# Evolution of the angular momentum of the dark matter subhaloes

Daiki Osafune[1], Keiichi Wada[2], Tomoaki Ishiyama[3], Takashi Okamoto[1]

1.Hokkaido University, 2.Kagoshima University, 3.Chiba University

## Introduction

To investigate the evolution of subhaloes, substructures of dark matter haloes, is important for understanding the evolution of dark matter halo and galaxies. However, the mechanism of acquisition of angular momentum of subhaloes is not clear. The major axis of the dark matter subhalo tends to be in the radial direction of the host halo, and it was caused by the tidal field of the host halo (Knebe et al. 2020). Therefore, we infer that the subhaloes gain angular momentum from the torque exerted by the tidal force of the host halo, and we investigated the influence of the host halo on the angular momentum of the subhaloes using high-resolution cosmological N-body simulation data.

## Data : Shin-Uchuu simulation

We analyzed the high-resolution cosmological N-body simulation data, Shin-Uchuu simulation (Ishiyama et al. 2021).

| Name | $N$ | $L$ $(h^{-1}\mathrm{Mpc})$ | $\epsilon$ $(h^{-1}\mathrm{kpc})$ | $m_p$ $(h^{-1}M_\odot)$ |
|---|---|---|---|---|
| Shin-Uchuu | $6400^3$ | 140.0 | 0.4 | $8.97\times10^5$ |

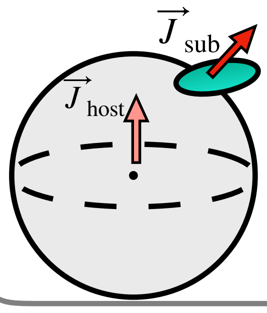
$N$ : the total numbers of particle  $L$ : box length
$\epsilon$: softening length  $m_p$: particle mass

Haloes and subhaloes are identified by ROCKSTAR halo finder (Behroozi et al. 2013a) and merger tree are constructed by the consistent tree code (Behroozi et al. 2013b). We restricted our sample to subhalos with $N > 10^3$ particles and analyzed about $1.4\times10^6$ samples at $z=0$.

## Analysis : The angle between vectors of angular momentum

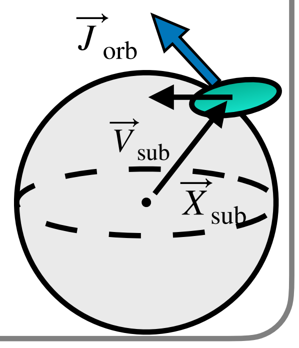
We calculated the angle between the internal angular momentum (spin) of the subhalo ($\mathbf{J}_{\mathrm{sub}}$), host halo ($\mathbf{J}_{\mathrm{host}}$) and the orbital angular momentum of the subhalo ($\mathbf{J}_{\mathrm{orb}}$) and investigated its dependence on the distance from the center of the host halo ($r/R_{\mathrm{host}}$).

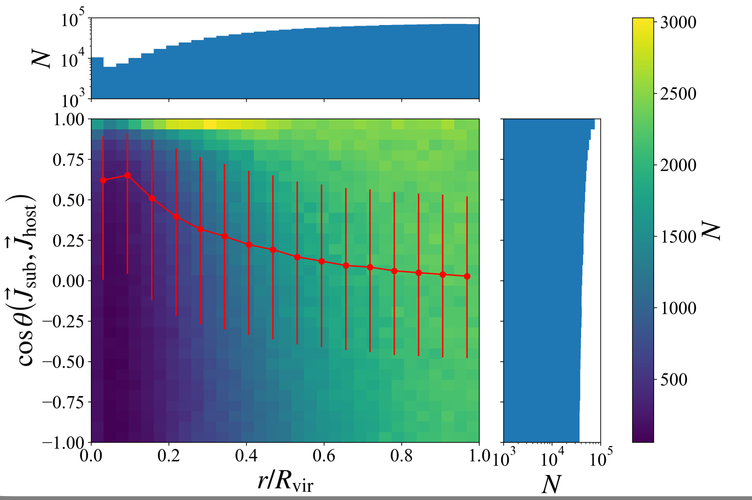
We calculated $\mathbf{J}_{\mathrm{orb}}$ and $r/R_{\mathrm{host}}$ based on the position, radius, and velocity in the data.




$$\cos\theta(\mathbf{X}_1,\mathbf{X}_2) \equiv \frac{\mathbf{X}_1\cdot\mathbf{X}_2}{|\mathbf{X}_1|\,|\mathbf{X}_2|}$$

$$\mathbf{X}_{1,2} = \mathbf{J}_{\mathrm{host}},\ \mathbf{J}_{\mathrm{host}}\ \text{or}\ \mathbf{J}_{\mathrm{orb}}$$




## Result 1: Dependence of $\cos\theta(\mathbf{J}_{\mathrm{sub}},\mathbf{J}_{\mathrm{host}})$ on the position at $z=0$

**Fig.1** : Sub-halo distribution divided by $r/R_{\mathrm{host}}$ and $\cos\theta(\mathbf{J}_{\mathrm{sub}},\mathbf{J}_{\mathrm{host}})$ bins.
・The 1D (2D) Histgram shows the number of subhaloes belonging to bins $r/R_{\mathrm{host}}$ or (and) $\cos\theta(\mathbf{J}_{\mathrm{sub}},\mathbf{J}_{\mathrm{host}})$, divided into 32 bins.
・Redline and error bars represent median and 25th and 75th percentile

・At the outskirt of the host halo ($0.6 \lesssim r/R_{\mathrm{host}}$), $\mathbf{J}_{\mathrm{sub}}$ is oriented randomly.

・At near the center of the host halo ($r/R_{\mathrm{host}} \lesssim 0.4$), $\cos\theta(\mathbf{J}_{\mathrm{sub}},\mathbf{J}_{\mathrm{host}})$ tends to increase toward the center, i.e. $\mathbf{J}_{\mathrm{sub}}$ tends to orient in the same direction as $\mathbf{J}_{\mathrm{host}}$.

## Result 2: Dependance of $\cos\theta(\mathbf{J}_{\mathrm{sub}},\mathbf{J}_{\mathrm{host}})$ on $M_{\mathrm{sub}}/M_{\mathrm{host}}$

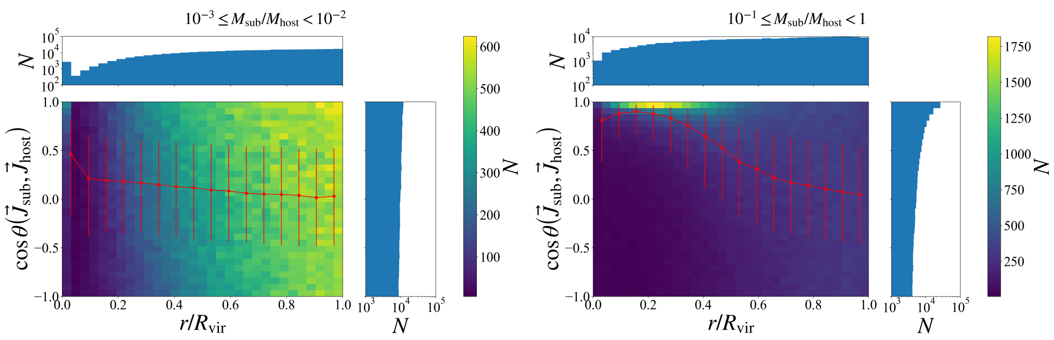



**Fig.2**: Same as Fig.1 but sample with $10^{-3} \le M_{\mathrm{sub}}/M_{\mathrm{host}} < 10^{-2}$( left panel) and $10^{-1} \le M_{\mathrm{sub}}/M_{\mathrm{host}} < 1$(right panel)

・When $M_{\mathrm{sub}}/M_{\mathrm{host}}$ is large (right), many subhaloes exist near the center of host halo, and the tendency is stronger than Result1.
・On the other hand, when $M_{\mathrm{sub}}/M_{\mathrm{host}}$ is small (left), fewer subhalos are exist near the center than on the outskirt of the host halo, and the direction of the angular momentum of subhaloes tends to be random to the center of the host halo from the outskirt of the host halo.

## Result 3: Subhalo orbit and spin of subhalo and host halo

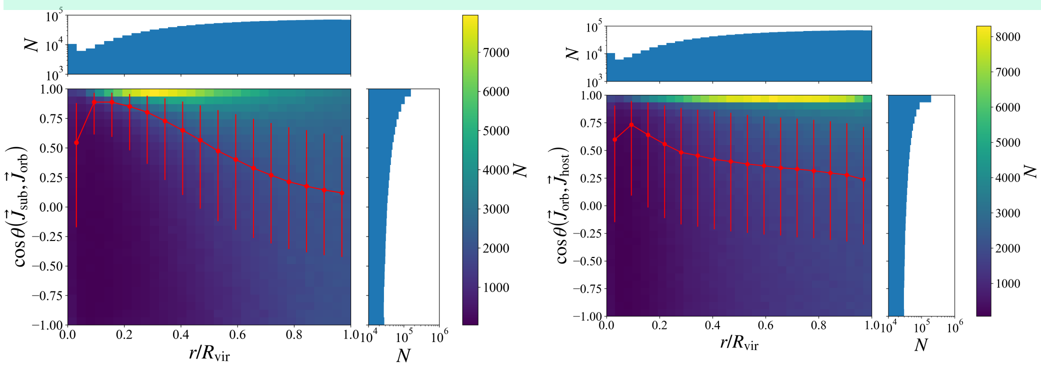



**Fig.3**: Same as Fig.1 but the Y-axis of left and right panel represent $\cos\theta(\mathbf{J}_{\mathrm{sub}},\mathbf{J}_{\mathrm{orb}})$ and $\cos\theta(\mathbf{J}_{\mathrm{orb}},\mathbf{J}_{\mathrm{host}})$ respectively.

・The spin and orbital momentum of subhaloes tends to align near the center of the host halo.
・It is consistent with the scenario where angular momentum is gained by tidal torque from the host halo.
・The direction of the orbital angular momentum of many subhaloes is aligned with the spin direction of the host halo.

## Summary and Discussion

・The subhalo acquires $\mathbf{J}_{\mathrm{sub}}$ in the same direction as $\mathbf{J}_{\mathrm{orb}}$ due to the tidal force exerted by the host halo.
・$\mathbf{J}_{\mathrm{orb}}$ tends to align with the direction of $\mathbf{J}_{\mathrm{host}}$.
・As a result, $\mathbf{J}_{\mathrm{sub}}$ and $\mathbf{J}_{\mathrm{host}}$ tend to be oriented in the same direction near the center of the host halo.
・The dependence on the $M_{\mathrm{sub}}/M_{\mathrm{host}}$ is due to the difference in timescales falling in the center.

## Reference

・Knebe, A., et al. 2020, MNRAS, 495, 3002
・Ishiyama T., et al., 2021, MNRAS, 506, 4210
・Behroozi P.S., et al. 2013a, ApJ, 762, L109
・Behroozi P.S., et al. 2013a, ApJ, 763, L18