Halo interactions
in the Horizon Run 4 simulation


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Outline

1 Introduction

2 Simulation and method

3 Halo interaction rate in the Horizon Run 4

4 Alignment of interacting haloes
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4 Alignment of interacting haloes
Motivations

- ΛCDM predicts hierarchical structure formation: halo mergers
- Galaxy mergers and interactions are observed
- Merger can trigger star-formation, morphological transformations, fuel central black-hole, ...
- Distant interactions also matter (Park et al 2008, Hwang & Park 2015)
- Major merger have a dramatic impact (morphology transformation, significant mass increase; e.g., Toomre & Toomre 1972)
- Minor mergers also matter: more frequent (Bournaud et al 2007)
- How about flybys? Not much studied (notable exception: Sinha & Holley-Bockelmann 2012)
- Role of the environment: voids, walls, filaments, clusters
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Main questions

- How do haloes interact within the large-scale structures?
- How do interactions shape haloes?
Flybys in cosmological simulations

- Sinha & Holley-Bockelmann (2012): importance of flybys?
- $N$-body simulation:
  - Merger dominant at high $z$
  - For massive haloes ($>10^{11}$) and $z<2$, flybys important
- Small box ($50\,h^{-1}\text{Mpc}$: large-scale effects?)
- Down to $z=1$
- Observationally: close pairs as a proxy for merger rate. What about flybys? (cf. Tonnensen & Cen 2012)
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2 Simulation and method
   - The Horizon Run 4 simulation
   - Background density
   - Definitions

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The Horizon Run 4 simulation

Horizon Run 4 (J. Kim et al 2015, JKAS)

- N-body simulation using the GOTPM code in a WMAP5 cosmology
- 8000 CPU cores, 50 days at KISTI (Korea).
- \( L = 3.15 \, h^{-1}\text{Gpc} \), \( N = 6300^3 \) (\( \bar{d} = 0.5 \, h^{-1}\text{Mpc} \))
- 2LPT, \( z_{\text{ini}} = 100 \), 2000 timesteps
- 70 outputs, lightcone up to \( z = 1.39 \), merger trees

Catalogues

- Haloes detected with OPFOF, and subhaloes with PSB
- Minimum subhalo mass (20 particles): \( 1.8 \times 10^{11} \, h^{-1} M_\odot \)
- Use of a target (\( M_T > 5 \times 10^{11} \, h^{-1} M_\odot \)) and neighbour (\( M_N > 2 \times 10^{11} \, h^{-1} M_\odot \))
  catalogue
- Hereafter, “haloes” refer to PSB subhaloes (\( \leftrightarrow \) galaxies)
Large-scale density


To quantify the environment: $\rho_{20}$: density over 20 neighbours

$$\rho_{20} = \sum_{i=1}^{20} M_i W(r_i, h),$$

where $r_i$ is the distance to the $i^{th}$ neighbour, $M_i$ its mass, $W$ the SPH spline kernel, and $h$ the smoothing length.

Normalisation by $\bar{\rho} = \sum N M_i$:

$$1 + \delta = \rho_{20} / \bar{\rho}$$
Definitions

Interactions

A target $T$ is interacting if

- it is located with the virial radius of its neighbour $N$
- if $M_N > 0.4 \ M_T$
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3. Halo interaction rate in the Horizon Run 4
   - Influence of the large-scale density
   - Interaction rate as a function of the mass and density
   - Dependence on the mass ratio and distance
   - A closer look at the oblique branch

4. Alignment of interacting haloes
Interaction rate: background density


 Targets = all subhalos with
\[ M > 5 \times 10^{11} \, h^{-1} M_{\odot} \]

Background density: smoothed over 20 neighbours:
\[ \rho_{20} = \sum_{i=1}^{20} M_i W(r_i, h), \]

Top: PDF of the density of interacting targets
Middle: fraction of targets that are interacting
Bottom: Number of interaction per bin

Interactions occurs at \( 1 + \delta \simeq 10^3 \)
Mass and density dependence of the interaction fraction


Fit:

\[ \Gamma(M|\delta, z) = A_0 \text{erfc} \left( b \log_{10} \left( \frac{M}{M_*} \right) \right) \]

\[ A_0, M_*, \text{ and } b \text{ dependence on } (\delta, z): \]
Mass and density dependence of the interaction fraction


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**Targets**

**Interactions**

**Interaction rate**

**Fit**

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Mass and density dependence of the interaction fraction


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\( A_0, M_*, \) and \( b \) dependence on \((\delta, z)\):

\[ f(M, \delta) \]

1 + \( \delta \)

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Mass and density dependence of the interaction fraction


Fit:

\[ \Gamma(M|\delta, z) = A_0 \text{erfc} \left( b \log_{10} \left( \frac{M}{M_\ast} \right) \right) \]

$A_0$, $M_\ast$, and $b$ dependence on $(\delta, z)$:
Time evolution of the interaction rate


\[ \Gamma(a) = B \exp \left( - \left( \frac{1 - a}{A} \right)^\gamma \right) \]

- Increasing rate
- At “fixed” mass bin
  - Final interaction rate (B) higher for higher density
  - Rates saturates earlier at lower densities
- At “fixed” density
  - \( B \) decreases with \( M_T \) for the largest density bin

\( \Gamma/B \)
\[ d^2 N = f(p, q|M_T, \delta, z) \, dp \, dq \]

\[ p = \frac{d}{R_{\text{vir}, \text{nei}}} \]

\[ q = \frac{M_N}{M_T} \]

\[ z = 1.0 \]

\[ \delta < \Delta_1 \]

\[ \Delta_1 < \delta < \Delta_2 \]

\[ \delta \geq \Delta_2 \]
\[ d^2 N = f(p, q|M_T, \delta, z)dp dq \]
A closer look at the oblique branch

- $\theta = (r, v)$
- Low $q$: flatter distribution: more random; fewer infalling orbits
- Low $p$: flatter distribution, fewer receding orbits

- the oblique branch corresponds to radial orbits: 1st infall
- $0.5 < \cos \theta < 0.5$: random motions after 1st infall, oblique branch less prominent.
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   - Motivations
   - Alignment of the major axes of interacting pairs
Motivations
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- Galaxies form within the cosmic web: properties must be related to their environment
- The study of the alignment of the spins and shapes of haloes can shed light on galaxy formation within their environments
- Alignment as a probe of the large-scale structures
- Intrinsic alignment: source of systematics for weak lensing analysis
- From simulations: spins aligned with the intermediate axis of the tidal tensor Wang et al (2011)
- mass dependence: low-mass (massive) haloes have their spin parallel (orthogonal) to filaments Hahn et al (2007),
- Haloes in sheets have their spin in the plane
Method

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To detect an alignment signal of an angle $\theta = (u, v)$, following Yang et al 2006, we used the normalised pair count:

- Count the number of pairs $N(\theta)$ with angle $\theta$
- for $N_{\text{rand}} \simeq 200$, calculate $\langle N^R(\theta) \rangle$ and $\sigma_\theta$ the mean and std deviation of random permutations of $u$.
- We look at $f(\theta) = N(\theta)/\langle N^R(\theta) \rangle$
  - If $f \equiv 1$: No alignment (random)
  - If $f(\cos \theta \simeq \pm 1) \gg 1$: Alignment (parallel/anti parallel)
  - If $f(\cos \theta \simeq 0) \gg 1$: Anti-alignment (orthogonal)
- the strength of the signal (error bars) is given by $\sigma_\theta/\langle N^R(\theta) \rangle$. 
Shapes

\[ \gamma = (\mathbf{a}_T, \mathbf{r}) \]: angle between major axis (target) and direction neighbour

\[ \varepsilon = (\mathbf{a}_N, \mathbf{r}) \]: angle major between the major axis of the neighbour and the direction of the target
Higher densities \( \gamma = (a_T, r); q_T < 0.8 \)

Alignment stronger at low-\( \delta \) and low-\( z \); little mass dependence

Major axis aligned with the direction of the neighbour
\[ \alpha = (J_T, r) \]: angle between spin target and direction neighbour
\[ \phi = (J_T, J_N) \]: angle between target and neighbour neighbour spins
Strong time evolution, inversion of tendency: towards an alignment of spins.

High-$\delta$: weak alignment $\rightarrow$ strong

Low-$\delta$: spins para and anti-para $\rightarrow$ para
Alignment of prolate pairs

$$\gamma = (a_T, r); \, \varepsilon = (a_N, r);$$

- Neighbours are drawn at their angular position $\gamma$ proportionally to $P(\gamma)$.
- Neighbours located in the direction of the major axis.
- Neighbours point toward the Target.
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Summary and perspectives

- The unprecedented statistics of HR4 enable us to study the interaction rate and halo alignment as a function of the environment.
- The angular position neighbour is aligned with the major axis of the target.
- Alignment signal stronger at low redshift, increases with density, independent of mass.

- Comparison with observations: SDSS (in progress).
- Inclusion of hydrodynamics: morphological transformation, star formation, misalignment galaxy/halo.
- How does modified gravity affects interactions? (In progress).
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Target selection

- At $z = 4$, find $M_2(z = 4)$ the median mass of the targets. This defines two subsamples of equal numbers.
- Divide them into three equal subsamples according to the density with $\Delta_{2,1}, \Delta_{2,2}$.
- At lower $z$, find $M_i(z)$ and $\Delta_{j,i}(z)$ ($i \in \{0, 1, 2\}, j \in \{1, 2\}$) that yield the same number of targets per bin.
- About 4M targets per bin of $(M, \delta)$