Halo interactions in the Horizon Run 4 simulation

B. L'Huillier, C. Park & J. Kim (2015), MNRAS 451, 527
B. L'Huillier, C. Park & J. Kim (2016) MNRAS subm.

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Future Sky Surveys and Big Data
2016-04-25, KASI

KOREA INSTITUTE FOR ADVANCED STUDY

Cosmology Group at Korea Astronomy and Space Science Institute

Outline

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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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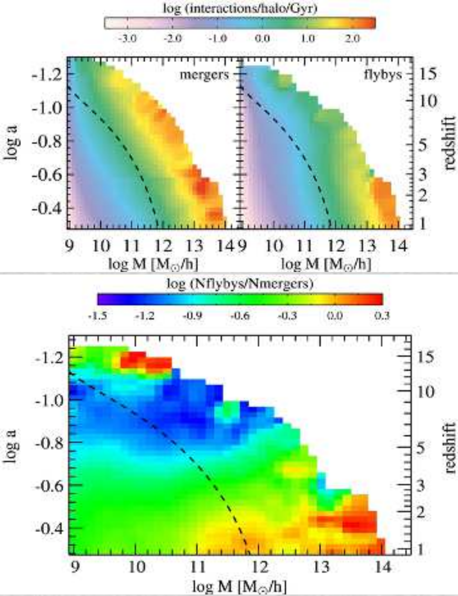
Main questions

- 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 ($50\,h^{-1}\mathrm{Mpc}$: large-scale effects?)
- Down to $z = 1$
- Observationally: close pairs as a proxy for merger rate. What about flybys? (cf. Tonnensen & Cen 2012)

Outline

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).
- $L = 3.15\,h^{-1}\mathrm{Gpc}$, $N = 6300^3$ ($\bar{d} = 0.5\,h^{-1}\mathrm{Mpc}$)
- 2LPT, $z_{\mathrm{ini}} = 100$, 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 ($M_\mathrm{T} > 5 \times 10^{11}\,h^{-1}M_\odot$) and neighbour ($M_\mathrm{N} > 2 \times 10^{11}\,h^{-1}M_\odot$) catalogue
- Hereafter, "haloes" refer to PSB subhaloes ($\leftrightarrow$ galaxies)

Large-scale density

B. L'Huillier, C. Park and J. Kim (2015) MNRAS 451, 527

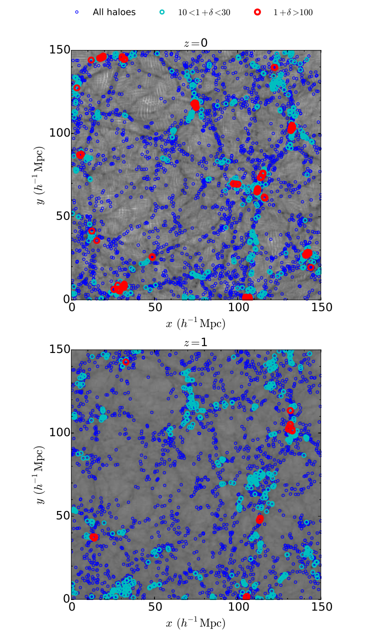
To quantify the environment: ρ_{20}: density over 20 neighbours

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

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

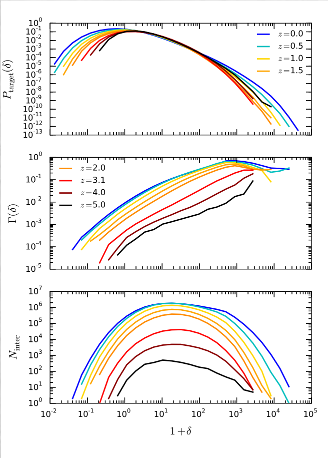
A target T is interacting if

- it is located with the virial radius of its neighbour N
- if $M_{\mathrm{N}} > 0.4\ M_{\mathrm{T}}$

Outline

Interaction rate: background density

B. L'Huillier, C. Park and J. Kim 2015, MNRAS 451, 527



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

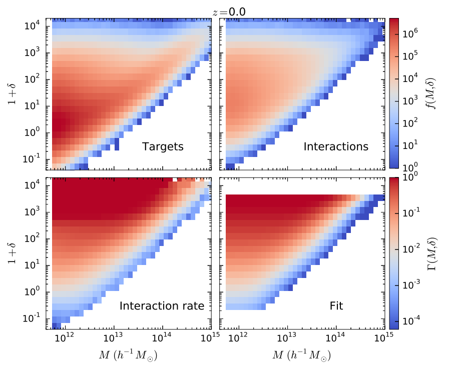
Interactions occurs at $1 + \delta \simeq 10^3$

Mass and density dependence of the interaction fraction

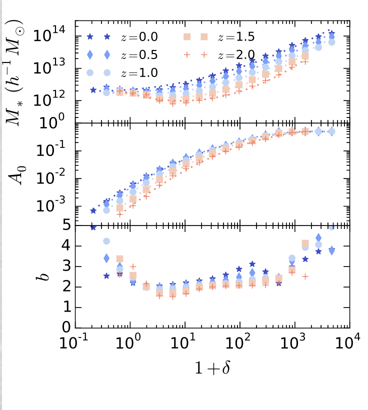
B. L'Huillier, C. Park and J. Kim 2015, MNRAS 451, 527

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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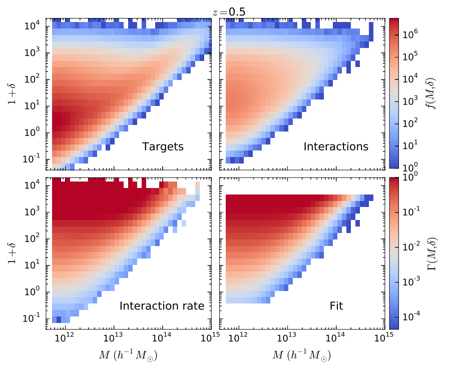

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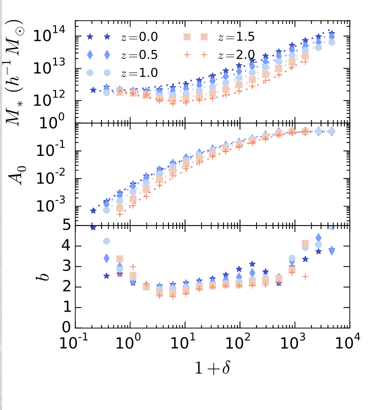

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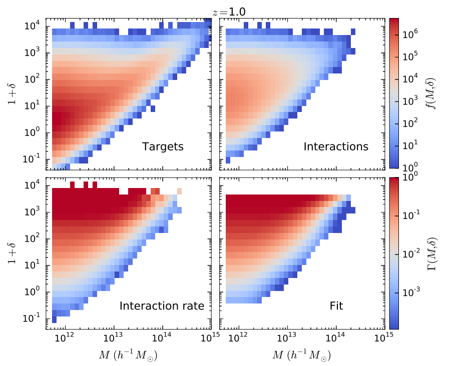

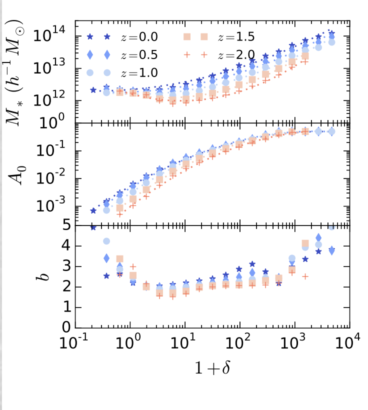

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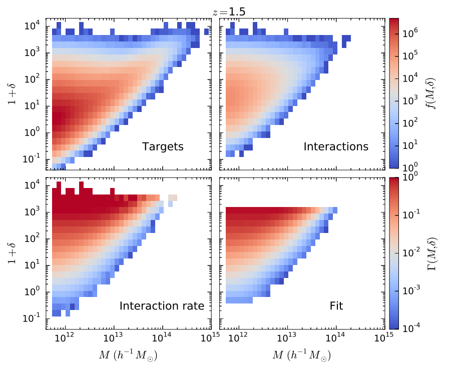

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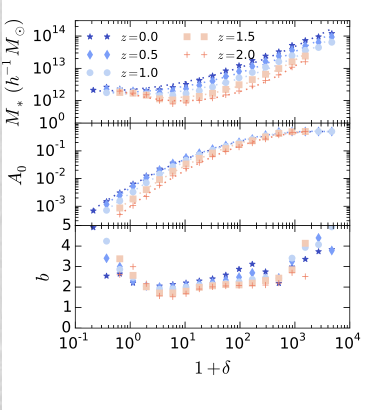

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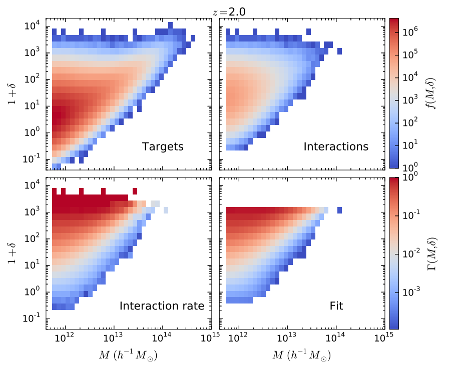

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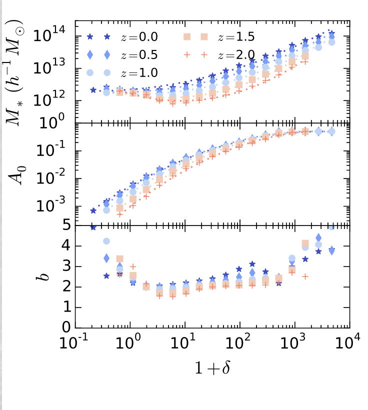

Time evolution of the interaction rate

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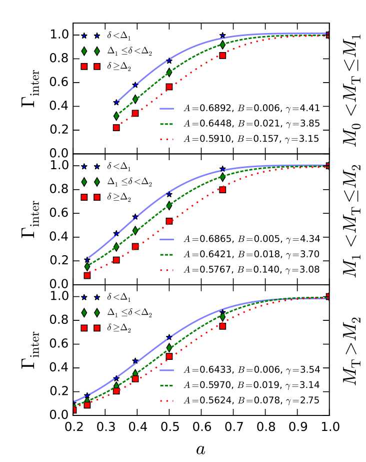
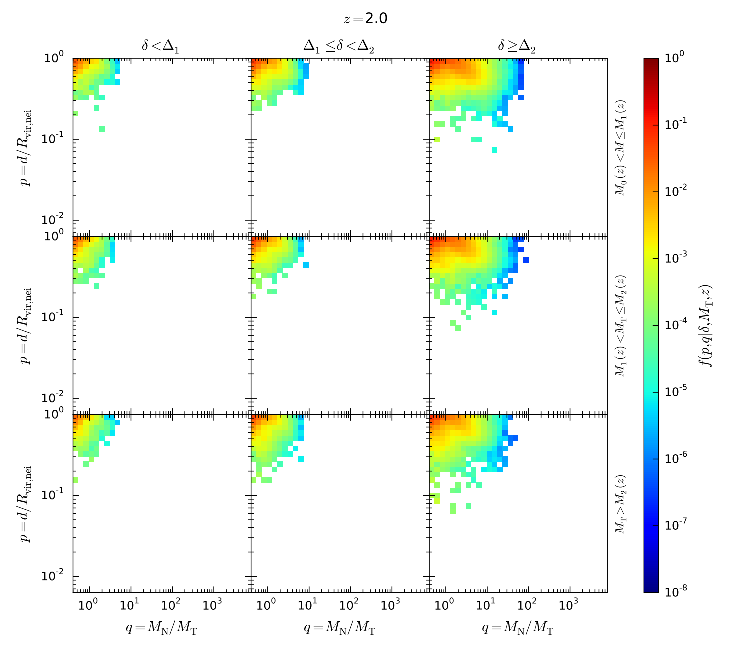


Γ / B

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

- 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

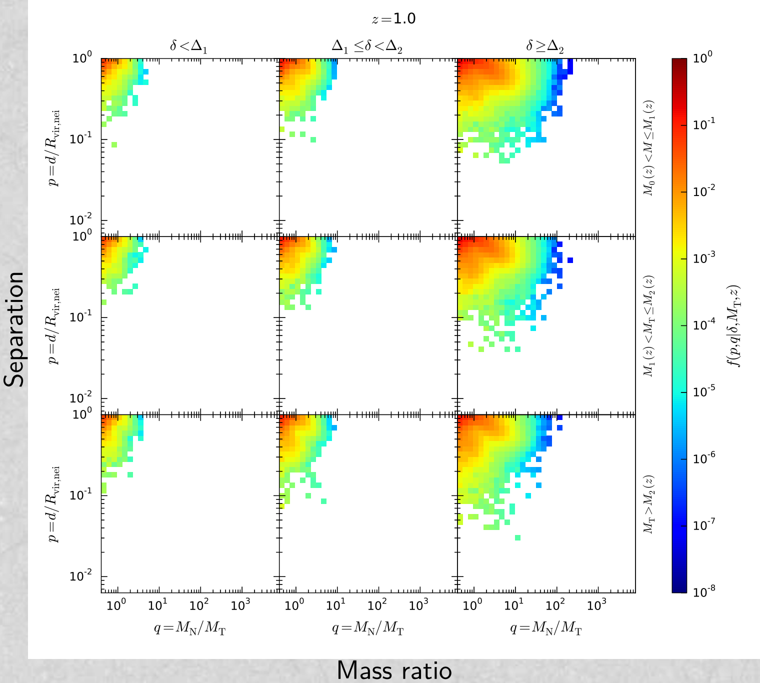
$$\mathrm{d}^2 N = f(p, q | M_{\mathrm{T}}, \delta, z)\,\mathrm{d}p\,\mathrm{d}q$$



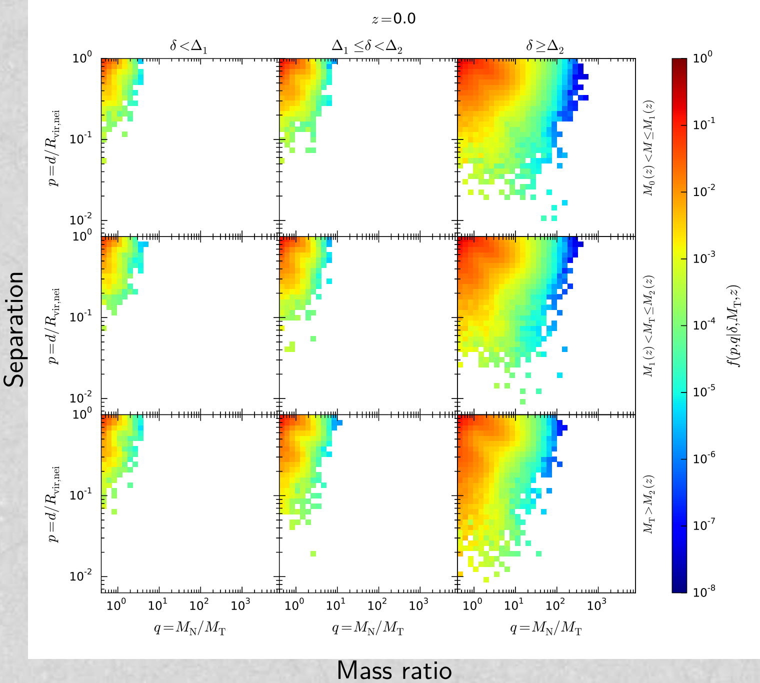
Separation

Mass ratio

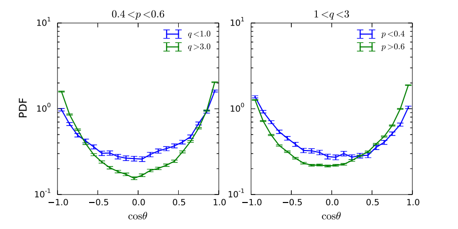
$$\mathrm{d}^2 N = f(p, q | M_\mathrm{T}, \delta, z)\mathrm{d}p\,\mathrm{d}q$$

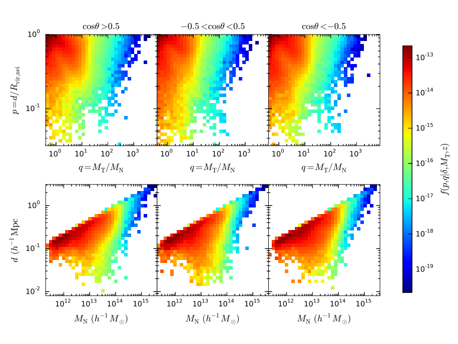


$$d^2N = f(p, q | M_T, \delta, z)\, dp\, dq$$



A closer look at the oblique branch





- $\theta = (\mathbf{r}, \mathbf{v})$
- 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.

Outline

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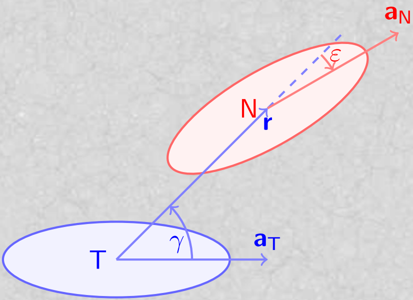
To detect an alignment signal of an angle $\theta = (\mathbf{u}, \mathbf{v})$, following Yang et al 2006, we used the normalised pair count:

- 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 $f(\theta) = N(\theta) / \left\langle N^{\mathrm{R}}(\theta) \right\rangle$
  - 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 $\sigma_\theta / \left\langle N^{\mathrm{R}}(\theta) \right\rangle$.

Shapes

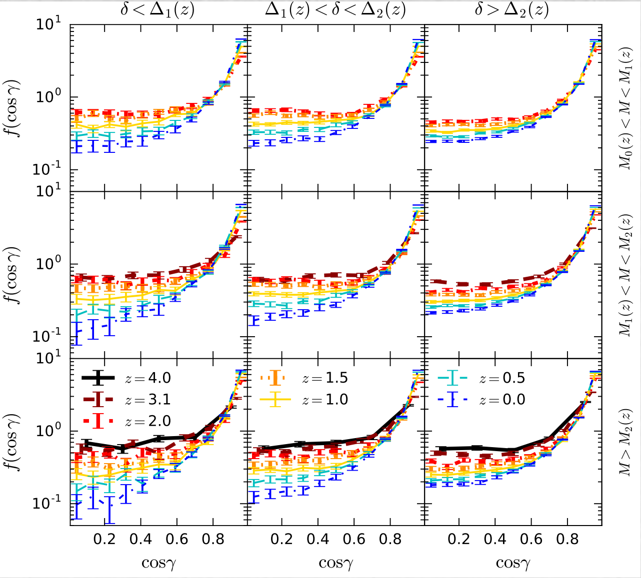


$\gamma = (\mathbf{a}_\mathsf{T}, \mathbf{r})$: angle between major axis (target) and direction neighbour

$\varepsilon = (\mathbf{a}_\mathsf{N}, \mathbf{r})$: angle major between the major axis of the neighbour and the direction of the target

$\gamma = (\mathbf{a}_\mathsf{T}, \mathbf{r})$; $q_\mathsf{T} < 0.8$

Higher densities →

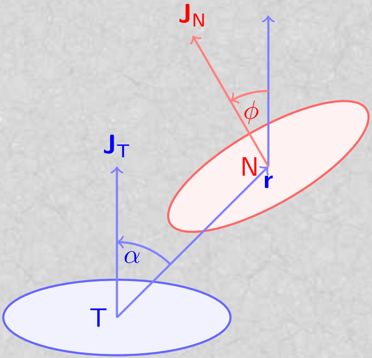


Higher masses ↓

Alignment stronger at low-δ and low-z; little mass dependence

Major axis aligned with the direction of the neighbour

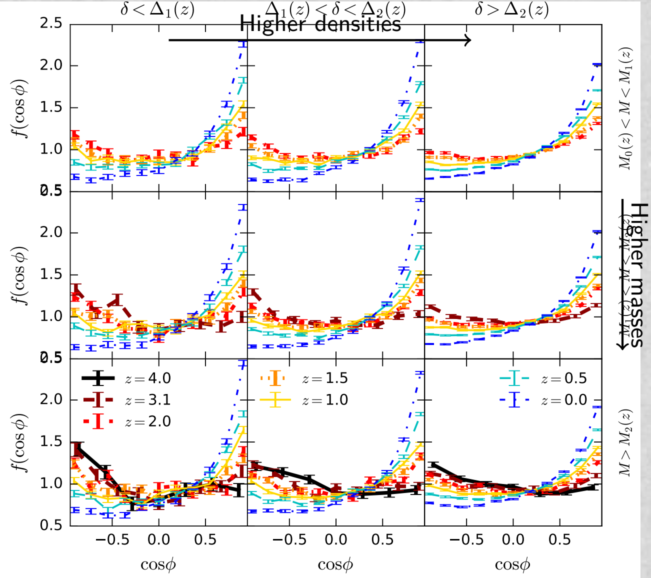
Spins



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

$\phi = (\mathbf{J}_\mathrm{T}, \mathbf{J}_\mathrm{N})$: angle between target and neighbour neighbour spins

$\phi = (\mathbf{J_T}, \mathbf{J_N})$

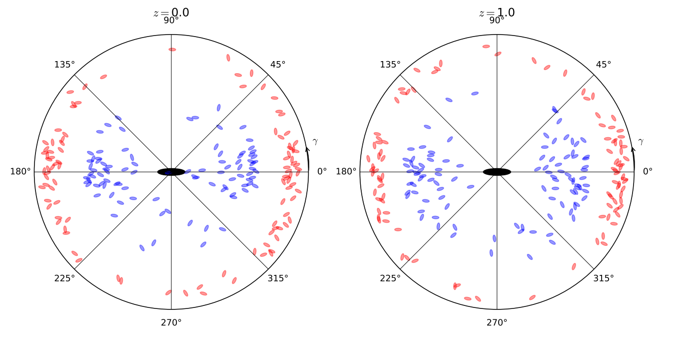


Strong time evolution, inversion of tendence: towards an alignment of spins.

High-δ: weak alignment $\rightarrow$ strong

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

Alignment of prolate pairs



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

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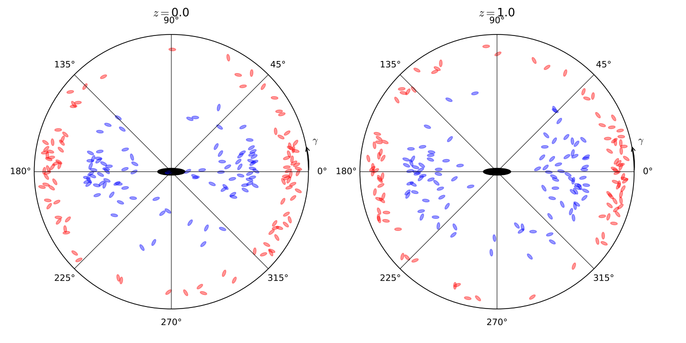

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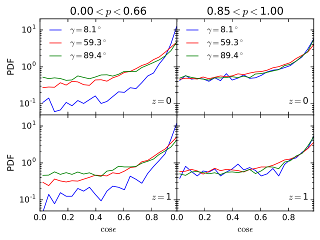

Summary and perspectives

- The unprecedented statistics of HR4 enable us to study the 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 affects interactions? (In progress)

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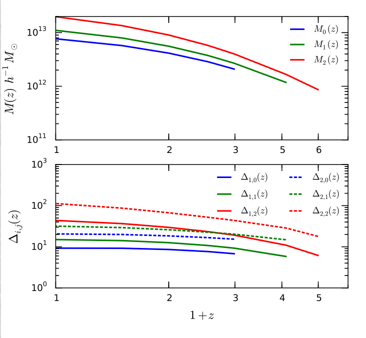
감사합니다!

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, δ)



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