Probing the azimuthal environment of galaxies around clusters

*From cluster core to cosmic filaments*

Gouin C., Aghanim N., Bonjean V., Douspis M.

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Credit: Dolag et al. 2015

Orsay - Tartu Workshop 11/06/2020
How can we quantify the anisotropies in the density field around clusters?

What are the impacts of such anisotropic environments on galaxy properties?

**Aims**

- Probe the anisotropies in galaxy distribution around clusters
  - as function of cluster distance, cluster mass, and galaxy type
  - to investigate both environment-driven galaxy evolution & local geometry of the density field

Galaxy clusters = nodes of LSS

Cluster outskirts = ideal place to probe:
- the topology /geometry of the cosmic web
- to study structure formation/evolution
- The impact on galaxy properties?
Probing the azimuthal environment of galaxies around clusters

*From cluster core to cosmic filaments*

<table>
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### Data & Method - 1. Data - Galaxies around clusters

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<td>0.1&lt;z&lt;0.3 and $9.5 &lt; \log(M_*[M_\odot]) &lt; 11.5$</td>
<td>~6400 clusters richness &gt; 20</td>
<td>Wise X SCOSMOS (Bilicki et al, 2016)</td>
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- **SFR+ Mstar Bonjean et al, 2019**
  - Star-forming galaxies (d2ms<0.4)
  - Passive/transitioning galaxies (d2ms>0.4)

- ~6400 Clusters from SDSS (Wen et al, 2012)
  - Redshift slices around clusters with $\sigma_z = 0.06$
  - Projection along the los
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<td>MAGNETICUM LC</td>
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**Light-cone of Magneticum**

1/8 th of the sky

Hirschmann et al. (2014) and Dolag et al. (2015)
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<td></td>
</tr>
<tr>
<td><strong>Case 3</strong></td>
<td>0.05&lt;z&lt;0.45 and No stellar mass cut</td>
<td>~ 12800 clusters</td>
<td>MAGNETICUM LC</td>
</tr>
<tr>
<td></td>
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<td>M_{200} &gt; 1 \times 10^{14} M_☉</td>
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</tbody>
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A larger data set to accurately predict the anisotropies in the density field around clusters

Light-cone of Magneticum
Hirschmann et al. (2014) and Dolag et al. (2015)
Data & Method - 2. A statistical method for filamentary pattern detection

Multipole moments of galaxy distribution around clusters

A decomposition of 2-D galaxy distribution around galaxy clusters (Schneider et al, 1997)

\[ Q_m(\Delta R) = \int_{\Delta R} R \, dR \int_0^{2\pi} d\phi \, e^{im\phi} \sum_g(R, \phi) \]

to characterise the angular asymmetries

- Galaxies are used as a tracer of the underlying density field around clusters
- Method previously applied on DM particles in simulation (Gouin et al, 2017), and on GRF in theoretical point of view (Codis et al, 2017).
Harmonic power

Average over a larger number of clusters

\[ \langle |Q_m|^2 \rangle = \frac{1}{N_{\text{clusters}}} \sum_i |Q_m|^2_i \]

Mean of the modulus, since \( \text{Im}(\langle Q_m \rangle) = 0 \), the phase is null in average

\( Q_m \)

Multipole orders

1 2 3 4 5 6 7 8 ....
Harmonic power

\[ Q_m \]

Average over a larger number of clusters to statistically probe the anisotropies

\[
\langle |Q_m|^2 \rangle = \frac{1}{N_{clusters}} \sum_i |Q_m|^2
\]

Mean of the modulus, since \( \text{Im}(\langle Q_m \rangle) = 0 \)
the phase is null in average

Harmonic power excess

Contrast multipolar spectra near clusters to the overall cosmic structures

\[ \tilde{Q}_m \propto \frac{\langle |Q_m|^2 \rangle_{\text{clusters}}}{\langle |Q_m|^2 \rangle_{\text{randoms}}} \]

What are in excess to background density field?
Data & Method - 2. A statistical method for filamentary pattern detection

Harmonic power - example

\[ \langle |Q_m|^2 \rangle \]

Harmonic power excess

\[ \tilde{Q}_m \propto \frac{\langle |Q_m|^2 \rangle_{\text{clusters}}}{\langle |Q_m|^2 \rangle_{\text{randoms}}} \]

Normalised by random profile
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Accepted to A&A - arXiv:1912.00655
Results - 1. Radial evolution of asymmetries around clusters in simulation (Case3)

Asymmetries in galaxy distribution as function of the radial aperture

Gouin et al, 2020
Results - 1. **Radial evolution of asymmetries around clusters in simulation (Case 3)**

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Gouin et al, 2020
Results - 1. Radial evolution of asymmetries around clusters in simulation *(Case3)*

Asymmetries in galaxy distribution as function of the radial aperture

Gouin et al, 2020
Results - 1. Radial evolution of asymmetries around clusters in simulation (Case3)

Asymmetries in galaxy distribution as function of the radial aperture
Results - 1. Radial evolution of asymmetries around clusters in simulation (Case 3)

Asymmetries in galaxy distribution as function of the radial aperture

Elliptical cluster shape

\[ R = [0-1] R_{500} \]
\[ R = [1-2] R_{500} \]

\[ Q_m \]

\[ m=2 \]
Results - 1. Radial evolution of asymmetries around clusters in simulation (Case3)

Asymmetries in galaxy distribution as function of the radial aperture

Complex anisotropic structure

Filamentary patterns [2-8] R$_{500}$

<table>
<thead>
<tr>
<th>Multipole orders</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>…</th>
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<tr>
<td>multipole order m</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
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<tbody>
<tr>
<td>Mpc</td>
<td>-10</td>
<td>-7.5</td>
<td>-5</td>
<td>-2.5</td>
<td>0</td>
<td>2.5</td>
<td>5</td>
<td>7.5</td>
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<th>R</th>
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<th>[5-6] R$_{500}$</th>
<th>[6-7] R$_{500}$</th>
<th>[7-8] R$_{500}$</th>
<th>Q$_{m}$</th>
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<tr>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
<td>2.0</td>
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Results - 2. Asymmetries in observation (Case 1) and simulation (Case 2)

WISExSCOSMOS galaxies around WHL clusters (Case 1)

Magneticum mock galaxy catalog around simulated clusters (Case 2)

\[ R = [0-2]R_{500} \]

\[ R = [2-8]R_{500} \]

Ellipsoidal shape

Filamentary pattern

\[ \tilde{Q}_m \]

\begin{align*}
\tilde{Q}_1 & \approx 1.8 \\
\tilde{Q}_2 & \approx 1.4 \\
\tilde{Q}_3 & \approx 1.0 \\
\tilde{Q}_4 & \approx 0.8 \\
\tilde{Q}_5 & \approx 0.6 \\
\tilde{Q}_6 & \approx 0.4 \\
\tilde{Q}_7 & \approx 0.2 \\
\tilde{Q}_8 & \approx 0.0 \\
\end{align*}

Multipole orders

Gouin et al, 2020
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Mean angular scale

\[ m_{\text{mean}} = 4.20 \pm 0.09 \]
\[ m_{\text{mean}} = 4.58 \pm 0.19 \]

Median angular scale

\[ m_{\text{median}} = 3.13 \pm 0.10 \]
\[ m_{\text{median}} = 3.43 \pm 0.19 \]
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Connectivity (2D) in literature

~3.7 at z=0.5 from DM simulation (Codis 2018)

~3 - 4 for low-z clusters in observations (Sarron 2019, Malavasi 2019, Darragh-Ford 2019 …)

Disperse filaments

Note: different method & radial aperture
Results - 3. **Radial aperture correlation in observation (Case 1)**

Can the filamentary structures penetrate deeply into clusters and preferentially orientate the cluster core?

Correlation between $R_1 = [0-2]R_{500}$ and $R_2 = [2-8]R_{500}$
Can the filamentary structures penetrate deeply into clusters and preferentially orientate the cluster core?

Correlation coefficients of multipole moments between $R_1$ & $R_2$

Significative correlation at $m=n=2$
Results - 3. Radial aperture correlation in observation (Case 1)

Can the filamentary structures penetrate deeply into clusters and preferentially orientate the cluster core?

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Results - 3. Radial aperture correlation in observation (Case 1)

Can the filamentary structures penetrate deeply into clusters and preferentially orientate the cluster core?

Correlation between \( R_1 = [0-2]R_{500} \) and \( R_2 \)

Correlation coefficients of multipole moments between \( R_1 \) & \( R_2 \)

Significative correlation at \( m=n=2 \)

The correlation at \( m=2 \) decreases with cluster distance

Correlation coefficient at \( m=n=2 \) as function of \( R_2 \)
Very locally a density peak is elliptical and has two ridges

But further away, the skeleton bifurcates and number of filaments increases with the distance to the peak

Codis et al (2018)

Results - 3. Radial aperture correlation in observation (Case 1)

Can the filamentary structures penetrate deeply into clusters and preferentially orientate the cluster core?

Correlation between clusters nodes and large scale structure

Correlation between

\[ R_1 = [0-2]R_{500} \]

\[ R_2 = [2-8]R_{500} \]
Results - 4. Cluster mass dependancy (Case 1)

WISExSCOSMOS galaxies around WHL clusters

\[
\begin{align*}
20 < \text{richness} & \leq 25 & \text{richness} > 30 \\
M_{200} & \sim 1.2 \times 10^{14} M_\odot & M_{200} & \sim 2.7 \times 10^{14} M_\odot
\end{align*}
\]

The elliptical shape is more marked in richer clusters

Richer clusters present a stronger filamentary pattern, and higher connectivity (angular scale)

Gouin et al, 2020
Results - 4. Cluster mass dependancy (Case 1)

WISExSCOSMOS galaxies around WHL clusters

\[
\begin{align*}
20 < \text{richness} &\leq 25 & 25 < \text{richness} &\leq 30 & \text{richness} > 30 \\
M_{200} &\sim 1.2 \times 10^{14} M_\odot & M_{200} &\sim 1.6 \times 10^{14} M_\odot & M_{200} &\sim 2.7 \times 10^{14} M_\odot
\end{align*}
\]

In agreement with current studies massive objects look like more connected to low-mass one.

Local connectivity of groups with 0.5<z<1.2

Darragh-Ford et al 2019

theoretically, see Aragón-Calvo et al. 2010; Pichon et al. 2010; Codis et al. 2018

Observational study, see also Sarron et al 2019
Results - 5. Galaxy type dependency (Case 1 and Case 2)

Which type of galaxy trace the asymmetries in galaxy distribution? The role of cluster environment?

- Passive and star-forming WISExSCOSMOS galaxies around WHL clusters (Case 1)
- Passive and star-forming mock galaxy dates from Magneticum (Case 2)

The contribution of SF galaxies increases with cluster distance

A gradient of SF activity in anistropic structures, from cluster centre to the filaments?

Gouin et al, 2020
Which type of galaxy trace the asymmetries in galaxy distribution? The role of cluster environment?

Passive and star-forming WISExSCOSMOS galaxies around WHL clusters (Case 1)

The contribution of SF galaxies increases with cluster distance

An gradient of SF activity inside asymmetric structures from cluster centre to the LSS

Galaxies infalling along filaments are systematically more quenched than their isotropic counterparts

Results - 5. Galaxy type dependancy (Case 1 and Case 2)

Which type of galaxy trace the asymmetries in galaxy distribution? The role of cluster environment?

Passive and star-forming WISExSCOSMOS galaxies around WHL clusters (Case 1)

Passive galaxies in cosmic filaments are located closer to clusters than their SF counterpart (for low-z clusters)

Galaxies in filaments are systematically more quenched than their counterparts infalling from other directions

Fraction of passive galaxies

Sarron et al 2019

Salerno et al 2020

See also Kraljic et al, 2018; Lotz et al 2018; …
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Radial evolution of angular features in galaxy distribution around clusters (from 1 to 10 Mpc)

Elliptical core shape and filamentary patterns

Mass dependancy: Massive clusters are more connected and more elliptical

Correlation between inner & filaments around clusters

Alignment of elliptical cluster core with filamentary structures

Gradient of galaxy activity in filaments around clusters