Correlations between galaxy angular momenta and initial conditions

Pavel Motloch

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

With Ue-Li Pen, Hao-Ran Yu

INTRODUCTION

Motivation

- Galaxies have an “extra” degree of freedom: angular momentum

- Can we use it to improve reconstruction of the initial conditions in the local Universe?

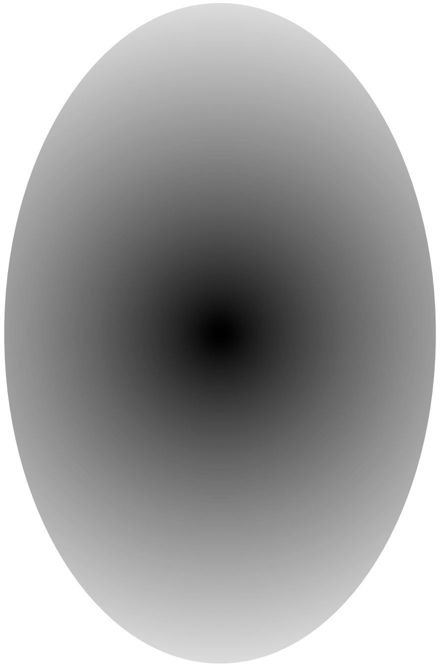
Motivation

- Approach #1: Study in simulations
  - Hao-Ran’s talk tomorrow
- Approach #2: Head first into the data
  - This talk

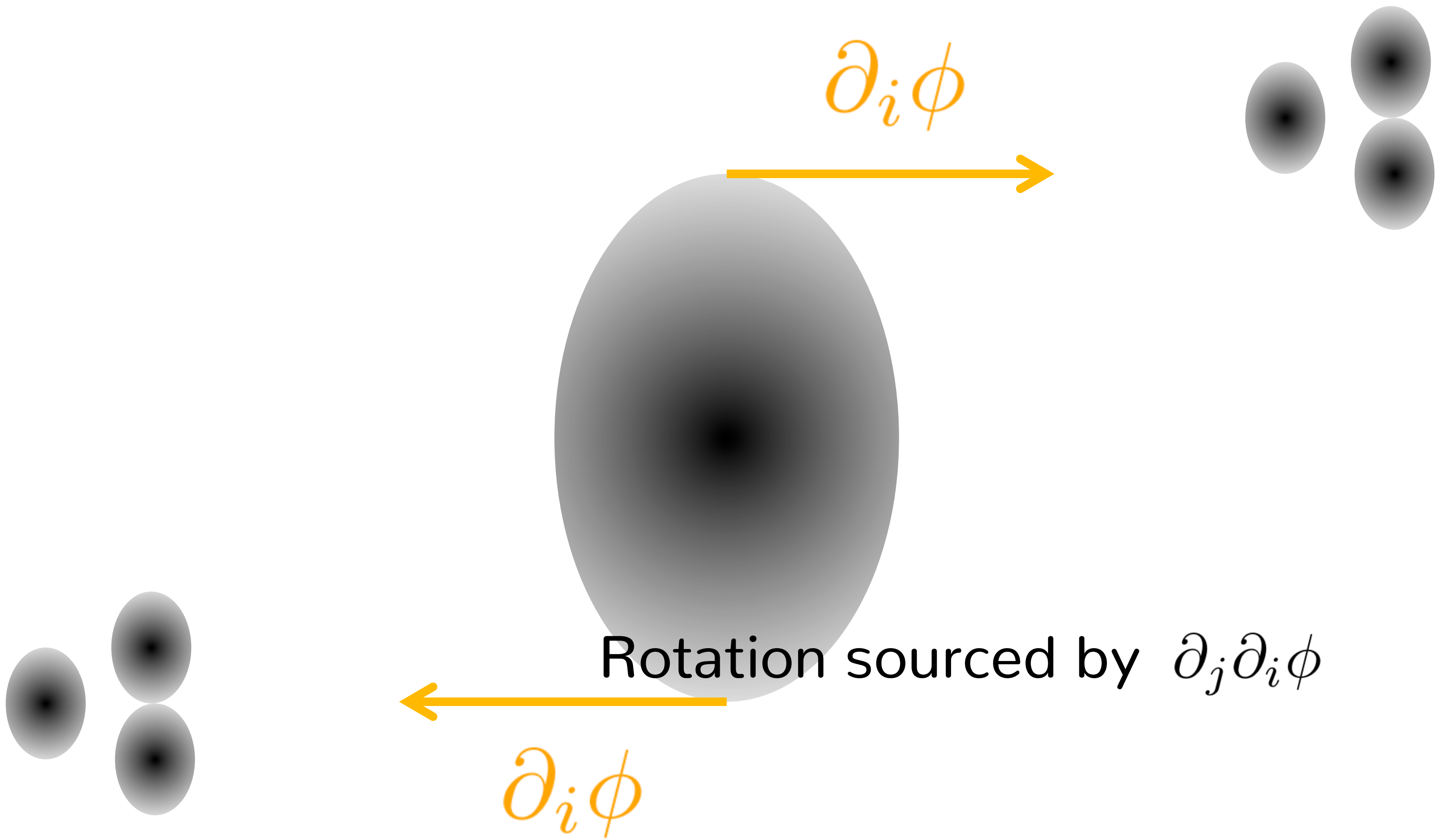
Motivation

- Can we use current data to find any relation between galaxy angular momenta and initial conditions? Is there any imprint of ICs?
- Potentially exciting – probing 1-2 h^{-1} Mpc
- DESI will deliver lots of spectroscopic gal.

Overdensity under gravity



Torque



$\partial_i\phi$
Rotation sourced by $\partial_j\partial_i\phi$
$\partial_i\phi$

Tidal Torque Theory

- S. White 1984, Porciani+ 2002, …

$$L_i \propto \epsilon_{ijk} I_{jm} \partial_m \partial_k \phi$$

Halo spin

Protohalo moment of inertia

Tidal field

Complications

- Late time nonlinearities, galaxies / haloes

Angular momentum direction only

- Simpler to measure
- Simulations show it is a robust probe
- Shorthand: spin

Overall strategy

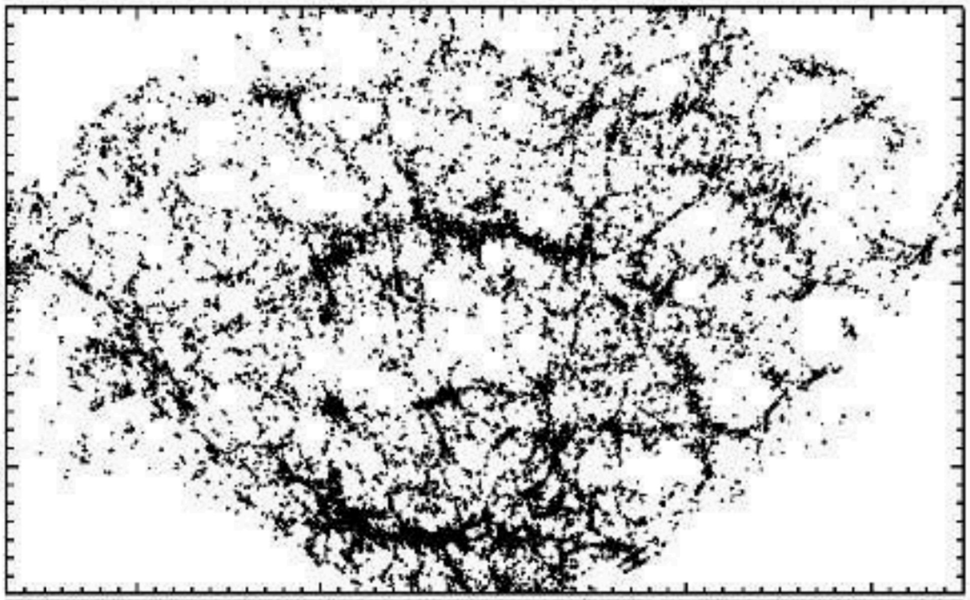
- Take ICs obtained from galaxy positions
- Derive an observable (tidal field, …)
- Correlate with galaxy spin
- Compare with expectations assuming no correlation

RECONSTRUCTED INITIAL CONDITIONS

Reconstructing IC

- Project ELUCID (Wang+ 2016)

- Use SDSS galaxy positions to reconstruct initial density field in the SDSS volume



Reconstructing IC

- Find galaxy groups in SDSS
- Use DM halo profiles to get $z = 0$ density field
- Iterate using Hamiltonian Monte Carlo:
  - Pick initial conditions
  - Evolve forward in time
  - Compare with data, find best match

Reconstructing IC

- Galaxies with redshift 0.01 – 0.12
- Only retain haloes above 10^{12} solar masses
- Before comparison, fields smoothed with Gaussian filter (4 h^{-1} Mpc)

CORRELATIONS WITH GALAXY SHAPES

arXiv 2111.12578

Spins from shapes of spiral galaxies

- Thin circular disk approximation – angular momentum perpendicular to the disk

Pen + 2000, Lee+ 2007

Spins from shapes of spiral galaxies

- Two components – radial (along the line of sight) and tangential

$$\vec{L} = \vec{L}_R + \vec{L}_T$$

- Unit vector

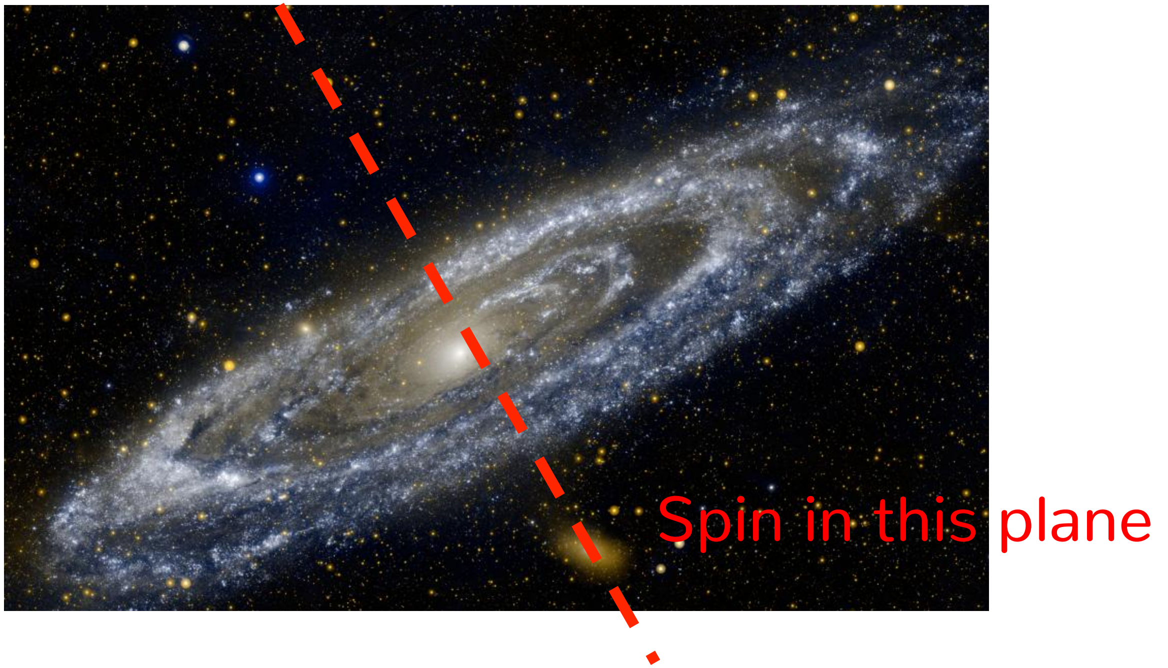
Spins from shapes of spiral galaxies

- Size of the radial component proportional to the axis ratio of the image

$$\left|\vec{L}_R\right| = \frac{b}{a}$$

Spins from shapes of spiral galaxies

- Direction of the tangential component determined by the position angle (along the minor axis)

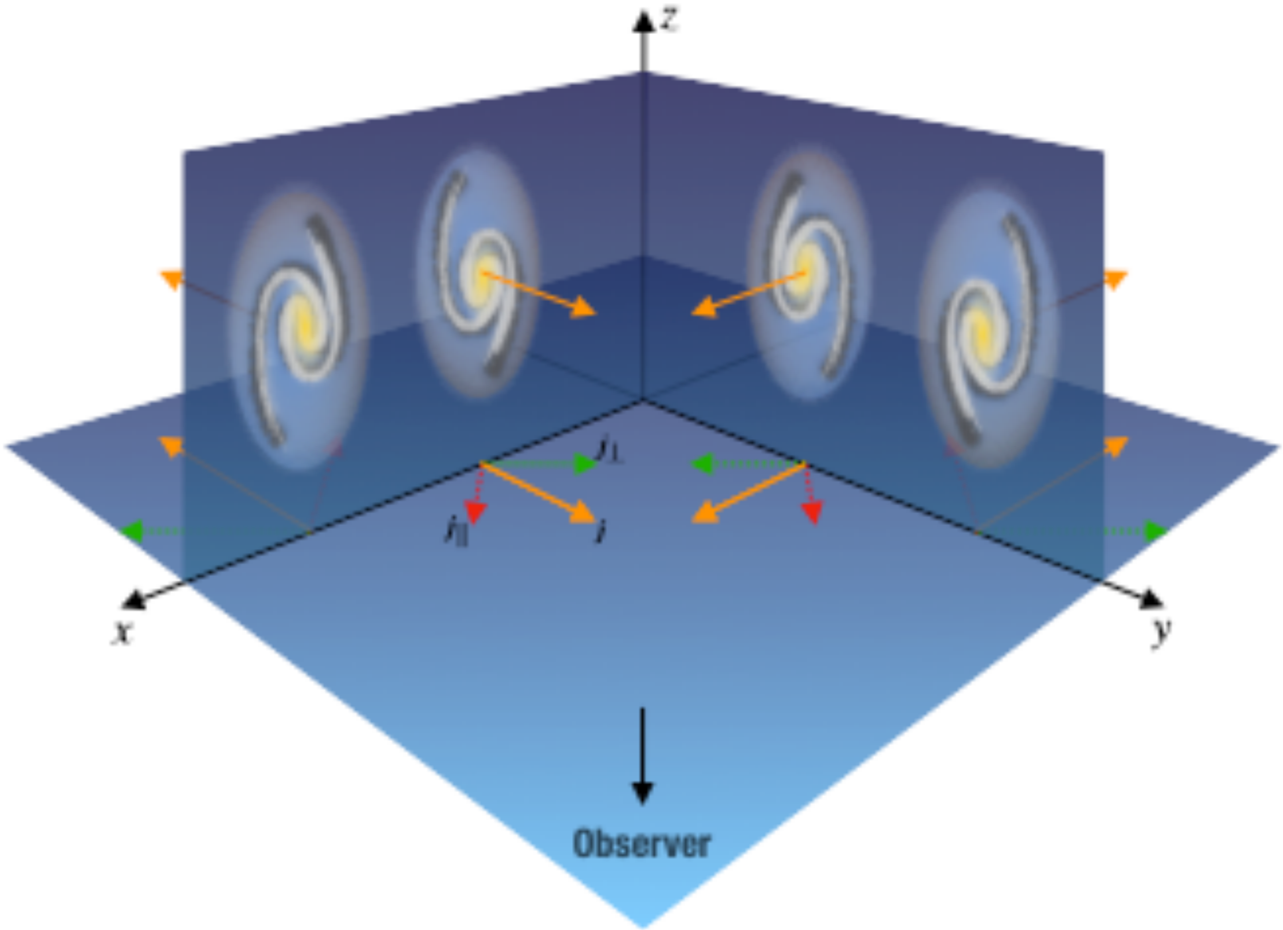


Four-fold degeneracy

- From the shape alone, we can not determine the sign of neither the radial, nor the tangential component of spin

- Our observables have to honor this

Four-fold degeneracy



Data

- SDSS spectroscopic galaxies
- Shape: de Vaucouleurs profile
- In volume with known ICs
- In haloes above 10^{12} solar masses
- Remaining ~ 50k galaxies

How to find spirals - Galaxy Zoo

Tidal field tensor

- Second derivative of gravitational potential, with trace subtracted and normalized

$$T_{ij} = \partial_{ij} \phi^{r}_{\mathrm{ini}}$$

← Smoothing

$$\tilde{T}_{ij} = T_{ij} - \frac{\delta_{ij}}{3} \sum_{k} T_{kk}$$

$$\hat{T}_{ij} = \frac{\tilde{T}_{ij}}{\sqrt{\sum_{ij} \tilde{T}_{ij}^2}}$$

Tidal field tensor

- In eigen-coordinates

$$\lambda_- \leq \lambda_0 \leq \lambda_+$$

$$\hat{T}_{ij} = \begin{pmatrix} \lambda_+ & 0 & 0 \\ 0 & \lambda_0 & 0 \\ 0 & 0 & \lambda_- \end{pmatrix}$$

- Where

$$\begin{aligned} \lambda_- + \lambda_0 + \lambda_+ &= 0 \\ \lambda_-^2 + \lambda_0^2 + \lambda_+^2 &= 1 \end{aligned}$$

Lagrangian coordinates

- Have to undo the galaxy displacement – use the reference simulation to move between the Eulerian and Lagrangian coordinates

Correlation

- For each galaxy calculate

$$L_R \hat{T} L_R \equiv \sum_{ij} L_{R,i} \hat{T}_{ij} L_{R,j}$$

$$L_T \hat{T} L_T \equiv \sum_{ij} L_{T,i} \hat{T}_{ij} L_{T,j}$$

- Average over the galaxies
- Notice: No sign ambiguity

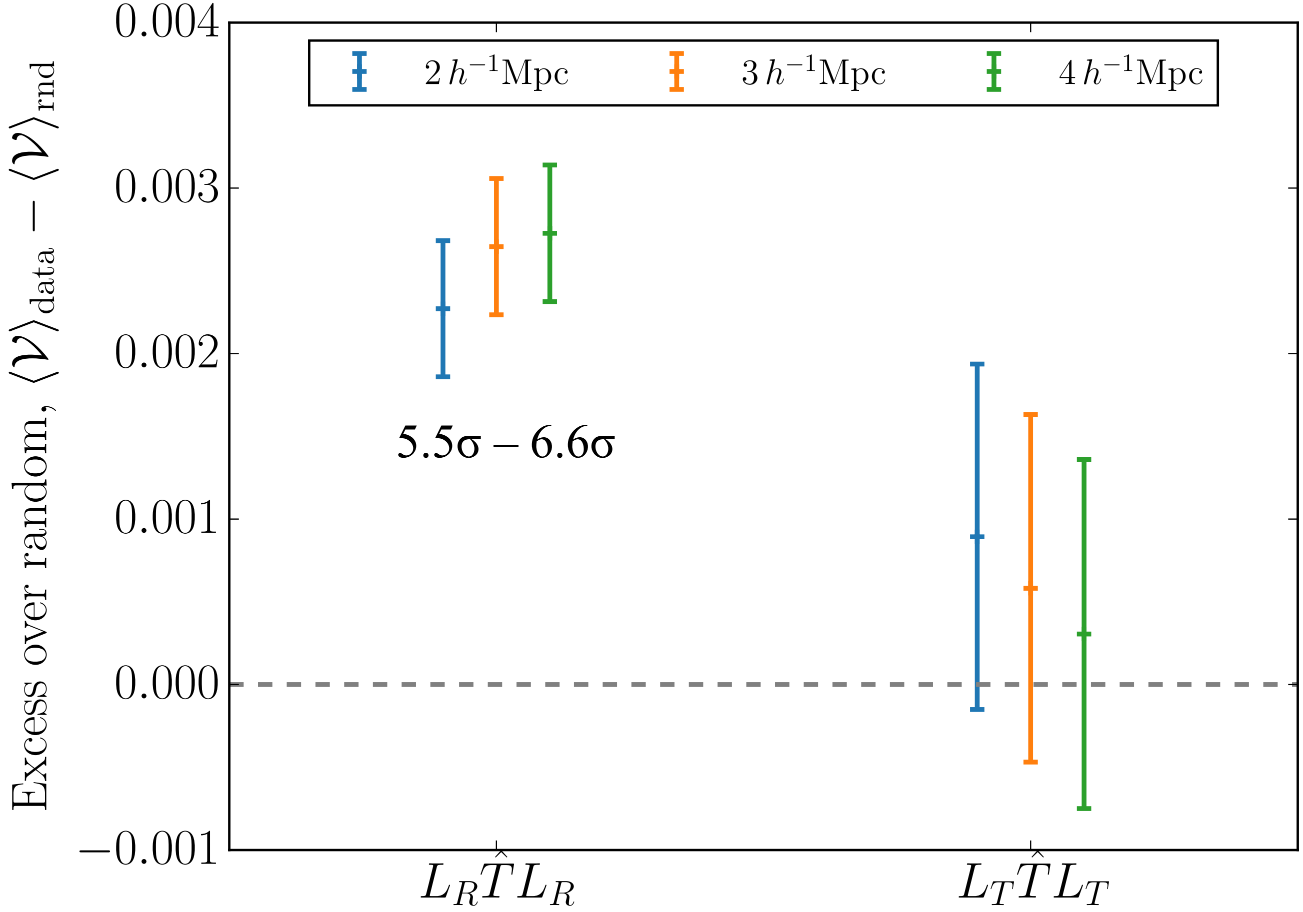
Statistical significance

- We randomly shuffle the position angles and axis ratios among galaxies (many times) and calculate mean and standard deviation

- Significance

$$S = \frac{|\langle V \rangle_{\mathrm{data}} - \langle V \rangle_{\mathrm{rnd}}|}{\sigma_{\langle V \rangle}}$$

Results



0.004
0.003
0.002
0.001
0.000
−0.001
Excess over random, $\langle\mathcal{V}\rangle_{\rm data} - \langle\mathcal{V}\rangle_{\rm rnd}$
$2\,h^{-1}$Mpc
$3\,h^{-1}$Mpc
$4\,h^{-1}$Mpc
5.5σ – 6.6σ
$L_R\hat{T}L_R$
$L_T\hat{T}L_T$

Somewhat unexpected

- Expected to vanish in TTT as under

$$\phi \to -\phi$$

we have

$$\begin{aligned} L &\to L \\ \hat{T} &\to -\hat{T} \end{aligned}$$

Simpler statement

- We found excess $L_R \hat{T} L_R$
- When the radial-radial component of $\hat{T}$ is large, $|L_R|$ is large and vice versa
- Now:
  - $|L_R|$ is the axis ratio
  - Radial-radial component of $\hat{T}$ tells us about tidal field orientation

Simpler statement

- Galaxies tend to be preferentially face on when the major axis of the initial tidal field (λ_+) is aligned with the line of sight

- Similarly for edge on / minor axis

More observables

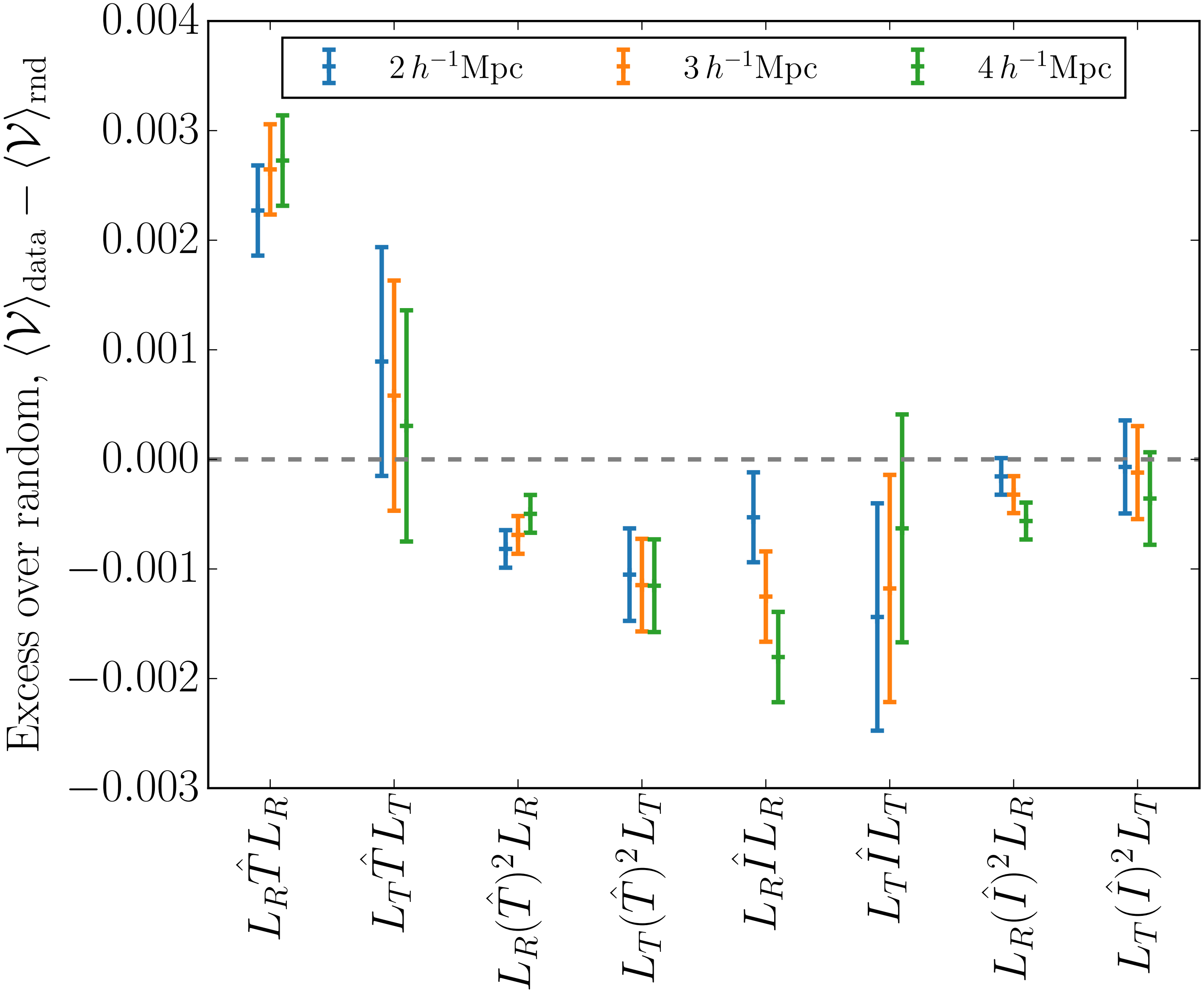
- At the beginning of the study not clear which observable to choose – we tried several

More observables

- Second power of $\hat{T}$ (see model Lee+ 2000)
- First and second power of $\hat{I}$, which is similarly constructed from the initial density field

$$
\begin{aligned}
I_{ij} &= \partial_{ij}\rho^r_{\rm ini} \\
\tilde{I}_{ij} &= I_{ij} - \frac{\delta_{ij}}{3}\sum_k I_{kk} \\
\hat{I}_{ij} &= \frac{\tilde{I}_{ij}}{\sqrt{\sum_{ij}\tilde{I}^2_{ij}}}
\end{aligned}
$$

More observables



Vector observables

- Recall TTT

$$L_i \propto \epsilon_{ijk} I_{jm} \partial_m \partial_k \phi$$

- Very good approximation of the direction

$$L_i \approx L_i^{\rm IC} \equiv \epsilon_{ijk} \partial_j \partial_m \rho \partial_m \partial_k \phi$$

Vector observables

- Look at

$$\left|L_R \cdot L^{\mathrm{IC}}\right|, \left|L_T \cdot L^{\mathrm{IC}}\right|$$

- Absolute value because of the 4-fold degener.
- Average over the galaxies, compare with statistics of shuffled catalogs

Vector observables

- Finally: theoretical arguments for spins correlated with intermediate axes of $\hat{T}$, $\hat{I}$ (Lee+ 2000)

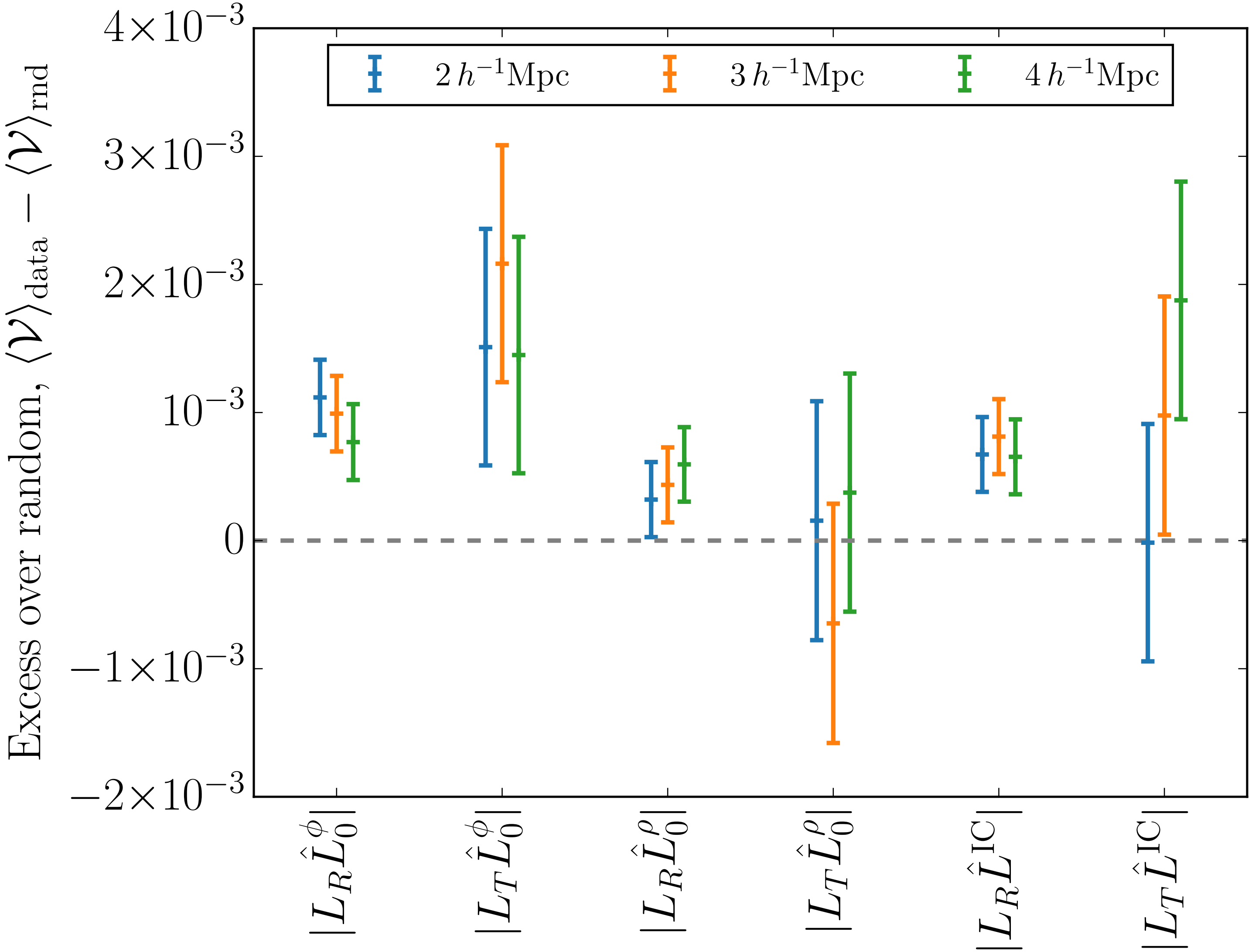
$$L_i \propto \epsilon_{ijk} I_{jm} \partial_m \partial_k \phi$$

$$\begin{aligned} L_+ &\propto (\lambda_0 - \lambda_-) I_{0-} \\ L_0 &\propto (\lambda_+ - \lambda_-) I_{+-} \\ L_- &\propto (\lambda_+ - \lambda_0) I_{+0} \end{aligned}$$

$$\hat{T}_{ij} = \begin{pmatrix} \lambda_+ & 0 & 0 \\ 0 & \lambda_0 & 0 \\ 0 & 0 & \lambda_- \end{pmatrix}$$

- Again, average abs. value of scalar product

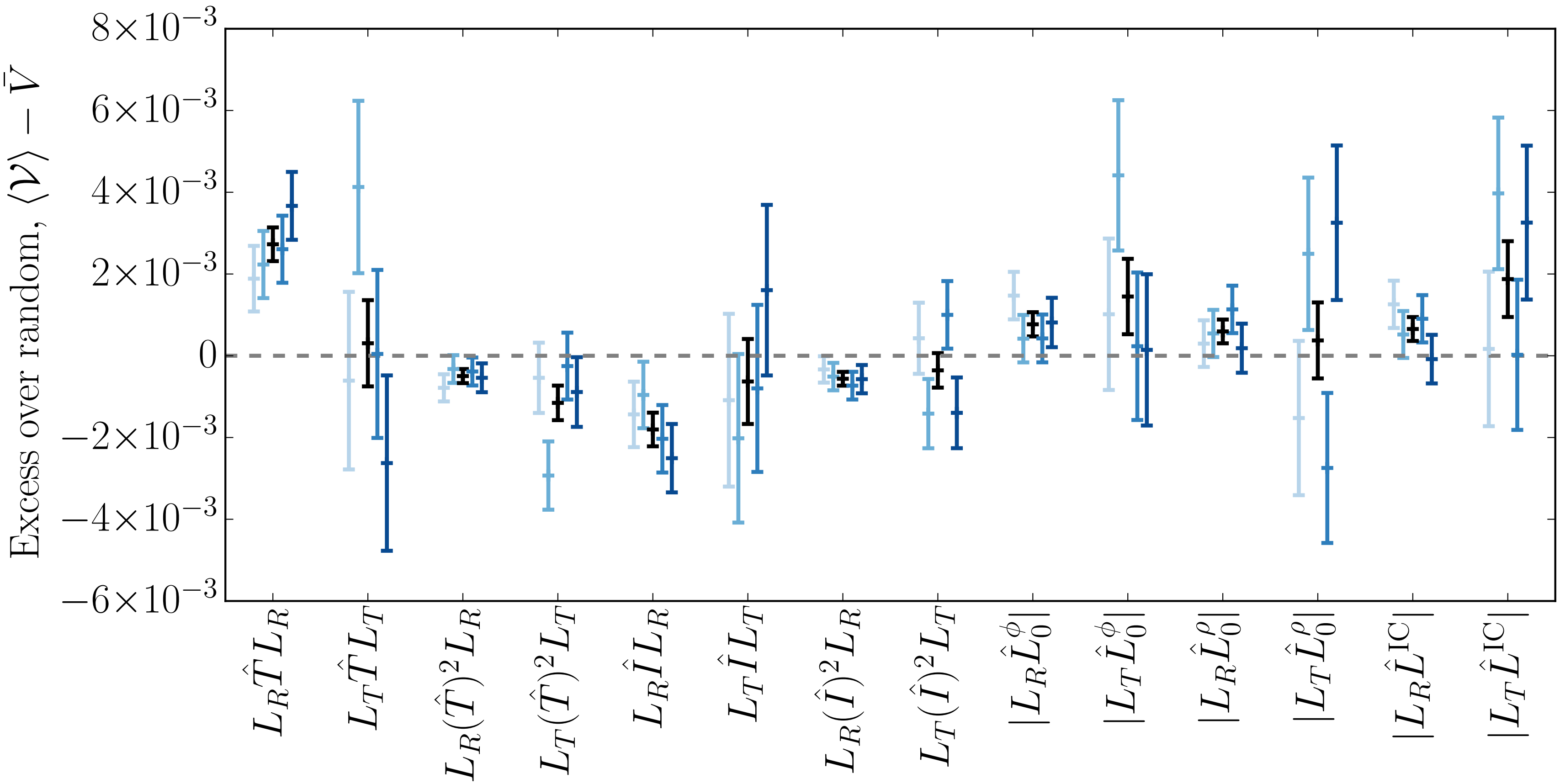
Vector observables



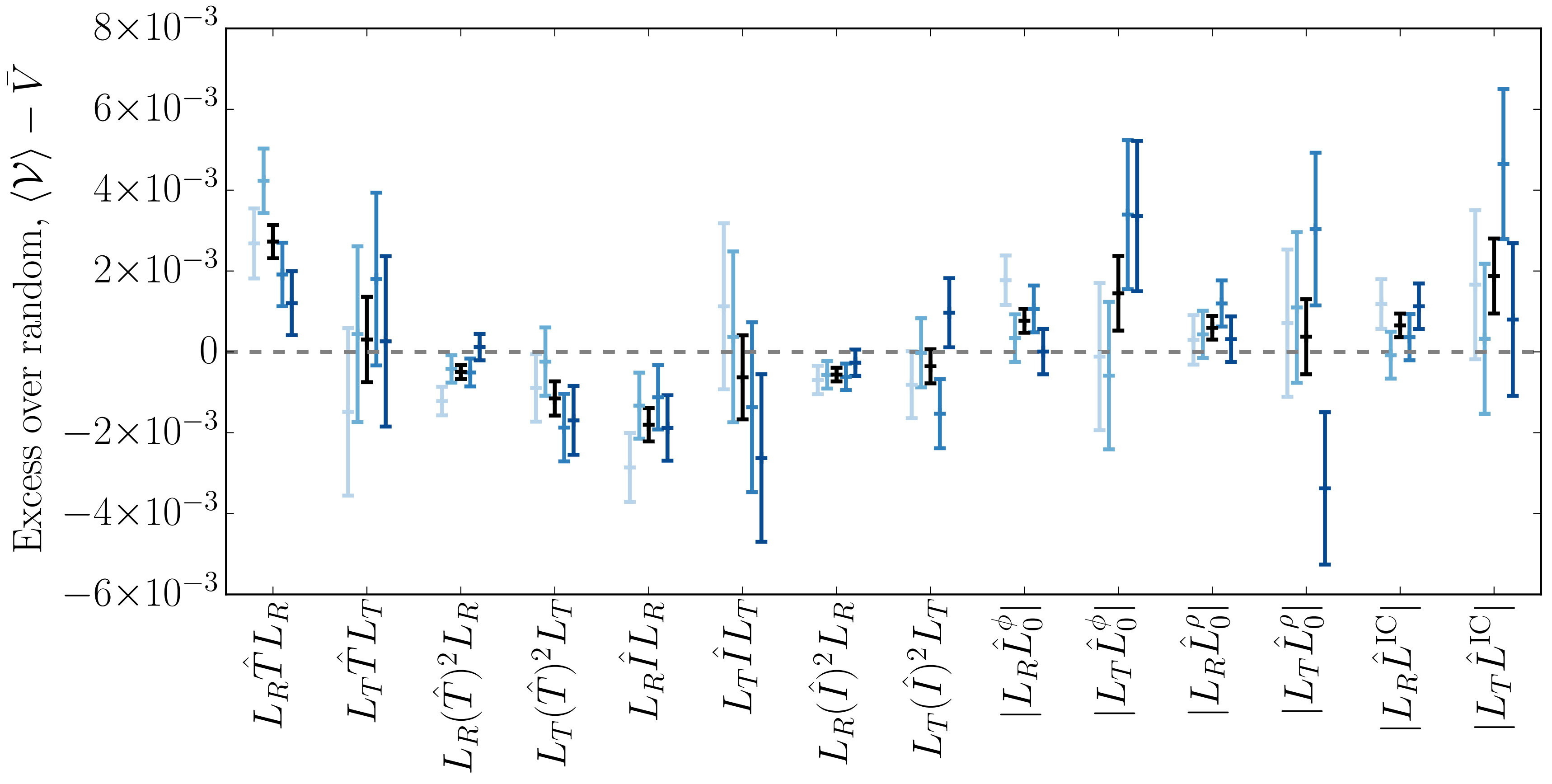
Systematics checks

- Intrinsic flatness correction
- SDSS filters (red / green)
- Exponential fit instead of de Vaucouleurs
  - Significance of $\hat{T}$ correlation drops to 4.9 – 5.7σ

Systematics – DM halo mass



Systematics - redshift



Overall detection significance

- We looked at 42 observables
  - 3 smoothing scales
  - 2 spin components (radial / tangential)
  - 7 functions of IC
- Global significance: 5.2σ
  - after considering correlations between observables

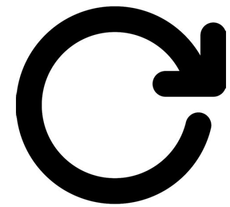
Why not higher significance?

- Is it because the ELUCID ICs are not well determined at the scales that matter or because correlation erased by late time evolution, …?

CORRELATIONS WITH OTHER PROXIES

arXiv 2003.04800

Clockwise / anticlockwise



- This one: Angular momentum into the plane
- Determine the sign of L_R (1 bit)

Galaxy Zoo

GALAXY ZOO.org
Welcome
Home
The Science
How to Take Part
Galaxy Analysis
Forum
Press & News
FAQ
Links
Contact Us
Login
Register
Galaxy Tutorial
Galaxy Analysis
Galaxy Analysis
Welcome to Galaxy Zoo's view of the Universe. If you're here you should already have seen the Tutorial, but feel free to go and remind yourself. There's no need to agonise for too long over any one image, just make your best guess in each case.
Galaxy Ref:
588010880371851294
Choose the Galaxy Profile by clicking the buttons below
CLOCK
ANTI
EDGE ON/ UNCLEAR
SPIRAL GALAXY
ELLIPTICAL GALAXY
STAR / DON'T KNOW
MERGERS
Show Grid Overlay on the next Image

Quantifying correlation

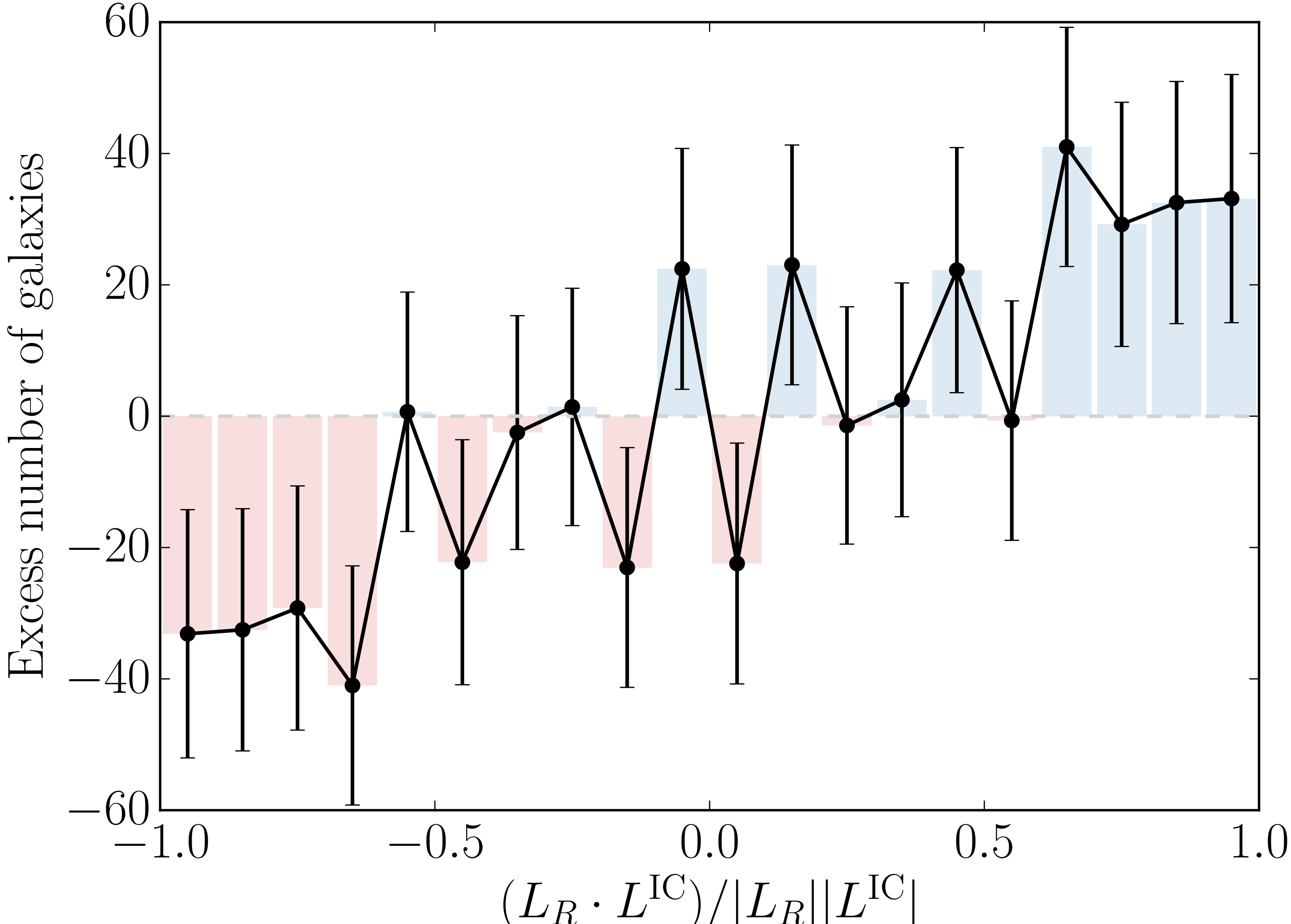
- Scalar product of unit vectors

$$\mu = \left\langle \frac{\vec{L}_R \cdot \vec{L}^{\mathrm{IC}}}{\left|\vec{L}_R\right| \left|\vec{L}^{\mathrm{IC}}\right|} \right\rangle_{\mathrm{data}}$$

- Reminder:

$$L_i \approx L_i^{\mathrm{IC}} \equiv \epsilon_{ijk} \partial_j \partial_m \rho \partial_m \partial_k \phi$$

Results



Anti-aligned spins

Aligned spins

Results

- We find excess

$$\mu_{\rm exc} = (1.34 \pm 0.42) \times 10^{-2}$$

- So: CW/ACW also contains info about the initial conditions

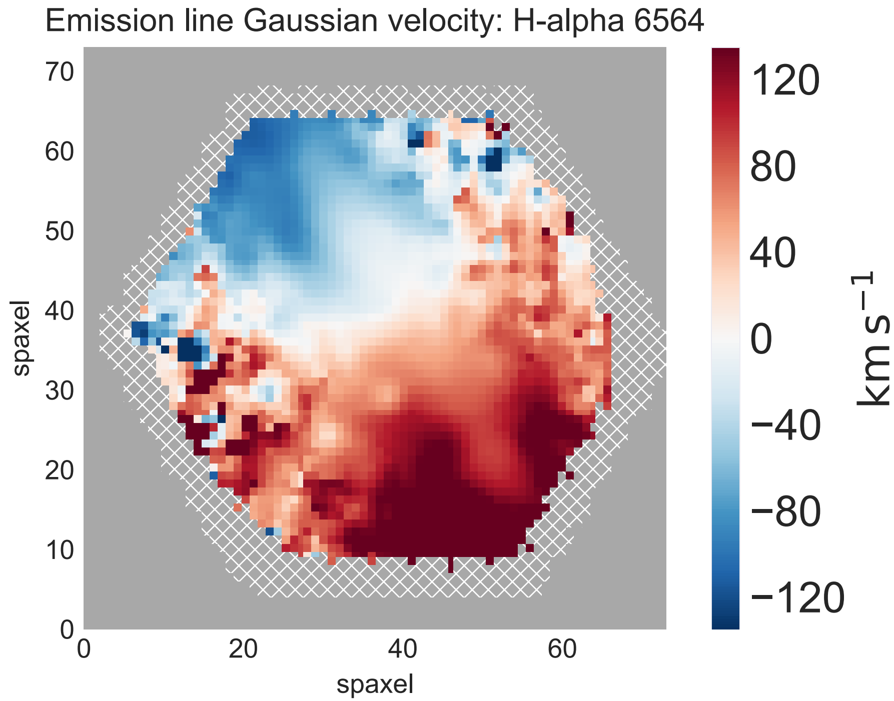
- Expected to be more robust wrt systematics

Beyond Galaxy Zoo

- Train machine learning to determine the winding of the spiral arms automatically

Integral Field Spectroscopy

- MANGA, SAMI surveys



Results

- Correlation weaker than for CW/ACW, but does not decrease the detection significance much as the galaxy sample is small

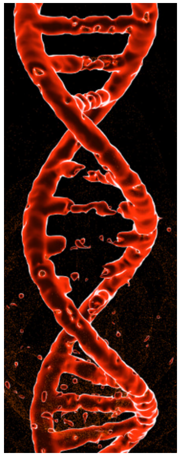
CHIRALITY VIOLATIONS

arXiv 2111.12590

Chirality

- Left and right chirality

DNA



Mirror image

- Homogeneous, isotropic Universe can be chiral

Chirality in physics

- Weak interactions are chiral
- Gravity? Inflation?

$$\mathcal{L}_{int} = f(\Phi) R^{\lambda}{}_{\sigma\mu\nu} \tilde{R}_{\lambda}{}^{\sigma\mu\nu}$$

- Imprint in the LSS?

Chiral correlations of galaxy spins

- We have a vector field L^{IC} constructed from initial conditions
- Separate into right and left helical components
- Check whether galaxy spins (CW/ACW) correlate with both equally

Helicity separation

- In Fourier space

$$\tilde{L}^{\mathrm{IC}}_{\alpha,a}(\mathbf{k}) \equiv \sum_b \mathbb{P}^{\alpha}_{ab}(\mathbf{k})\tilde{L}^{\mathrm{IC}}_{b}(\mathbf{k}), \quad \alpha \in \{\mathrm{left}, \mathrm{right}\}$$

- Where

$$\mathbb{P}^{\alpha}_{ab}(\mathbf{k}) = \frac{1}{2}\left[\left(\delta_{ab} - \hat{k}_a\hat{k}_b\right) \pm i\sum_c \epsilon_{abc}\hat{k}_c\right]$$

Results

- Define

$$\mu_\alpha = \left\langle \frac{\vec{L}_R \cdot \vec{L}_\alpha^{\mathrm{IC}}}{\left|\vec{L}_R\right| \left|\vec{L}_\alpha^{\mathrm{IC}}\right|} \right\rangle_{\mathrm{data}} \qquad \alpha \in \{\mathrm{left}, \mathrm{right}\}$$

Results

- Then

$$\mu_{\text{left}} = (0.41 \pm 0.53) \times 10^{-2}$$
$$\mu_{\text{right}} = (1.99 \pm 0.53) \times 10^{-2}$$

$$\mu_{\text{left}} - \mu_{\text{right}} = (-1.58 \pm 0.75) \times 10^{-2}$$

Results

- Data consistent with no parity violation
- Vanishing correlation with right helical component ruled out at 3.8σ
- The other maximally chirality violating case still allowed

More general

- Search for parity violations in general 4PTF (Cahn+ 2021)

SUMMARY

Summary

- We found that galaxy shapes correlate with initial tidal field.
- There is also IC information in the clockwise/ anticlockwise orientation of spiral galaxies
- We used galaxy spins to study chiral violations

THANK YOU