The rates and types of halo interactions

L'Huillier, Park & Kim (2015) MNRAS 451, 5046
L'Huillier, Park & Kim (in prep.)

Benjamin L'Huillier (KIAS)
(루이리예, 벤자민)

with Changbom Park & Juhan Kim (KIAS)

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KOREA INSTITUTE FOR ADVANCED STUDY

Outline

Outline

Introduction

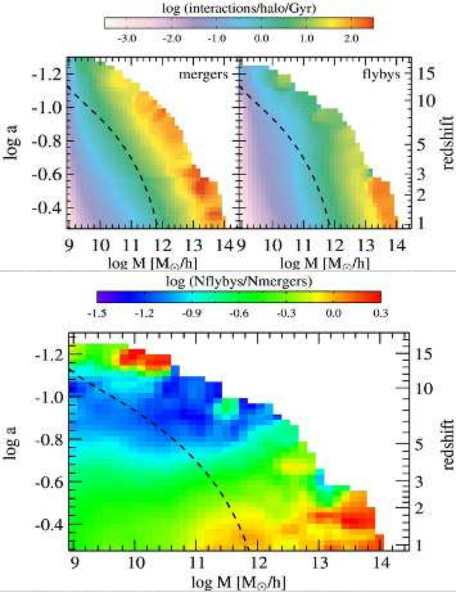
Galaxy evolution in a cosmological context

- ΛCDM Universe: dominated by cold dark matter (DM) & dark energy
- Large-scale structures: cosmic web of knots, filaments, walls and voids
- DM overdensities collapse $\rightarrow$ virialized DM haloes
- Galaxies form in DM haloes
- Hierarchical model: small structures merge into more massive ones
- DM dominates the dynamics, baryon physics important on small scales

Motivations

- Halo mergers expected from ΛCDM; galaxy mergers observed
- Merger can trigger star-formation, morphological transformations, fuel central black-hole, ...
- Distant interactions also matter (Park et al 2008, Sinha & Holley-Bockelmann 2012, 2015)

Flybys in cosmological simulations



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

The rates and types of halo interactions

In a hierarchical ΛCDM Universe, galaxies evolve via secular evolution (formation of bars, bulges, spiral structure, ...), interactions with their neighbours (major and minor mergers, flybys, ...) and smooth gas accretion

- Major merger have a dramatic impact (morphology transformation, significant mass increase) (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: field, groups and cluster

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Main questions

- What kind of interaction has the most significant impact?
- How does it change with redshift, mass ratio, impact parameter, environment?
- How do interaction shape galaxies?

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Outline

Simulation: Horizon Run 4

Horizon Run 4 (J. Kim et al, in prep.)

- N-body simulation using GOTPM, WMAP5 cosmology
- $L = 3.15\, h^{-1}\mathrm{Gpc}$, $N = 6300^3$ DM "particles" ($\bar{d} = 0.5\, h^{-1}\mathrm{Mpc}, M \approx 1 \times 10^{10}\, h^{-1} M_\odot$)
- 8000 CPU cores, 50 days at KISTI
- Ideal for environment studies of galaxies

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 ($M_\mathrm{T} > 5 \times 10^{11}\, h^{-1} M_\odot$) and neighbour ($M_\mathrm{N} > 2 \times 10^{11}\, h^{-1} M_\odot$) catalogue
- Hereafter, "haloes" refer to PSB subhaloes ($\leftrightarrow$ galaxies)

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Large-scale *mass* density

(Not number)

To quantify the environment: ρ_{20}: density smoothed 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 a cubic spline smoothing kernel, and h the smoothing length.
Normalisation by $\bar{\rho} = \sum_{\mathrm{N}} M_i$:

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

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Definitions

Interactions

A target T is interacting if it is located with the virial radius of its neighbour N, an if $M_{\mathrm{N}} > 0.4\ M_{\mathrm{T}}$

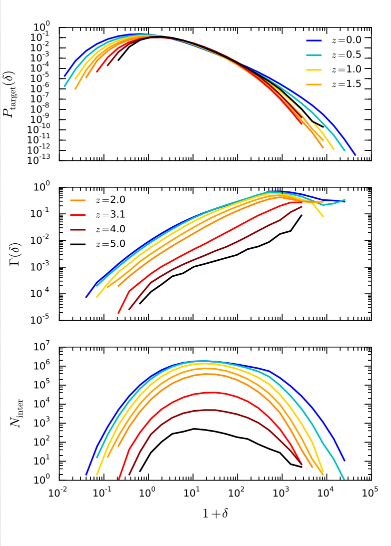
- Theoretical studies: merger rate = number of events per time unit per halo mass.
- Observationally: Fraction of galaxies interacting.
- We chose the 2nd approach and define the interaction fraction Γ as the fraction of target haloes interacting.

Outline

Outline

Interaction rate: background density

L'Huillier, Park & Kim 2015, MNRAS 451, 5046



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

Bottom: fraction of targets that are interacting

Interactions occurs at $1 + \delta \simeq 10^3$

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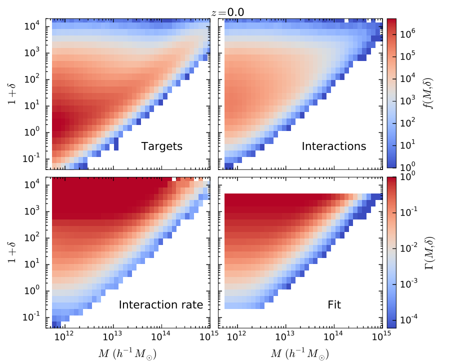
Mass and density dependence of the interaction fraction

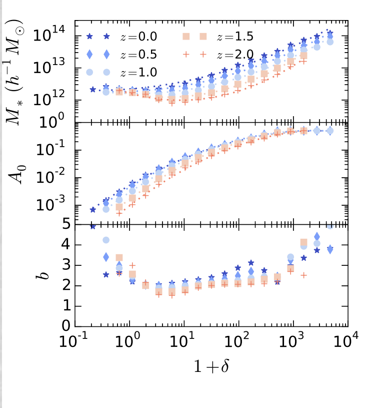
L'Huillier, Park & Kim 2015, MNRAS 451, 5046

Fit:

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



A_0, M_*, and b dependence on (δ, z):



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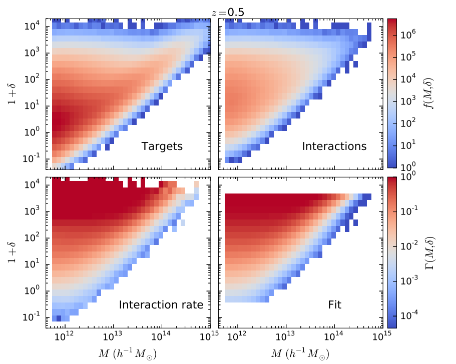

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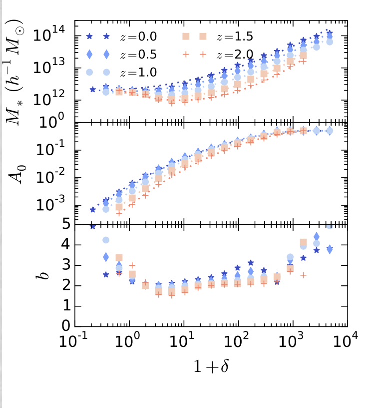

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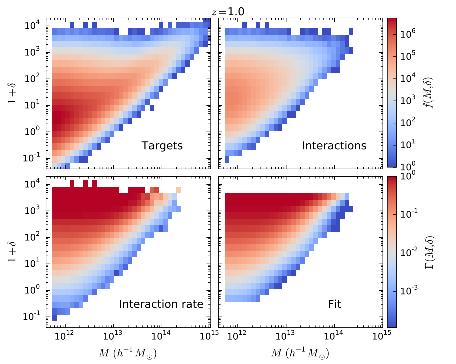

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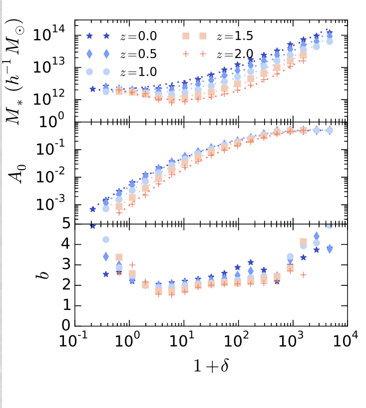

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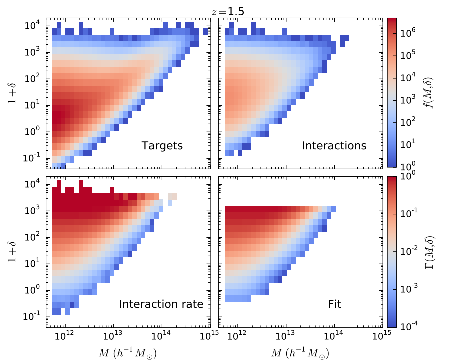

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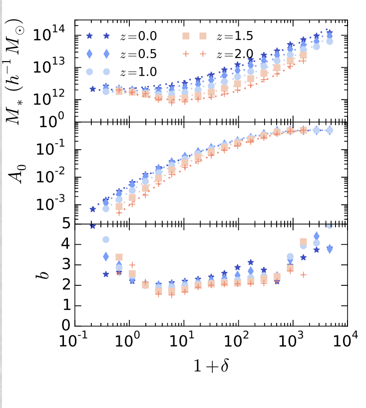

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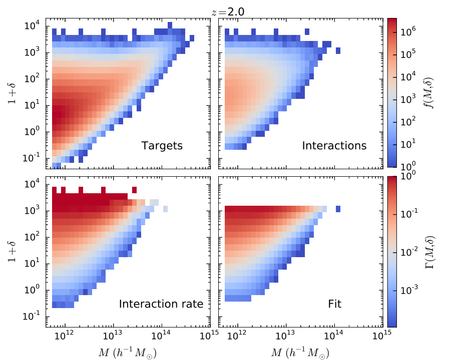

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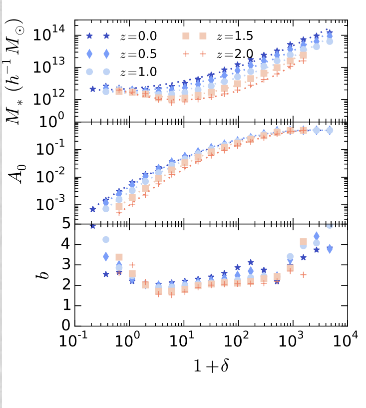

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Method

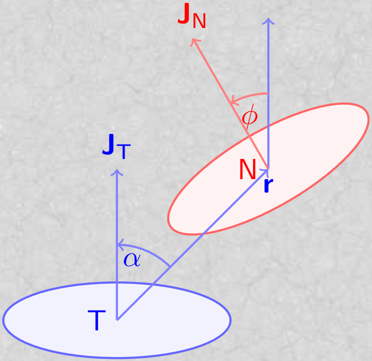
L'Huillier, Park & Kim, MNRAS, in prep.

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

- Count the number of pairs $N(\theta)$ with angle θ
- for $N_{\mathrm{rand}} \simeq 200$, calculate $\left\langle N^{\mathrm{R}}(\theta) \right\rangle$ and σ_θ the mean and std deviation of random permutations of $\mathbf{u}$.
- We look at $f(\theta) = N(\theta) / \left\langle N^{\mathrm{R}}(\theta) \right\rangle$
- the strength of the signal is given by $\sigma_\theta / \left\langle N^{\mathrm{R}}(\theta) \right\rangle$.
- alignment if $f(\cos\theta \simeq 1) \gg 1$
- anti-alignment if $f(\cos\theta \simeq 0) \gg 1$

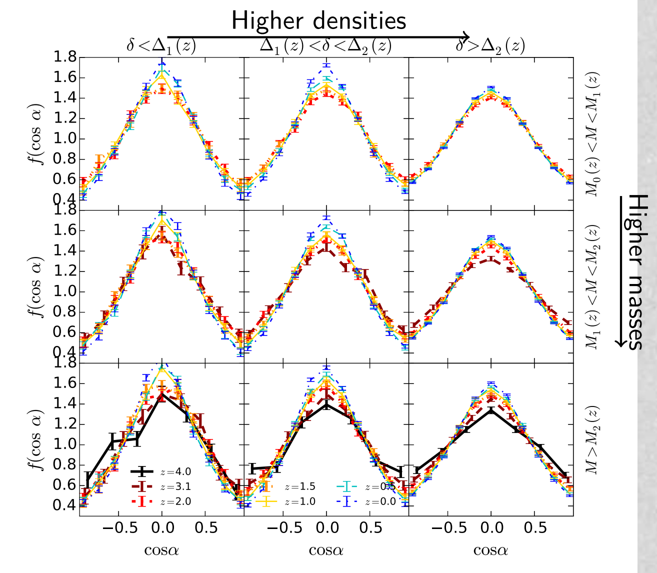
Outline

Spins



$\alpha = (\mathbf{J}_\mathsf{T}, \mathbf{r})$: angle between spin target and direction neighbour
$\phi = (\mathbf{J}_\mathsf{T}, \mathbf{J}_\mathsf{N})$: angle between target and neighbour neighbour spins

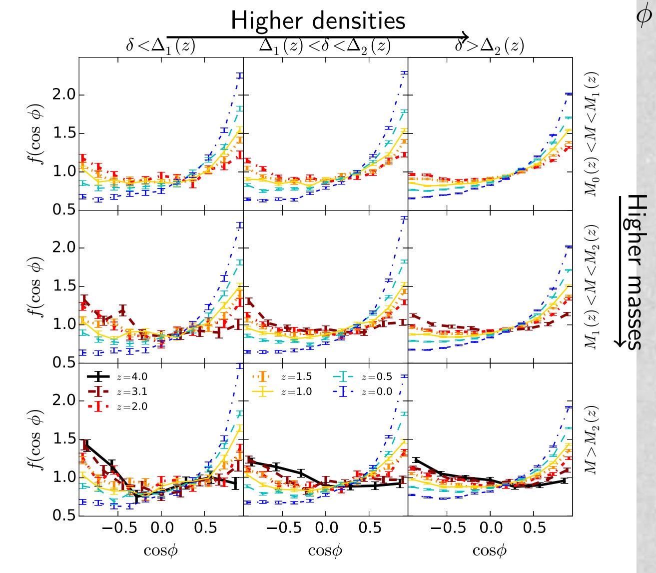
$\alpha = (\mathbf{J_T}, \mathbf{r})$



Strong anti-alignment signal, stronger at low-δ; time-dependence: signal stronger at lower z; little mass dependence

Neighbours are in the plane of rotation

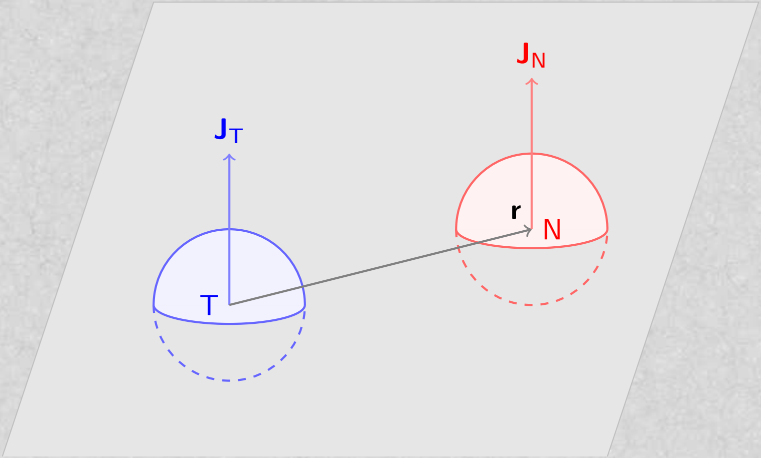
$\phi = (\mathbf{J}_\mathsf{T}, \mathbf{J}_\mathsf{N})$



Strong time evolution, inversion of tendence: towards an alignment of spins.

High-δ: weak alignment $\rightarrow$ strong

Low-δ: spins para and anti-para $\rightarrow$ para



$\mathbf{J}_\mathrm{T} \parallel \mathbf{J}_\mathrm{N}$; $\mathbf{J}_\mathrm{T} \perp \mathbf{r}$

Outline

Summary

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- We study the interaction rate and the pair alignments in the HR4 simulation as a function of the environment
  - Large box: environment study and good statistics
  - High resolution: target haloes more massive than $5 \times 10^{11}\, h^{-1} M_\odot$
- We provide a new fit $\Gamma(M, \delta|z)$ and $\Gamma(z|M, \delta)$
- Major axes: strong alignment $(\mathbf{a}_\mathrm{T}, \mathbf{a}_\mathrm{N})$, stronger at low-$\delta$ and z, little mass dependence. Strong alignment of $\mathbf{a}_\mathrm{T}$ and $\mathbf{r}$.
- Spins: The spin of the target is anti-aligned with the halo plane. Stronger at low-δ and z. $\mathbf{J}_\mathrm{T}$ and $\mathbf{J}_\mathrm{N}$ become more and more aligned as z decreases. Spins are aligned with the minor axis

Perspectives

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- Comparison with observation (interaction rate & alignments)
- Use of a merger tree to distinguish merger and flybys
- Use of an improved galaxy–subhalo assignment scheme for the catalogue
- Inclusion of hydrodynamics: morphological transformation, star formation, ...
- Also misalignment haloes – galaxies

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감사합니다!