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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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)
Outline

1 Introduction

2 Simulation and method
   - The Horizon Run 4 simulation
   - Background density
   - Definitions

3 Halo interaction rate in the Horizon Run 4

4 Alignment of interacting haloes
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 (↔ galaxies)
Large-scale mass 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 \( \bar{\rho} = \sum N M_i \):

\[
1 + \delta = \frac{\rho_{20}}{\bar{\rho}}
\]
Definitions

Interactions

A target $T$ is interacting if

- it is located with the virial radius of its neighbour $N$
- if $M_N > 0.4 \ M_T$
Outline

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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
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_*, and b dependence on (\delta, z):
Mass and density dependence of the interaction fraction


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

![Graph showing dependencies]
Mass and density dependence of the interaction fraction


Fit:

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

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

\[ f(M, \delta) \]

\[ z = 0.0, 0.5, 1.0, 1.5, 2.0 \]
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
\[ d^2 N = f(p, q|M_T, \delta, z) dp \, dq \]

\[ \delta < \Delta_1 \quad \Delta_1 < \delta < \Delta_2 \quad \delta \geq \Delta_2 \]

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

\[ q = M_N/M_T \]

Separation

Mass ratio

\[ z = 2.0 \]

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

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

\[ M_T > M_2(\varepsilon) \]

\[ M_T < M_1(\varepsilon) \]

\[ M_1(\varepsilon) < M_T < M_2(\varepsilon) \]

\[ \varepsilon \]

\[ (\varepsilon, M_T, z) \]

\[ f(p, q, \delta, M_T, z) \]

\[ 10^0 \]
\[ 10^{-1} \]
\[ 10^{-2} \]
\[ 10^{-3} \]
\[ 10^{-4} \]
\[ 10^{-5} \]
\[ 10^{-6} \]
\[ 10^{-7} \]
\[ 10^{-8} \]

\[ 10^0 \]
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\[ 10^{-1} \]
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\[ 10^{-3} \]
\[ 10^{-4} \]
\[ 10^{-5} \]
\[ 10^{-6} \]
\[ 10^{-7} \]

\[ \frac{d^2 N}{dp dq} = f(p, q|M_T, \delta, z) \]

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

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

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\[ (\varepsilon, M_T, z) \]

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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.
Introduction

Simulation and method

Halo interaction rate in the Horizon Run 4

Alignment of interacting haloes
  - 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

\[ \gamma = (a_T, r) \]: angle between major axis (target) and direction neighbour

\[ \varepsilon = (a_N, r) \]: 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
Neighbours are drawn at their angular position $\gamma$ proportionaly to $P(\gamma)$.

Neighbours located in the direction of the major axis

Neighbours point toward the Target
Alignment of prolate pairs

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- Neighbours located in the direction of the major axis
- Neighbours point toward the Target
Summary and perspectives

- The unprecedented statistics of HR4 enable us to study the interaction rate and the 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 affect interactions? (In progress).
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ありがとうございます!
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 $(M, \delta)$

Redshift-evolution of $M_i(z)$ and $\Delta_{j,i}(z)$