The impact of Cosmic Web on Galactic spin

Can we predict the spin of galaxies on the cosmic web from first principles?



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Outline

• How discs build up from persistent cosmic web?

- What is the statistics of spin orientation?
- Why galaxies's spin flip relative to filament? Why the transition mass? Lagrangian view

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Why do we care?

• Galaxy formation is not a ID manifold (aka assembly bias)

- AM stratification drives morphology
- Weak lensing

Elliptical galaxy

Are want



Spiral galaxy



Different Angular momentum stratification

The Virtual (hydrodynamical) universe z=99.00 $t_{\rm dyn} \sim 1/\sqrt{\rho}$ log density

2 kpc

Agertz et al. (2009)

we see steady cold flows + recurrent disk reformation LSS drives secondary infall & SPIN ALIGNMENT



Disks form along filaments embedded in walls with spin // to filament



#

DM

Gas

Gas tracing particle: follow shocks

Typical setting: one wall one filament

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in fact 8 corkscrew/ sub-filament...

loci of 3rd shock

Note the high **helicity** of flow: AM rich quasi-**polar** accretion

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Explain this !

Disks form because LSS are large (dynamically young) and (partially) an-isotropic : they induce persistent angular momentum advection of cold gas along filaments which stratifies accordingly so as to (re)build discs continuously.

This is the raison d'être of cosmic web :-)

Typically one wall one filament: dynamical implication?

HINT: initial galactic infall is AM rich & quasi polar in the CGM



spin // to embedding filament

Tidal Torque Theory in one cartoon

Can we understand where spin and vorticity alignments come from?

-usual tidal torque theory

$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$

inertia tensor of halo I_{ij}

YES! via conditional TTT subject to PBS

Hoyle 56, Peebles 69, Doroshkevich 70, White 84).

Et Voilà !



Peak background split in 3D





Does this anisotropic biassing have a dynamical signature? yes! in term of spin!

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Orientation of the spins w.r.t the filaments

Horizon 4Pi:

DM only 2 Gpc/h periodic box 4096³ DM part. 43 million dark halos at z=0

(Teyssier et al, 2009)

10 000 000 hrs CPU



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Excess probability of alignment between the spins and their host filament



See also: Aragon-Calvo+07, Hahn+07, Sousbie+08, Paz+08, Zhang+09, Libeskind+13, Aragon-Calvo 13, Dubois+14

Explain transition mass?

Transition mass versus redshift:





Explain transition mass?

Transition mass versus redshift: what's wrong???





Tidal torque theory with a peak background split near a **saddle**



The Lagrangian view of spin/LSS connection The Idea

walls/filament/peak locally bias differentially tidal and inertia tensor: spin alignment reflect this in TTT

The picture

Geometry of spin near saddle: point reflection symmetric distribution, 1/10 of 'naive size'

The Maths

2D theory

3D theory

Very simple ab initio prediction for mass transition

How to sum up wall & filaments in one point process?

flattened saddle point

BBKS like theory possible for spin

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How to sum up wall & filaments in one point process?

flattened saddle point

TTT in vicinity of filament?

BBKS like theory possible for spin

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Can we understand where spin and vorticity alignments come from?



-anisotropy of the cosmic web: surrounding of a saddle point with typical geometry



Tidal/Inertia mis-alignment



Tidal/Inertia mis-alignment



spin wall -filament



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Spin structure Flattened filament AM vectors near Saddle $L_k = \varepsilon_{ijk} I_{li} T_{lj}$ $\approx \varepsilon_{ijk} H_{li} T_{lj}$ Zel'dovich flow KIAS Nov 1st 2016






Does it work with log-Gaussian Random Fields?

point reflection symmetry for realistic sets of saddles from log GRF



Figure 11. Alignment of 'spin' along e_z in 2D as a function of quadrant rank, clockwise. As expected, from one quadrant to the next, the spin is flipping sign.



Tuesday, 1November, 16

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© The Maths

© 2D theory

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TT@ saddle?

the Gaussain joint PDF of the derivatives of the field, $\mathbf{X} = \{x_{ij}, x_{ijk}, x_{ijkl}\}$ and $\mathbf{Y} = \{y_{ij}, y_{ijk}, y_{ijkl}\}$ in two given locations (\mathbf{r}_x and \mathbf{r}_y separated by a distance $r = |\mathbf{r}_x - \mathbf{r}_y|$) obeys

$$\operatorname{PDF}(\mathbf{X}, \mathbf{Y}) = \frac{1}{\det |2\pi \mathbf{C}|^{1/2}} \times$$

$$\exp\left(-\frac{1}{2}\begin{bmatrix}\mathbf{X}\\\mathbf{Y}\end{bmatrix}^{\mathrm{T}}\cdot\begin{bmatrix}\mathbf{C}_{0}&\mathbf{C}_{\gamma}\\\mathbf{C}_{\gamma}^{\mathrm{T}}&\mathbf{C}_{0}\end{bmatrix}^{-1}\cdot\begin{bmatrix}\mathbf{X}\\\mathbf{Y}\end{bmatrix}\right),\quad(A2)$$
subject to the "saddle" constraints (2D)
$$\overset{height}{x_{0,2}+x_{2,0}=\nu,\ x_{1,2}+x_{3,0}=0,\ x_{0,3}+x_{2,1}=0,\ ^{zero\ gradient}}\kappa\cos(2\theta)=\frac{1}{2}\left(x_{4,0}-x_{0,4}\right),\ \kappa\sin(2\theta)=-x_{1,3}-x_{3,1}.$$

$$\overset{parametrized\ curvatu}{x_{1,2}+x_{2,0}=\mu}$$

re

Define the spin at point \mathbf{r}_y along the z direction as the anti-symmetric contraction of the de-traced tidal field and hessian: (2D)

$$L(\mathbf{r}_{y}) = \varepsilon_{ij} \overline{y}_{il} \overline{y}_{jmml} = (y_{2,0} - y_{0,2}) (y_{1,3} + y_{3,1}) + \frac{y_{1,1}}{2} (y_{0,4} - y_{4,0}) - \frac{y_{1,1}}{2} (y_{4,0} - y_{0,4}) .$$
(A3)

It is then fairly straightforward to compute the corresponding constrained expectation, $\langle L|\mathrm{pk}\rangle$, for L as

$$L_z(r,\theta,\kappa,\nu) = \int L(\mathbf{Y}) PDF(\mathbf{X},\mathbf{Y}|pk) d\mathbf{X} d\mathbf{Y}.$$
 (A4)

e.g. for n=-2 Incredibly simple prediction !

$$L_{z} = \kappa \frac{r^{4} \sin(2\theta)}{144} e^{-\frac{r^{2}}{2}} \left(\sqrt{6}\kappa \left(r^{2} - 4\right) \cos(2\theta) + 6\nu\right)$$
asymmetry
finite extent
anti-ymmetry

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e.g. for n=-2 Incredibly simple prediction ! $\int_{25}^{25} \int_{0.325}^{0.325} \int_{0.35}^{0.325} \int_{0.35}^{0.3$









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walls/filament/peak locally bias differentially tidal and inertia tensor: spin alignment reflect this in TTT

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Geometry of spin near saddle: point reflection symmetric distribution, 1/10 of 'naive size'

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- 2D theory
- 3D theory

Very simple ab initio prediction for mass transition

In order to compute the spin distribution, the formalism developed in Section 2 is easily extended to 3D. A critical (including saddle condition) point constraint is imposed. The resulting mean density field subject to that constraint becomes (in units of σ_2):

$$\delta(\mathbf{r},\kappa,I_1,\nu|\text{ext}) = \frac{I_1(\xi_{\phi\delta}^{\Delta\Delta} + \gamma\xi_{\phi\phi}^{\Delta\Delta})}{1-\gamma^2} + \frac{\nu(\xi_{\phi\phi}^{\Delta\Delta} + \gamma\xi_{\phi\delta}^{\Delta\Delta})}{1-\gamma^2} + \frac{15}{2} \left(\mathbf{\hat{r}}^{\mathrm{T}} \cdot \overline{\mathbf{H}} \cdot \mathbf{\hat{r}}\right) \xi_{\phi\delta}^{\Delta+}, \quad (3.1)$$

where again $\overline{\mathbf{H}}$ is the detraced Hessian of the density and $\hat{\mathbf{r}} = \mathbf{r}/r$ and we define in 3D $\xi_{\phi x}^{\Delta +} \approx \xi_{\phi \delta}^{\Delta +} = \langle \Delta \delta, \phi^+ \rangle$, with $\phi^+ = \phi_{11} - (\phi_{22} + \phi_{33})/2$. Note that $\hat{\mathbf{r}}^{\mathrm{T}} \cdot \overline{\mathbf{H}} \cdot \hat{\mathbf{r}}$ is a scalar quantity defined explicitly as $\hat{r}_i \overline{H}_{ij} \hat{r}_j$. As in 2D, the expected spin can also be computed. In 3D, the spin is a vector, which components are given by $L_i = \varepsilon_{ijk} \delta_{kl} \phi_{lj}$, with $\boldsymbol{\epsilon}$ the rank 3 Levi Civita tensor. It is found to be orthogonal to the separation and can be written as the sum of two terms

$$\mathbf{L}(\mathbf{r},\kappa,I_1,\nu|\mathrm{ext}) = -15\left(\mathbf{L}^{(1)}(r) + \mathbf{L}^{(2)}(\mathbf{r})\right) \cdot \left(\hat{\mathbf{r}} \cdot \boldsymbol{\epsilon} \cdot \overline{\mathbf{H}} \cdot \hat{\mathbf{r}}\right), \qquad (3.2)$$

where $\mathbf{L}^{(1)}$ depends on height, ν , and on the trace of the Hessian I_1 but not on orientation

$$\begin{split} \mathbf{L}^{(1)}(r) &= \begin{pmatrix} \nu \\ 1 - \gamma^{\pm} \end{bmatrix} \begin{bmatrix} (\xi_{\phi\phi}^{\Delta +} + \gamma \xi_{\phi\delta}^{\Delta +}) \xi_{\delta\delta}^{\times \times} - (\xi_{\phi\delta}^{\Delta +} + \gamma \xi_{\delta\delta}^{\Delta +}) \xi_{\phi\delta}^{\times \times} \end{bmatrix} \\ & \text{height} \\ & \text{shape} \quad I_{2} \\ & + \underbrace{I_{2}}_{1 - \gamma^{2}} \begin{bmatrix} (\xi_{\phi\delta}^{\Delta +} + \gamma \xi_{\phi\phi}^{\Delta +}) \xi_{\delta\delta}^{\times \times} - (\xi_{\delta\delta}^{\Delta +} + \gamma \xi_{\phi\delta}^{\Delta +}) \xi_{\phi\delta}^{\times \times} \end{bmatrix} \end{bmatrix} \mathbb{I}_{3} \,, \end{split}$$

and $L^{(2)}(\mathbf{r})$ now depends on $\overline{\mathbf{H}}$ and on orientation:

$$\begin{split} \mathbf{L}^{(2)}(\mathbf{r}) &= -\frac{5}{8} \left[2((\xi_{\phi\delta}^{\Delta +} - \xi_{\phi\delta}^{\Delta\Delta})\xi_{\delta\delta}^{\times \times} - (\xi_{\delta\delta}^{\Delta +} - \xi_{\delta\delta}^{\Delta\Delta})\xi_{\phi\delta}^{\times \times}) \overline{\mathbf{H}} \right. \\ &+ ((7\xi_{\delta\delta}^{\Delta\Delta} + 5\xi_{\delta\delta}^{\Delta +})\xi_{\phi\delta}^{\times \times} - (7\xi_{\phi\delta}^{\Delta\Delta} + 5\xi_{\phi\delta}^{\Delta +})\xi_{\delta\delta}^{\times \times}) (\hat{\mathbf{r}}^{\mathrm{T}} \cdot \overline{\mathbf{H}} \cdot \hat{\mathbf{r}}) \mathbb{I}_{3} \right] \,, \end{split}$$



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Servision Very simple ab initio prediction for mass transition

3D Transition mass ?

Lagrangian theory capture spin flip !

Transition mass associated with **size** of quadrant



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Geometry of the saddle provides **a natural 'metric'** (local frame as defined by Hessian @ saddle) relative to which **dynamical evolution** of DH is predicted.

cloud effect



Figure 5. Left: logarithmic cross section of $M_p(r, z)$ along the most likely (vertical) filament (in units of $10^{12} M_{\odot}$). Right: corresponding cross section of $\langle \cos \hat{\theta} \rangle(r, z)$. The mass of halos increases towards the nodes, while the spin flips.

geometric split

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mass split

Geometry of the saddle provides **a natural 'metric'** (local frame as defined by Hessian @ saddle) relative to which **dynamical evolution** of DH is predicted.

cloud effect



Figure 6. Mean alignment between spin and filament as a function of mass for a filament smoothing scale of 5 Mpc/h. The spin flip transition mass is around $4 \, 10^{12} M_{\odot}$.

mass split

geometric split

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Explain transition mass?

Transition mass versus redshift: problem solved!





Figure 5. top: Density caustic; Bottom: Zeldovitch mapping of the spin distribution KIAS Nov 1st 2016









Take home message...

- Morphology (= AM stratification) driven by LSS in cosmic web: explain Es & Sps where, how & why from ICs
- Signature in correlation between spin and internal kinematic structure of cosmic web on larger scales.
- Process driven by simple biassed clustering dynamics:
 - requires updating TTT to saddles: simple theory :-)
 - can be expressed into an Eulerian theory via vorticity

Where galaxies form does matter, and can be traced back to ICs Flattened filaments generate point-reflection-symmetric AM/vorticity distribution: they induce the observed spin transition mass

For galaxy formation: Geometry matters !

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arxiv: 1504.06073

Merci !

Evidences of galaxy spin - filament alignment

Cosmic Filament

See also:

Aragon-Calvo+ 2007, Hahn+ 2007, Paz+ 2008, Zhang+ 2009, Codis+ 2012, Libeskind+ 2013, Aragon-Calvo 2013, Dubois+ 2014

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Geometry of the vorticity cross-section

Vorticity vector field

-- Part2: galaxies and their environment --

Laigle+15

Vorticity generation

Laigle+15

Initial phase of structure formation: laminar and curl-free flows This is no longer valid at the shell-crossing



Filaments are extracted with the DISPERSE code (Sousbie+11)

-- Part2: galaxies and their environment --

Geometry of the vorticity cross-section





-- Part2: galaxies and their environment --

Geometry of the vorticity cross-section



Vorticity vector field

-- Part2: galaxies and their environment --

Laigle+15

Halo spin-vorticity alignment

Laigle+15





