collaboration [10, 11].

They first pre-processed SDSS data to create a catalog of galaxy groups [39] and then determined mass of each group via a luminosity-based abundance matching. They corrected for peculiar velocities and only retained groups in the Northern Galactic Cap, redshift range 0.01 ≤ z ≤ 0.12 and with masses above \( 10^{12} M_\odot \). The space was then tessellated according to which galaxy group was the closest. Within the resulting sub-volumes, particles were placed randomly, in accordance with the expected density profile for halo of given mass. This particle distribution represents today’s density field.

In the second step of the reconstruction, ELUCID collaboration ran a Particle-Mesh (PM) dynamics code repeatedly in a Hamiltonian Monte Carlo fashion to determine the best fit initial conditions. For each random set of initial conditions, the PM code was used to calculate the corresponding value of today’s density field. By comparing this density field with that determined from the SDSS data, it was possible to construct a probability measure on the space of the initial conditions. Due to inaccuracies of the PM code on small scales, both density fields were smoothed on a scale of 4 Mpc/h before comparison. Iteratively probing the space of initial conditions then allowed ELUCID to find the initial conditions that best describe the local galaxy data.

From these best fit initial conditions, we calculate the initial gravitational potential \( \phi \) from the Poisson equation and use (1) to predict the galaxy spins \( J^\IC \).

B. Galaxy Spins

We base our determination of the sign of \( J^\theta \cdot \hat{r} \) on the fact that for spiral galaxies the orientation of the angular momentum of the galaxy’s gas is closely related to the sense of rotation of galaxy’s spiral arms (clockwise or anti-clockwise, i.e. in the sense of the letters Z or S). To determine the direction of the radial component of \( J^\theta \), it is thus sufficient to determine whether given galaxy rotates clockwise or anti-clockwise, with the radial component of galaxy spin aligned \( (S = 1) \) resp. anti-aligned \( (S = -1) \) with its position vector. This classification is not a perfect determination of the galaxy angular momentum, with about 4% of galaxies having angular momentum that is pointed in the opposite direction than that inferred from the orientation of the spiral arms [40], but this effect is not expected to bias the results.

We use a catalog of galaxies classified as “clockwise spiral galaxy” and “anticlockwise spiral galaxy” by Galaxy Zoo [41], a citizen science project where members of the public visually classified properties of almost \( 9 \times 10^9 \) objects. For each object, summary statistics of the voting results are publicly available and we obtained them.
through CasJobs\textsuperscript{\textcopyright}. We only consider objects classified by at least 80\% of votes as either “clockwise spiral galaxy” or “anti-clockwise spiral galaxy”. Our final catalog contains 12022 galaxies and the corresponding values of $S$.

C. Galaxy Positions

From CasJobs we also obtain redshift and sky position for each galaxy in our sample. This allows us to find the galaxy’s three-dimensional position and use it to interpolate $J^{IC}$, making use of an inverse displacement field of the reconstructed simulation. The line of sight vector $\hat{r}$ is also obtained directly from the galaxy position.

IV. RESULTS

To construct the vector field $\mathbf{J}^{IC}$, we need to choose a scale $r$ with which to smooth the initial conditions. For this work, we choose $r = 3 \, h^{-1}\text{Mpc}$, as it is the smoothing scale that for current data leads to the maximal correlation $\mu^\|\|$ in [9].

Using the (anti-)clockwise classifications of the SDSS galaxies and the initial conditions as determined by the ELUCID collaboration, we find

\begin{align}
\mu^L &= (0.41 \pm 0.53) \times 10^{-2} \\
\mu^R &= (1.99 \pm 0.53) \times 10^{-2}.
\end{align}

The parity-odd variable $\mu_-$ is then

\begin{align}
\mu_- &= (-1.58 \pm 0.75) \times 10^{-2},
\end{align}

formally a 2.1 $\sigma$ deviation from the value of zero expected in a parity invariant universe. Notice that the error bars suggest that $\mathbf{J}^{IC}_L/|\mathbf{J}^{IC}|$ and $\mathbf{J}^{IC}_R/|\mathbf{J}^{IC}|$ are essentially uncorrelated, which we also checked explicitly.

The parity even combination

\begin{align}
\mu^\parallel &= \mu^L + \mu^R = (2.40 \pm 0.74) \times 10^{-2}.
\end{align}

is detected with similar significance as $\mu^\parallel$, 

\begin{align}
\mu^\parallel &= (1.80 \pm 0.53) \times 10^{-2}.
\end{align}

The two are not identical despite

\begin{align}
\mathbf{J}^{IC} = \mathbf{J}^{IC}_L + \mathbf{J}^{IC}_R,
\end{align}

as normalization of the vectors in Eq. (11) and (12) is a nonlinear operation.

V. DISCUSSION

In this work we searched for signature of parity violations in the angular momenta vectors of the SDSS galaxies. We found a mild preference for galaxy spins to correlate more strongly with the right helical component of the vector field $\mathbf{J}^{IC}$ built from the initial density field according to (1), but this preference is not statistically significant for the currently available galaxy sample and initial condition reconstruction. Given current uncertainties, the data is thus consistent with no parity violation. At the same time, our result is at present also consistent with the maximally violating case $\mu^L = 0, \mu^\parallel \neq 0$, while the other maximally violating case $\mu^R = 0, \mu^\parallel \neq 0$ is excluded at about 3.8$\sigma$.

In principle, there are other parity-odd observables one can construct beyond $\mu^-$. Another possibility would be for example

\begin{align}
\Delta \mu^\parallel = \left\langle |\mathbf{S} \hat{r} \cdot \left( \mathbf{J}^{IC}_L - \mathbf{J}^{IC}_R \right) / |\mathbf{J}^{IC}| \right\rangle,
\end{align}

which differs from \$\mu^\parallel\$ by only a sign in the numerator (see (20)). However, this statistic is quite sensitive to galaxies with small $|\mathbf{J}^{IC}|$, which leads to a strongly non-Gaussian distribution and long tails. The reader can contrast this with $\mu^\parallel_{L/R}$ that are both limited to $[-1, 1]$ and no single galaxy can dominate the $\mu^\parallel$-statistics, which is the reason behind our choice.

We need to stress that the error bar estimates quoted in this work represent only the statistical uncertainty. In principle, there can also be systematic uncertainties affecting our results. These can arise for example from biases of the human observers classifying the galaxies as clockwise/anticlockwise [42] or from the scanning strategy of the survey, that can break the parity in subtle ways. Given that in this work we found no statistically significant chirality violation, we do not attempt to perform the involved computations that would be necessary to estimate these systematic uncertainties.

In the nearest future, data from Dark Energy Spectroscopic Instrument [43] will allow us to notably shrink the error bars of the $\mu^\parallel$ measurement. Improving the reconstruction on smaller spatial scales will be especially interesting, because simulations suggest that the quadratic formula (1) can lead to correlations up to an order of magnitude stronger than what is currently achievable. Additional improvements are then expected from leveraging the extensive theoretical and observational knowledge of the origin of galaxy spins [17–19, 22, 23, 28, 29, 31–38, 44–46] to further tighten the relationship between the galaxy spins and initial conditions and improve on the simple formula Eq. (1). Another interesting follow-up work would be to pick a particular model of chiral breaking and propagate this breaking all the way to the final galaxy spins, to get an estimate of how big an effect one might expect to observe.

\textsuperscript{\textcopyright} https://skyserver.sdss.org/CasJobs/
While this draft was being finalized, a related work [47] appeared, where an alternative strategy to search for primordial chirality violations (using four-point functions of the galaxy density field) was introduced.

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Appendix A: Alternative statistic

In principle, any potential chiral violation present in our Universe can also cause differences between the statistical properties of the reconstructed vector fields $J_{IC}^L$ and $J_{IC}^R$. For example, it is possible to compare variances of these vector fields by evaluating

\[
\eta = \frac{\langle |J_{IC}^L|^2 \rangle_V - \langle |J_{IC}^R|^2 \rangle_V}{\langle |J_{IC}|^2 \rangle_V},
\]  

where the subscript reminds us we are averaging only over the volume in which we have reconstructed initial conditions and we normalize by the variance of $J_{IC}$ for convenience. Detecting nonzero $\eta$ would suggest either an uncorrected systematic, or a sign of primordial chirality violation.

With vector fields $J_{IC}^L, J_{IC}^R, J_{IC}^C$ obtained from the reconstructed initial conditions smoothed with the smoothing scale $r = 3 \, h^{-1} \text{Mpc}$, we get

\[
\eta = (-0.8 \pm 1.4) \times 10^{-3}. 
\]  

(A2)

To estimate the error bar, we ran 14 simulated $\Lambda$CDM universes, calculated $\eta$ in each and took the standard deviation of these results. These simulations were performed using the $N$-body code CUBE \[48\] and were run on a $512^3$ grid representing volume $(500h^{-1}\text{Mpc})^3$. Unlike in the data, we do not perform any reconstruction and build $J_{IC}$ from the true initial conditions. This means the error bars in (A2) are somewhat underestimated.

A more rigorous analysis, including comparing power spectra of $|J_{IC}^L|$ and $|J_{IC}^R|$, would necessarily involve deconvolving the window function and goes beyond the scope of the present work.