Correlating galaxy shapes and initial conditions: an observational study

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Using data from the Sloan Digital Sky Survey we study correlations between directions of galaxy angular momenta determined from images of spiral galaxies and various observables derived from the reconstructed initial conditions. We find an apparent systematic effect consistent with galaxy-orientation-dependent selection function. After restricting our attention to the brightest half of the galaxies where this systematic effect is presumed to be absent, we find hints of excess/deficit correlation for two observables. Interestingly, tidal torque theory predicts excess/deficit correlation in exactly these two observables. After correcting for the redshift space distortions, the significance of these correlations drops below 3σ threshold. We do not find any other systematic issues, but a thorough systematic analysis goes beyond the scope of this work.

I. INTRODUCTION

Galaxy surveys have been instrumental in enhancing our understanding of the Universe [1–4]. Beyond the traditional analyses, it is useful to think about how to extract additional information from the large number of galaxies that will be discovered in the following years [5, 6].

One of the suggestions has been using measurements of galaxy angular momenta, that can extend our understanding of physics at megaparsec scales [7–9]. Such measurements can aid with reconstruction of the initial conditions (ICs) in the Universe [7, 8] and help to constrain neutrino masses [10], primordial gravitational waves [11], primordial non-Gaussianity [12] and chirality violations in the early Universe [9]. Better knowledge of initial matter distribution in the local volume would also aid studies of galaxy formation.

In our current understanding, the dark matter haloes acquire angular momenta from the inhomogeneous tidal field that torques the non-spherical protohalo early on [13–17]. At late times, interactions with the nearby large scale structure notably complicate the picture [16–37].

Despite these late time effects, it turns out that the direction of the halo angular momentum retains a significant amount of the initial information [9]. Naturally, we can not directly measure angular momenta of dark matter haloes. Fortunately, spins¹ of galaxies tend to be correlated with spins of their dark matter haloes [38, 39], and so there is a potential to use measurements of galaxy spins to probe the initial conditions in the local Universe.

It seems that the amplitude of the dark matter halo’s angular momentum also retains information about the initial conditions [40] (but see [16, 39]). However, in this work we only consider the angular momenta directions, especially given the experimental cost involved in determining the amplitudes of galaxy angular momenta.

The prospect that measurements of galaxy spins might help with the reconstruction of the initial conditions in the Universe requires an observational verification. We made a first step in this direction in [41], where we found a correlation between the galaxy spins of a sample of about 15000 galaxies and initial conditions reconstructed from positions of a larger sample of galaxies [42]. Unfortunately, due to the limited number of galaxies we could only confirm this correlation with an ∼3σ confidence. To achieve this result, we combined a set of galaxies for which integral field spectroscopy data are available with a set of spiral galaxies with known senses of rotation of their spiral arms.

At least in principle we have access to a significantly larger dataset of galaxy spins. Assuming that each spiral galaxy forms a thin disk with its spin pointing perpendicularly to the plane of the disk, we can utilize shape measurements of spiral galaxies to determine their spins up to a so-called four-fold degeneracy (see below) [7]. Shape measurements of spiral galaxies, as a proxy for their spins, are thus potentially usable as an additional handle on the initial conditions of the Universe. In this paper we investigate to what extent such a proposition is currently viable by studying correlations between galaxy spin components determined solely from galaxy shapes and observables derived from the initial density field as measured using a traditional reconstruction technique. In contrast with [41], we trade a somewhat lower signal per galaxy (due to the four-fold degeneracy) for a larger number of galaxies. Unlike the previous studies such as [43], we study correlations of galaxy shapes with observ-

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¹ As a shorthand, here and in what follows we use “spin” to specifically only refer to the direction of the angular momentum of a halo/galaxy, ignoring its amplitude.
ables derived from the initial, not late time, density field.

This paper is organized as follows: In § II we describe how to determine galaxy spins from the galaxy shape measurements and discuss the four-fold degeneracy. Then we explain how we quantify correlations between galaxy spins and the initial conditions and list the observables built from the initial conditions we consider in this work. In § III we introduce the data used and in § IV we present our results. We conclude with discussion in § V.

We use indices $i, j, k, l$ to denote components of vectors and tensors in three dimensions.

II. THEORY

In this section we introduce the thin disk approximation that we use to connect measurements of galaxy shapes and their angular momenta. Then we describe how we quantify correlations between galaxy spins and various observables built from the initial conditions, before listing all such observables considered in this work.

A. Spins from shapes

Measuring the full 3D vector of galaxy angular momentum requires integral field spectroscopy, which is experimentally costly and can at the present only be obtained for several thousands of galaxies [44, 45]. Using an approximation in which spiral galaxies are considered to be thin disks allows us to use images of spiral galaxies to infer information about their angular momenta [23, 43]. Currently, tens of thousands of such images are available.

In this thin-disk approximation, matter is assumed to be circling around the galaxy center in the plane of the disk, implying that the galaxy angular momentum vector is perpendicular to the plane of the galaxy. This plane can be, up to a two-fold degeneracy, determined from the position angle $\alpha$ (measured relative to the north celestial pole, turning positive into the direction of the right ascension) and axis ratio $R$ of the galaxy image. Additional two-fold degeneracy then arises because from $\alpha$ and $R$ alone we are unable to determine whether the galaxy spin points towards or away from the observer.

The unit spin vector of such a galaxy in the local spherical coordinate frame $(L_r, L_\theta, L_\phi)$ can be determined through [46]

$$|L_r| = R,$$

$$L_\theta / L_\phi = \tan \alpha,$$  \hspace{1cm} (1)

where the four-fold degeneracy prevents us from determining the signs of $L_r$ and $L_\theta$ (and thus $L_\phi$) from the galaxy image alone.

In the equatorial Cartesian coordinates, the unit spin vector can be then determined from the right ascension and declination of the galaxy through [43]

$$\vec{L} = \vec{L}_R + \vec{L}_T,$$  \hspace{1cm} (2)

where we defined

$$\vec{L}_R \propto L_r (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$$

$$\vec{L}_T \propto L_\theta (\cos \theta \cos \phi, \cos \theta \sin \phi, -\sin \theta)$$

$$+ L_\phi (- \sin \phi, \cos \phi, 0)$$ \hspace{1cm} (3)

and $\theta = \pi/2 - \text{DEC}$ and $\phi = \text{RA}$. Because of the four-fold degeneracy, signs of $\vec{L}_{R,T}$ are ambiguous. Notice that in general neither of the vectors $\vec{L}_{R,T}$ has unit norm.

By default we consider spiral galaxies to be infinitesimally thin disks and use (1). To test for systematic effect of this assumption, we also consider non-zero intrinsic flatness $p$ of the spiral galaxies, where we replace $R$ in (1) with

$$R \to \sqrt{\frac{\max (R^2 - p^2, 0)}{1 - p^2}}.$$ \hspace{1cm} (4)

To derive this equation, one assumes that spiral galaxy is an ellipsoid with lengths of the principal axes in the ratio $1:1:p$. Then the observed projected axis ratio $R$ is related to the galaxy inclination angle $i$ according to

$$R = \sqrt{\cos^2 i + p^2 \sin^2 i},$$ \hspace{1cm} (5)

from which (4) follows given that (1) is just a special case of the more general

$$|L_r| = \cos i.$$ \hspace{1cm} (6)

The maximum in (4) just enforces that any galaxy with $R$ below $p$ is considered to have inclination angle $i = \pi/2$. Experimentally, $p$ of spiral galaxies has been measured to be $\sim 0.1 - 0.2$ [47].

B. Quantifying correlations

In this section we give an overview of how we quantify correlations between measurements of galaxy spins as represented by $\vec{L}_{R,T}$ and the initial conditions. In all cases, the initial conditions are represented by either a vector $V_i$ or a rank-two tensor $M_{ij}$ constructed from the second derivatives of the initial density $\rho_{ini}$, gravitational potential $\phi_{ini}$, or both. See the next section for the list of $V_i$ and $M_{ij}$ used in this work.

Considering first the rank-two variables of the form $M_{ij}$, we can form three scalar combinations

$$L_{RML_R} \equiv \sum_{ij} L_{R,i} M_{ij} L_{R,j},$$ \hspace{1cm} (7)

$$L_{TML_T} \equiv \sum_{ij} L_{T,i} M_{ij} L_{T,j},$$ \hspace{1cm} (8)

$$L_{TML_R} \equiv \sum_{ij} L_{T,i} M_{ij} L_{R,j},$$ \hspace{1cm} (9)

where for future convenience we suppressed the index structure on the left hand side. Given the four-fold degeneracy in determining $L_T$ and $L_R$, the last combination
can not be evaluated using the shape data alone. On the other hand, $L_{RMLR}$ and $LTMLT$ are invariant with respect to this degeneracy and can be used to study the correlations between galaxy spins and initial conditions.

With vector variables $V_i$ the situation is slightly more complicated, as the naive combinations $\tilde{L}_{R,T}\cdot \vec{V}$ are again indeterminate due to the uncertainty in the sign of $\tilde{L}_{R,T}$. We can form an invariant quantity by taking the absolute value of the scalar product,

$$|L_R V| \equiv \sum_i L_{Ri} V_i$$  \hspace{1cm} (10) \\

$$|L_T V| \equiv \sum_i L_{Ti} V_i$$  \hspace{1cm} (11) \\

which can be used to study the correlation of $\tilde{L}_{R,T}$ with the initial conditions. Notice that more information is available when we are able to break the degeneracy [41].

For each variable $V$ of the form $L_{\alpha} M L_{\alpha}$ or $L_{\alpha} V$ with $\alpha \in \{R,T\}$ we then evaluate the average $\langle V \rangle_{\text{data}}$ over the galaxies in our sample. To determine the probability of observing such $\langle V \rangle_{\text{data}}$ in case of uncorrelated spins $\tilde{L}_{R,T}$ and initial conditions (as represented by $M_{ij} / V_i$), we calculate $V$ for many mock galaxy catalogs in which the galaxy positions are kept fixed but we randomly shuffle the parameters $\alpha, R$ that determine the galaxy spins $\tilde{L}_{R,T}$. As a result, we get the mean and standard deviation $\langle V \rangle_{\text{data}}, \sigma(V)$ of this random mock distribution$^2$, which allows us to calculate the statistical significance of the detected excess correlation

$$S = \frac{|\langle V \rangle_{\text{data}} - \langle V \rangle_{\text{rnd}}|}{\sigma(V)}.$$  \hspace{1cm} (12) \\

Notice it is incorrect to shuffle the vectors $\tilde{L}_{R,T}$ themselves, because then these vectors would no longer be parallel to / perpendicular to the line of sight.

### C. Functions of initial conditions

In this section we introduce variables $M_{ij}, V_i$ we use to characterize the initial conditions and which we correlate with the galaxy spins described by $\tilde{L}_{R,T}$. It has been shown in both simulations [9] and observations [41] that galaxy spins correlate with the vector field $\tilde{L}^{IC}$ defined in terms of the smoothed initial density $\rho_{\text{ini}}$ and gravitational potential $\phi_{\text{ini}}$ as

$$L^{IC}_i = \sum_{jkl} \epsilon_{ijk} \left( \partial_j \phi_{\text{ini}}^r \right) \partial_k \rho_{\text{ini}}^r.$$  \hspace{1cm} (13) \\

This vector field is a straightforward extension of the standard tidal torque theory formula [15]

$$L^{TTT}_i \propto \sum_{jkl} \epsilon_{ijk} \left( \partial_j \phi \right) I_{lk},$$  \hspace{1cm} (14) \\

where $I_{lk}$ is the moment of inertia tensor of the protohalo. In (13), the fields have been smoothed with a Gaussian kernel with smoothing scale $r \sim O(h^{-1}\text{Mpc})$; this is represented by the superscript $r$. The unit norm vector field $\tilde{L}^{IC} = \tilde{L}^{IC} / |L^{IC}|$ is then the first observable built from the initial conditions we correlate with the galaxy spins.

It has long been understood that tidal field in the vicinity of a protohalo plays a crucial role in determining the halo’s spin [13–17]. Tidal torque theory suggests that galaxy spins should correlate with the second power of the unit traceless local shear tensor $T$ [8]. This tensor is built from the shear tensor, defined as

$$T_{ij} = \partial_{ij} \phi_{\text{ini}}^r,$$  \hspace{1cm} (15) \\

by first subtracting the trace

$$\tilde{T}_{ij} = T_{ij} - \frac{\delta_{ij}}{3} \sum_k T_{kk}$$  \hspace{1cm} (16) \\

and then normalizing

$$\hat{T}_{ij} = \frac{\tilde{T}_{ij}}{\sqrt{\sum_{ij} \tilde{T}_{ij}^2}}.$$  \hspace{1cm} (17) \\

This tidal torque theory prediction motivates us to take $(\hat{T})^2$ as our second variable.

The tidal-torque theory also predicts that the correlation $\langle L_{\alpha} \tilde{T} L_{\alpha} \rangle$ should vanish [8]: Assuming Gaussian initial conditions, initial perturbation $\phi_{\text{ini}}$ and its reverse $-\phi_{\text{ini}}$ are equally likely. However, the observable $\langle L_{\alpha} \tilde{T} L_{\alpha} \rangle$ is not invariant under the operation $\phi_{\text{ini}} \rightarrow -\phi_{\text{ini}}$ as $\tilde{T}_{ij}$ changes sign but the quadratic form $L_{\alpha,i} L_{\alpha,j}$ does not. Physically, tidal-torque theory predicts equal alignments of galaxy spins with major and minor principal axes of $T$, which leads to cancellations in $\langle L_{\alpha} \tilde{T} L_{\alpha} \rangle$. However, various studies suggest that tidal-torque theory provides an incomplete picture of how the galaxy angular momenta arise [16, 49]. Because of this, we also consider correlations with the first power of $\hat{T}$.

One can expect similar sensitivity to the second derivative of the initial density field, which can serve as a proxy for the protohalo’s moment of inertia [29, 41]. We thus also investigate correlations with first and second power of $I_{ij}$, defined similarly to $\hat{T}_{ij}$ but with $\phi_{\text{ini}}$ in (15) replaced by $\rho_{\text{ini}}^r$.

Finally, tidal-torque theory provides theoretical arguments that the galaxy spins should preferentially orient with the intermediate principal axis $\hat{T}_g^\phi$ of the shear tensor $\hat{T}$ [7]. In the limit where the tensor $\hat{T}$ can be used as a proxy for the protohalo moment of inertia, the same arguments can be used to justify expectation of correlation of galaxy spins with the intermediate principal axis.

$^2$ But notice this procedure can give a slightly underestimated standard deviation, see for example [48].
\( \hat{L}_0 \) of \( \hat{I} \). The two unit vectors \( \hat{L}^{\rho}_{0,\rho} \) are then the last two observables built from the initial conditions that we consider in this work.

Overall, we study correlations with seven objects constructed from the initial conditions: four matrices \( \hat{T}, (\hat{T})^2, \hat{I}, (\hat{I})^2 \) and three vectors \( \hat{L}^{\rho}_0, \hat{L}^\rho_0, \hat{L}^{1C} \). We correlate them with either \( \hat{L}_R \) or \( \hat{L}_T \), which leads to 14 combinations to study for each of the smoothing scales we consider. Because we talk about the initial conditions, all these variables are evaluated at the \textit{Lagrangian} positions of the galaxies.

III. DATA

In this section we present the data used in this work. We start by describing the initial conditions as reconstructed by the ELUCID Collaboration and then introduce the data used to determine angular momenta and positions of galaxies.

A. Initial conditions

The initial density field \( \rho_{\text{ini}} \) used in this work was obtained by the ELUCID Collaboration. Extended details about their methodology can be found in [42, 50].

They first created a catalog of galaxy groups from the Sloan Digital Sky Survey (SDSS) data [51] and then estimated mass of each group via a luminosity-based abundance matching. After correcting for peculiar velocities, they only retained groups in the Northern Galactic Cap, redshift range \( 0.01 \leq z \leq 0.12 \) and with masses above \( 10^{12} \text{M}_\odot \). 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 determined the best fit initial conditions by repeatedly running a Particle-Mesh (PM) dynamics code in a Hamiltonian Monte Carlo fashion. For each random set of initial conditions, the PM code was used to calculate the corresponding value of today’s density field. This density field was compared with that determined from the SDSS data and their relative closeness was quantified using a predefined measure. As the PM code is inaccurate on small scales, both density fields were smoothed with a Gaussian kernel with smoothing scale \( 4 \text{Mpc}/h \) 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 the best fit \( \rho_{\text{ini}} \), we use the Poisson equation to calculate the initial gravitational potential \( \phi_{\text{ini}} \).

In [41] we found that with ELUCID ICs, galaxy spins are best predicted when smoothing the initial conditions with \( r \sim 3 \text{Mpc}/h \). In this work we consider this smoothing scale, together with \( r \sim 2 \text{Mpc}/h \) and \( r \sim 4 \text{Mpc}/h \) to allow for the possibility of a potentially different optimal smoothing scale for the observables studied here.

B. Galaxy shapes and positions

Galaxy data used in this work were obtained by SDSS [4, 44] and we downloaded them from CasJobs\(^3\). First we use the Galaxy Zoo classifications [52] to select only spiral galaxies. For each such galaxy we obtain its right ascension, declination, redshift, position angle and axis ratio. As our default combination, for the position angle and axis ratio we use results of the fit of the exponential profile to the galaxy images obtained using the green SDSS filter. For systematic checks we also investigate other choices. As in our previous work, we only consider galaxies for which the closest ELUCID halo was at least \( 10^{12} \text{M}_\odot \) to avoid regions with poorly determined ICs.

For each galaxy, we calculate the vectors \( \hat{L}_{R,T} \) according to (3). The redshift and sky position then allows us to find each galaxy’s three-dimensional Euclidean position. Using the simulation run from the optimal ICs, we then find the galaxy’s inverse displacement, which we use to calculate the Lagrangian position of the galaxy.

Our full fiducial catalog contains 50361 galaxies in the volume in which ELUCID provides the initial conditions.

IV. RESULTS

In this section we first present measured excess correlations for all investigated observables when using the full sample of galaxies. Then we discuss an apparent systematic bias present in our results, possibly related to a galaxy-orientation-dependent selection function. After restricting our attention to the brighter half of galaxies, we find that only two observables show \( \sim 4 \sigma \) hints of an excess correlation. In the final part of this section we perform several other systematic checks on these two observables.

A. Using full galaxy catalog

In Fig. 1 we show excess correlation between the galaxy spins \( \hat{L}_{R,T} \) inferred from the galaxy shapes and various observables built from the initial conditions when we use the full galaxy sample. We summarize the detection significances \( S \) in Table 1. To estimate the error bars, we shuffled \( R \) and \( \alpha \) total of 40000 times, which is enough to converge the results to below 0.05 standard deviation.

\(^3\) https://skyserver.sdss.org/CasJobs/
The strongest correlation we find is with the tidal tensor $\hat{T}$, which is significant for all three investigated smoothing scales $r$. We also see strong excess correlation between the galaxy spins and $(\hat{T})^2$ smoothed with $r = 2h^{-1}\text{Mpc}$ and $r = 3h^{-1}\text{Mpc}$ and $\hat{I}$ smoothed with $r = 4h^{-1}\text{Mpc}$. No other excess correlation reaches 4$\sigma$ significance.

### B. Systematic bias in the faint subsample

As pointed out in [53], selection function of a gravitational survey generally depends on the spatial orientation of a galaxy relative to the observer’s line of sight. Emission from a disk galaxy will suffer more extinction when the galaxy is viewed edge on, potentially dropping below the survey detection threshold. Because galaxy orientation is sensitive to the local tidal field, such selection effect can in principle bias the correlations studied in this work.

To check for presence of this effect in our results, we split our galaxy sample into two approximately equal sized bins based on the galaxy magnitude. Specifically, we consider the resulting magnitude from the fit of the exponential profile to the galaxy image in the green SDSS filter, listed as $\text{expMag}_g$ in the SDSS database. If the galaxy-orientation-dependent selection effect exists, we expect it to mostly affect the fainter subsample of galaxies. Comparing the results between the subsamples then allows us to check for this systematic. Accidentally, the splitting magnitude roughly corresponds to the magnitude at which our sample becomes incomplete, see Fig. 2 for the distribution of $\text{expMag}_g$ in our full galaxy sample.

In Fig. 3 we plot the excess correlation for the four

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**TABLE I. Significances $S$ of excess correlations in terms of number of standard deviations when using the full galaxy sample.**

| Smoothing scale $r$ | $2h^{-1}\text{Mpc}$ | $3h^{-1}\text{Mpc}$ | $4h^{-1}\text{Mpc}$ |
|---------------------|---------------------|---------------------|---------------------|
| $L_R \hat{T} L_R$   | 4.9                 | 5.6                 | 5.7                 |
| $L_T \hat{T} L_T$   | 0.7                 | 0.3                 | 0.0                 |
| $L_R(\hat{T})^2 L_R$| 4.7                 | 4.0                 | 3.0                 |
| $L_T(\hat{T})^2 L_T$| 2.4                 | 2.6                 | 2.7                 |
| $L_R \hat{I} L_R$   | 1.4                 | 3.1                 | 4.3                 |
| $L_T \hat{I} L_T$   | 1.5                 | 1.1                 | 0.5                 |
| $L_R(\hat{I})^2 L_R$| 1.1                 | 1.9                 | 3.2                 |
| $L_T(\hat{I})^2 L_T$| 0.2                 | 0.2                 | 0.8                 |
| $|L_R L_R^0| $       | 3.8                 | 3.4                 | 2.9                 |
| $|L_T L_T^0| $       | 1.4                 | 2.2                 | 1.4                 |
| $|L_R L_T^0| $       | 1.2                 | 1.5                 | 1.8                 |
| $|L_T L_T^0| $       | 0.2                 | 0.8                 | 0.3                 |
| $|L_R L_T^1|$       | 2.2                 | 2.7                 | 2.3                 |
| $|L_T L_T^1|$       | 0.3                 | 1.1                 | 2.0                 |
observables with the largest detection significance in Table I — \( L_R \hat{T} L_R \), \( L_R (\hat{T})^2 L_R \), \( L_R \hat{I} L_R \) and \(|L_R L_0^\phi|\) — and all three smoothing scales for both the full galaxy sample and the bright/faint subsamples.

We find that the detections of excess correlation in \( L_R \hat{T} L_R \) and \( L_R \hat{I} L_R \) are clearly driven by the faint galaxy subsample. In the bright subsample, these observables are consistent with zero excess, which suggests that the excess correlations we found above arise because of an unaccounted-for systematic effect, such as the orientation-dependent selection bias mentioned above.

For \( L_R (\hat{T})^2 L_R \) and \(|L_R L_0^\phi|\) we find the opposite behavior: the detections are driven by the bright sample, with the faint sample being generally consistent with no excess. As we assume that the bright subsample is mostly complete, we further focus our attention only on this half of the galaxies. We further also only consider \( L_R (\hat{T})^2 L_R \) and \(|L_R L_0^\phi|\) constructed from the initial conditions smoothed with \( r = 2 h^{-1}\text{Mpc} \) that leads to the most significant detection. The detection significances are then formally \( 4.2\sigma \) and \( 4.0\sigma \), respectively.

We also note that significance of no other observable was notably boosted by restriction to the bright subsample of the galaxies.

### C. Other systematic checks

While a full study of all possible systematic effects goes beyond the scope of this work, to check for potential other systematics we perform several other tests. As motivated above, we only consider excess correlations of \( L_R (\hat{T})^2 L_R \) and \(|L_R L_0^\phi|\) built from the initial conditions smoothed with the smoothing scale \( 2 h^{-1}\text{Mpc} \). The results are shown in the top \((L_R (\hat{T})^2 L_R)\) and bottom \(|L_R L_0^\phi|\) parts of Fig. 4 and we give more details about the tests in what follows; we discuss the tests in the order in which they appear in Fig. 4. The left-most point in both parts of Fig. 4 represents our result from the previous section. In this section we do not consider the galaxies from the “faint” subsample at all, because of the issues uncovered in the previous section.

Up to this point we completely ignored the redshift space distortions (RSD). If we correct redshift of each galaxy by the same amount the ELUCID Collaboration corrected the redshift on the nearest dark matter halo, the detection significance goes down to \( 2.9\sigma \) for \( L_R (\hat{T})^2 L_R \) and \( 2.2\sigma \) for \(|L_R L_0^\phi|\). The shift in significance gives us an estimate of how big is the effect of correcting the (linear) RSDs, though one has to keep in mind there are also non-linear contributions to the RSD that can potentially contribute more (in either direction).

In the next three tests we investigated what happens when we use different determinations of galaxy shapes. Instead of the results of the exponential fit used as the default, we consider results of fits assuming the de Vaucouleurs profile of galaxies, the Stokes parameters \( Q \) and \( U \) based on weighted second moments of galaxy intensity or ellipticities based on galaxy isophotes (25 magnitudes per square arcsecond). The latter two determinations of galaxy shapes are based on galaxy images uncorrected for the point spread function (PSF). For the fits of the de Vaucouleurs profile we do not see a big change in the results. Using the Stokes parameters decreases the detection significance by \( 0.3\sigma - 0.4\sigma \). It may appear from Fig. 4 that the effect is bigger, but using the Stokes parameters shrinks the error bars due to a different distribution of \( R \) and this must be taken into account. Finally, analysis based on the isophotal quantities gives detection significance smaller by \( 0.4\sigma - 0.6\sigma \).

Next two tests investigated the assumption of galaxies as infinitely flat disks by assuming constant intrinsic flatness either \( p = 0.1 \) or \( p = 0.2 \) and correcting the galaxy inclinations according to (4). We do not find significant changes. In a similar vein, we tried “isotropising” the distribution of \( \alpha \) and \( R \) by uniformly redistributing each in the interval \([0, \pi]\) resp. \([0, 1]\) while keeping their original ordering unchanged [8]. So for example if the first galaxy had larger \( R \) than the second galaxy before the redistribution, it will have larger \( R \) after the redistribution. Again, we do not see our result notably changed.

We also repeated the analysis with galaxy shape parameters determined from the red SDSS images, to find only minute change to the results.

Finally, we further split the bright galaxy subsample into four bins in one of three different ways: either based on the galaxy redshift, or on the mass of the corresponding ELUCID halo or finally on the \( \text{expMag}_g \) magnitude. In all bins we find results consistent with the fiducial analysis, with the same sign of the excess correlation in
all bins. No clear trend is detected and the scatter between the bins serves as a rough sanity check on the size of our estimated error bars.

V. DISCUSSION

In this work we studied correlations between directions of galaxy angular momenta determined from galaxy shapes (specifically axis ratios and position angles fit from galaxy images) and various observables built from the initial conditions (density and gravitational potential), both based on SDSS data.

When considering the full galaxy sample, we found a formally statistically significant correlation between the radial component of the galaxy spins $\vec{L}_R$ and the tidal field in the vicinity of the protohalo. However, we find that this detection is driven by the faintest half of our galaxy sample and no significant excess is detected when using only the brightest half of the galaxies. This suggests that we are in fact detecting a systematic effect, possibly a galaxy-orientation-dependent selection function [53].

When we restrict our attention to the brightest half of the galaxies, where we do not expect this effect to matter, we see about 4σ hints of excess correlation in $L_R(T)^2L_R$ and $|L_R L_0^\phi|$, i.e. between the radial components of the galaxy spins $\vec{L}_R$ and the second power of the unit trace-less tidal tensor, respectively the intermediate principal axis vector of this tensor. Significance of these correlations drops below 3σ when we correct for the linear redshift space distortions. To test for further systematics, we altered the analysis in various ways and split the galaxies in bins depending on either galaxy redshift, halo mass or magnitude $\text{expMag}_g$. We did not find any other issues.

One of the checks we performed was using galaxy image axis ratios obtained from galaxy images uncorrected for the point spread function: either determined from the Stokes parameters $Q$ and $U$ as weighted second moments of galaxy intensity or from the isophotal quantities. We find that the detection significance drops by only 0.3σ–0.4σ respectively 0.4σ–0.6σ. While additive PSF systematics in fits of the de Vaucouleurs profile to SDSS galaxy images are important for studies of intrinsic alignments [54], this result suggests that such effect is not dominant in our cross-correlation study at current sensitivities.

One must keep in mind these systematic checks are not exhaustive and our results can still be contaminated by systematics. For example, based on our analysis we suspect that the SDSS galaxy sample is missing faint, edge-on galaxies. As a consequence, masses of galaxy groups in regions where the tidal field orientation leads to preferentially edge-on galaxies are expected to be underestimated by ELUCID. It is unclear to what extent such a bias affects the correlations we study without per-
FIG. 4. Investigating systematic effects: Comparing excess correlations for $L_R(T)^2 L_R$ (top) and $|L_R \hat{L}_0|$ (bottom), both smoothed with $r = 2h^{-1}$Mpc, for the fiducial analysis (leftmost point, also the gray band) and various changes to the analysis. We show how the results change when we correct for redshift space distortions (RSD), when we use other determinations of the galaxy shape (fits of de Vaucouleurs profile, Stokes parameters $Q$ and $U$ or isophotal ellipticities), when we consider intrinsic flatness with $p$ of 0.1 or 0.2, when we redistribute the axis ratio and position angle to form a uniform distribution, or when we use red filter images as the baseline. The last twelve points show results after splitting the data into four bins in either redshift, halo mass or magnitude expMag_g (bin 1 contains the closest / lightest / brightest galaxies). Dashed line represents no excess correlation.
forming an exhaustive, dedicated study that goes beyond the scope of this work. To fully understand this and other systematics, it would be necessary to start with a galaxy simulation that includes galaxy shapes, create a galaxy catalog, use it to reconstruct the initial conditions similarly to what ELUCID did and only then perform the analysis of this work. To name just a few other potential systematics, shape determination from the SDSS galaxy image can be biased for the edge-on galaxies and the same might in principle be true also for the redshift determination. Again, full determination of how these effects affect our results seems to require a separate study.

Despite these worries about additional systematic effects, we point out that the two correlations our analysis picks out as the most promising are the two correlations expected from the tidal torque theory arguments [8]. Tidal torque theory predicts preferred alignment of the galaxy spin with the intermediate axis of the tidal tensor, which translates into a deficit correlation in \(|\mathbf{L}R|''|L_R|''|L_0|''|\), which both agree with our results (Fig. 3).

We find that excess signals are mutually compatible when using either \(\hat{L}_R\) or \(\hat{T}_R\), galaxy spin vectors parallel and tangential to the line of sight. The error bars are always larger for correlations including \(\hat{T}_R\), which is understandable given that the position angle \(\alpha\) acts as an additional source of uncertainty. We also find that observables built from the tidal tensor \(\hat{T}\) are more promising than those built from \(\hat{I}\), the second derivatives of the density field. In hindsight, this is easy to understand, because from the Poisson equation we see that relative to \(\hat{T}\), the \(\hat{I}\) field puts higher weight on the small scale data, which are noisier in the reconstruction.

Overall, given SDSS catalog of galaxy shapes and initial conditions reconstructed from SDSS data, we are not able to find a statistically significant correlation between the two. Beyond the systematics study mentioned in the discussion, one area of future study is comparing reconstruction of initial conditions in a simulation, once with and once without galaxy spin data, to study the potential information gain. It will also be interesting to see how our analysis improves with the extended galaxy catalogs from DESI and potentially better reconstruction. Our work picks two observables that such studies should focus on.

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