粒子軌道に基づく
N体ハロー構造の解析

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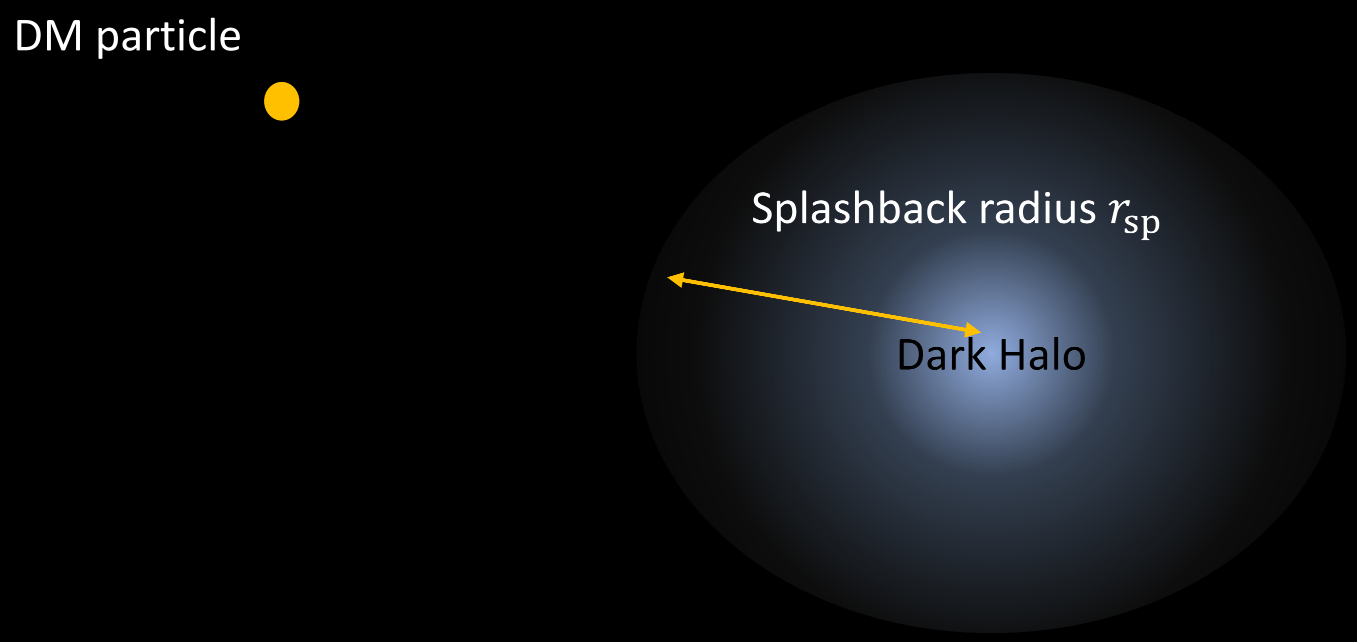
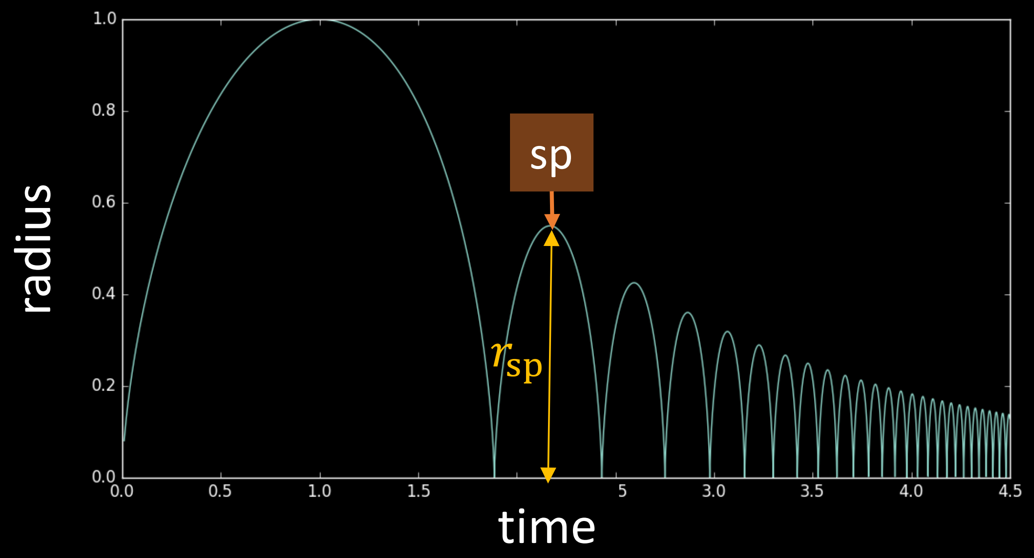
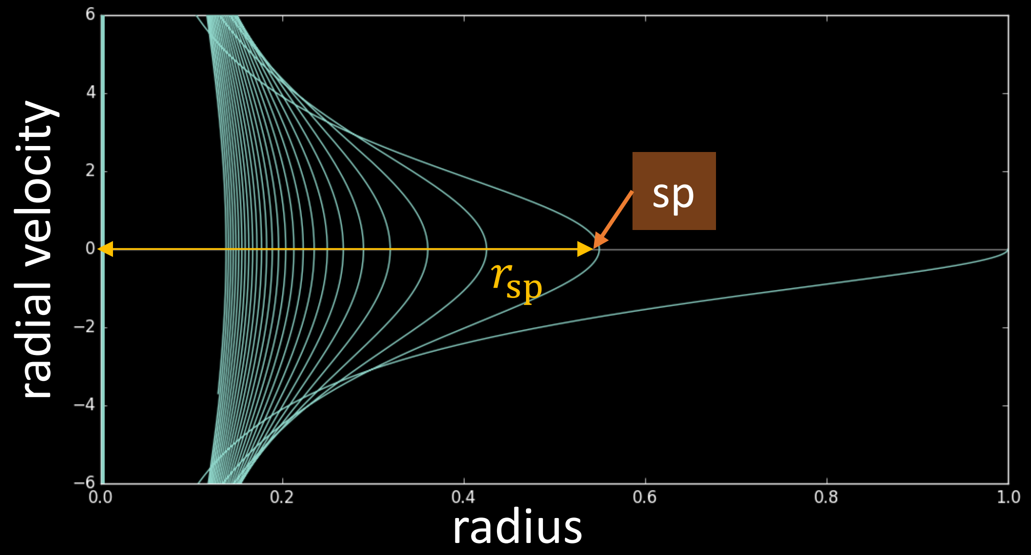
Introduction: What is Splashback Radius?



Splashback = first apocenter passage of particles, accreting to a halo.

ideal particle trajectory w/o angular momentum





Accretion of DM into a halo

$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{GM(t,r)}{r^2}\hat{\boldsymbol{r}}.$$

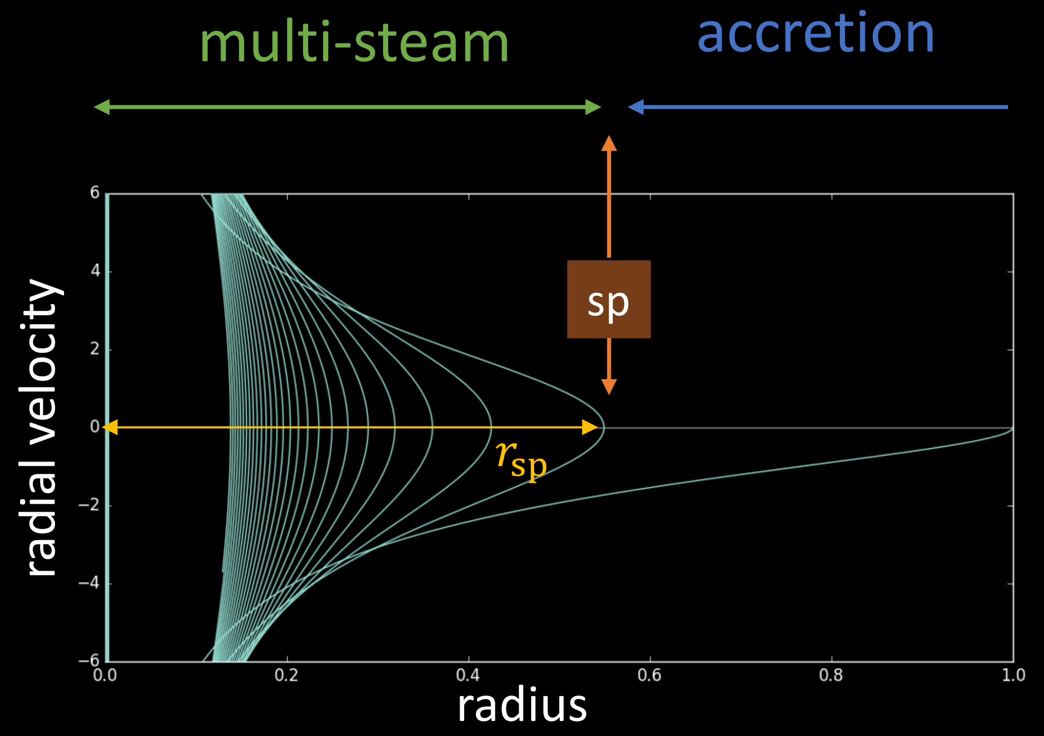
Cf. Fillmore & Goldreich (1984),
Adhikari, Dalal, Chamberlain (2014)

The first apocenter is
the "splashback point".

It is not so easy to analyze particle motion after shell-crossing in analytic way.

R_{sp} as Halo Boundary

This radius can be regarded as a physically-motivated halo boundary.



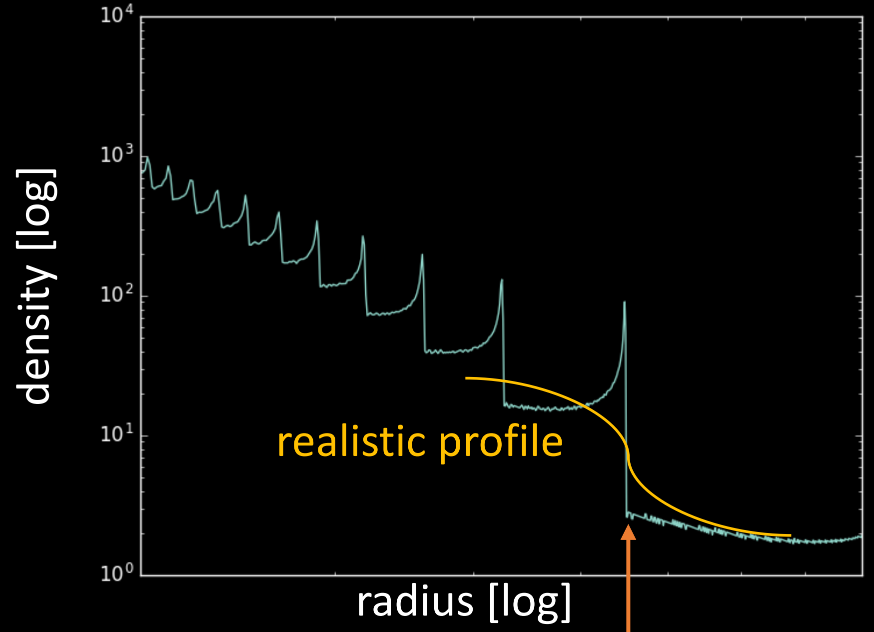
Splashback mass M_{sp} is a physically reasonable definition of halo mass.

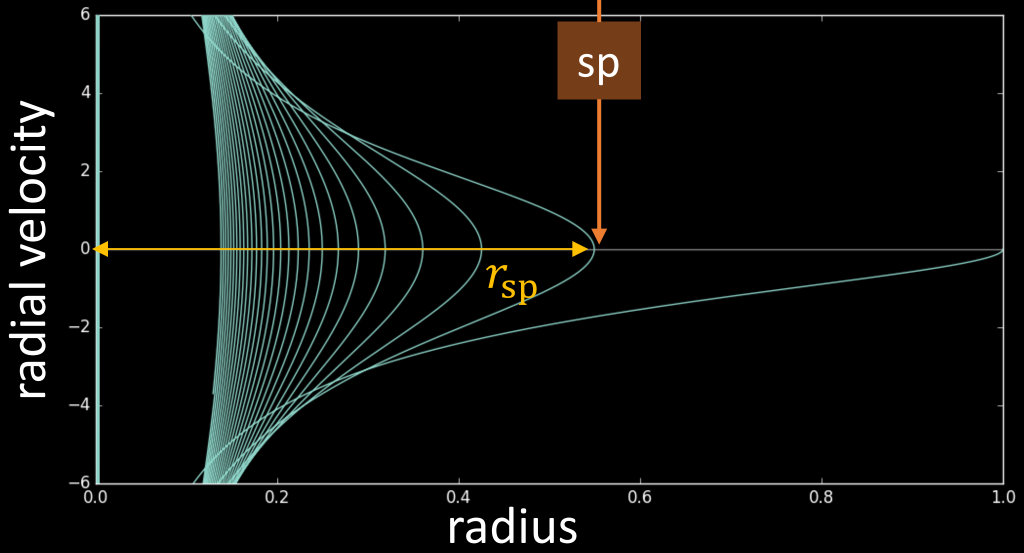
1. boundary between multi-stream region and accreting region

2. It does not exhibit "pseudo-evolution." (More, Diemer & Kravtsov 2015)

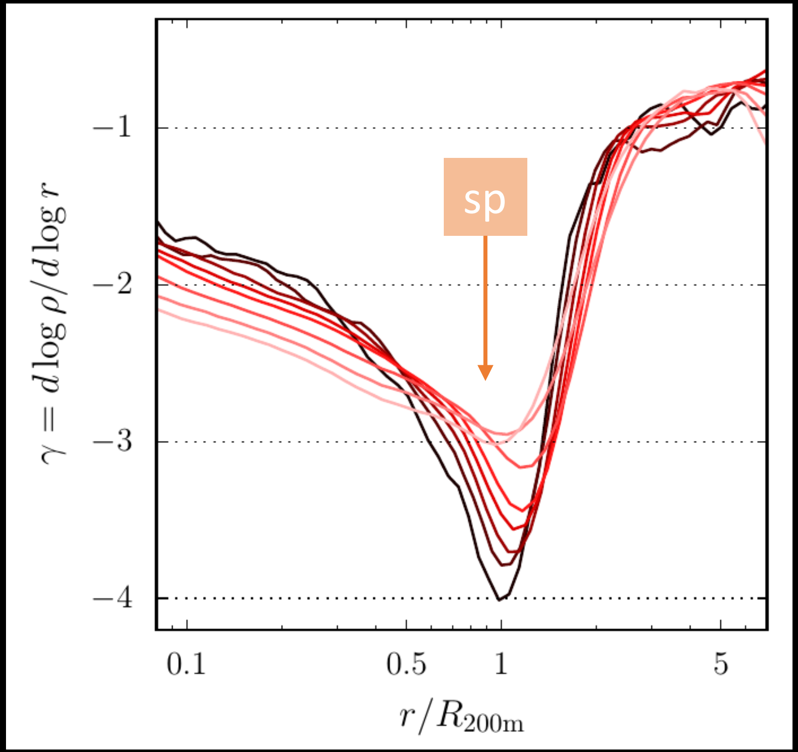
3. detectable signs in density profile

R_{sp} and Density Profile





We can detect splashback radius by density slope $\gamma = \frac{d \ln \rho}{d \ln r}$.



density slope of stacked N-body halo
(cited from Diemer & Kravtsov 2014)

Previous Works

- SPARTA algorithm: how to calculate $R_{\rm sp}$ in N-body simulation
  Diemer (2017)
- Application of SPARTA to investigate halo properties
  Diemer et al. (2017)

↑do not quantify asphericity

↓do not use particle data

- “Splashback Shell”
  Mansfield, Kravtsov & Diemer (2017)

Other works:

- $R_{\rm sp}$ depends on accretion rate and Ω_{m0}.
  Adhikari, Dalal & Chamberlain (2014), Shi (2016)
- Weak lensing
  More et al. (2016), Chang et al. (2017)
- Relation to Halo Assembly Bias
  More et al. (2016), P. Busch & S. White (2017)

Cf. Jing & Suto (2002)

Main idea of our work

1. It is possible to use not only the first apocenter, but also other apocenters.
2. It is possible to formulate asphericity of dark halos.

In order to do it, we define “period” of a particle as the number of apocenter-passages.

This method gives characterization of halos, based on purely dynamical structure without assumptions such that spherical overdensity or FoF.

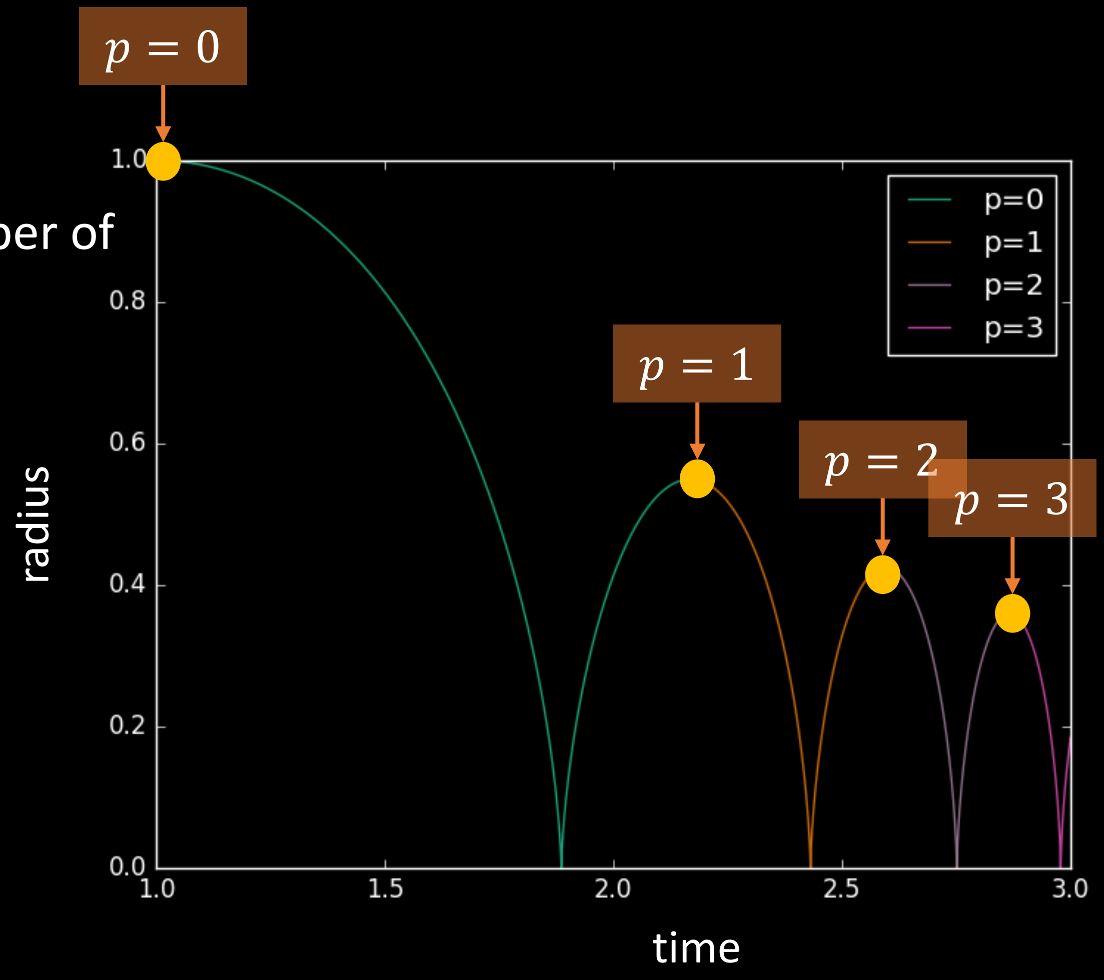
Definition of Period

We propose a new particle attribute “period.”

For each particles, we define period p as the number of apocenter-passages.

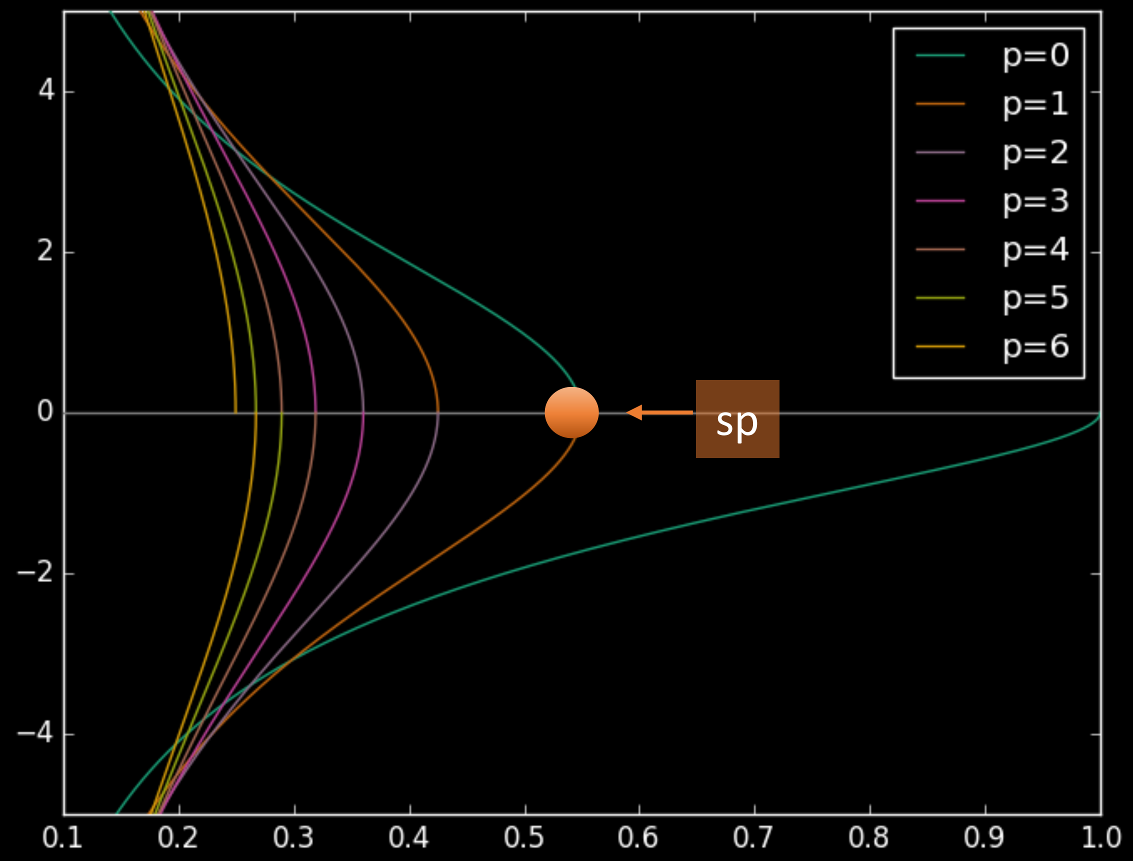
The point where $p = 0 \rightarrow 1$
is the splashback point.

-> “generalized splashback”



Meaning of Period

Clasiffication by period = decomposition of a halo into “phase shells.”



Particles whose p is a given value consist of:

1. Accreting component
2. Ascending component

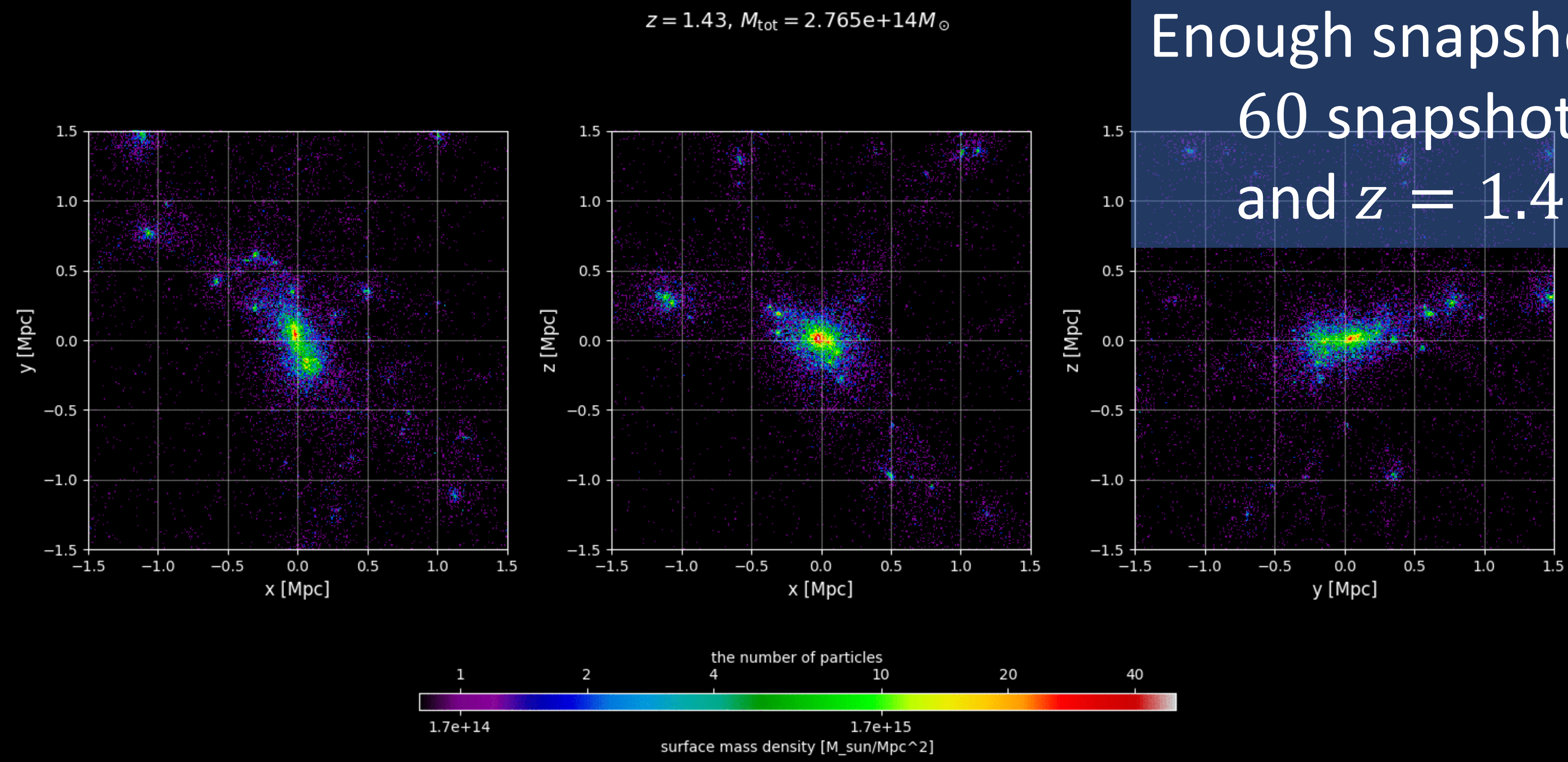
N-body Simulation

N-body simulation data is provided by Yann Rasera.

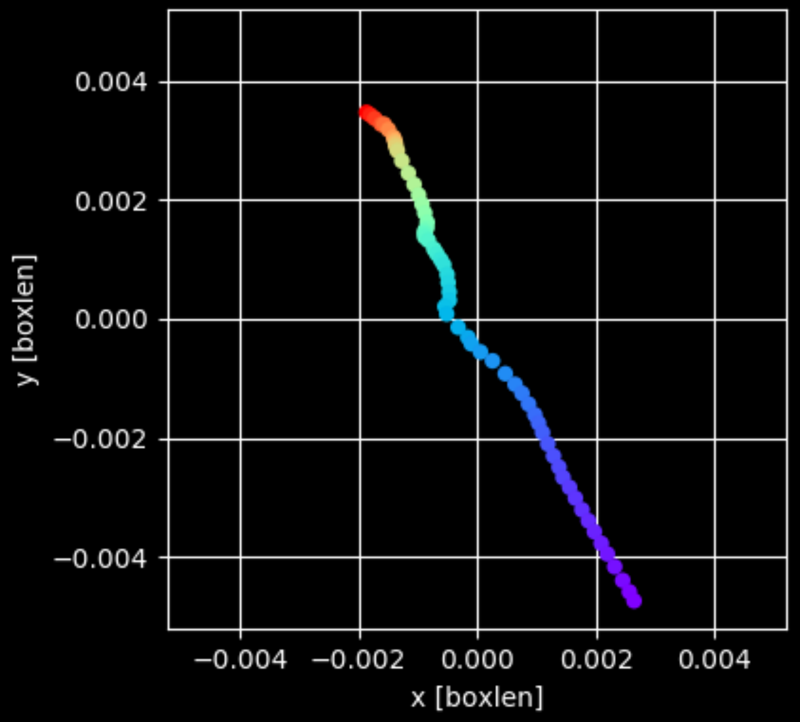
EdS universe ($\Omega_m = 1$), $L = 318$ Mpc/h, $N = (512)^3$, $H_0 = 72$ km/s/Mpc

Enough snapshots are stored:

60 snapshots between $z = 0$ and $z = 1.43$.



Halo Motion



We define "halo motion" by the following algorithm:

1. Choose N_p particles closest to the center of the halo.
2. Read the previous snapshot, and determine positions of these particles.
3. Set (density-weighted) center of mass of these particles as the "center" of the halo in this snapshot.
4. Repeat this procedure.

This reflects the motion of densest region of the halo.

Calculation of Period

1. Set $p = 0$ for every particles in the initial snapshot.

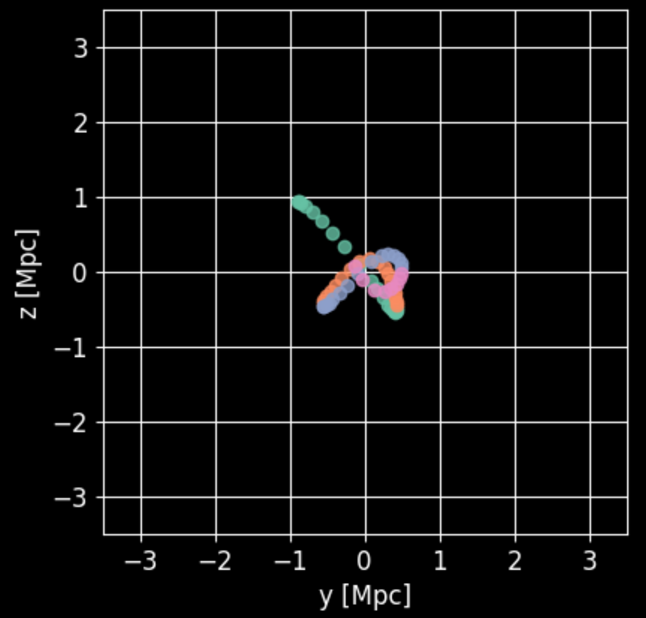
2. Read following data, and if

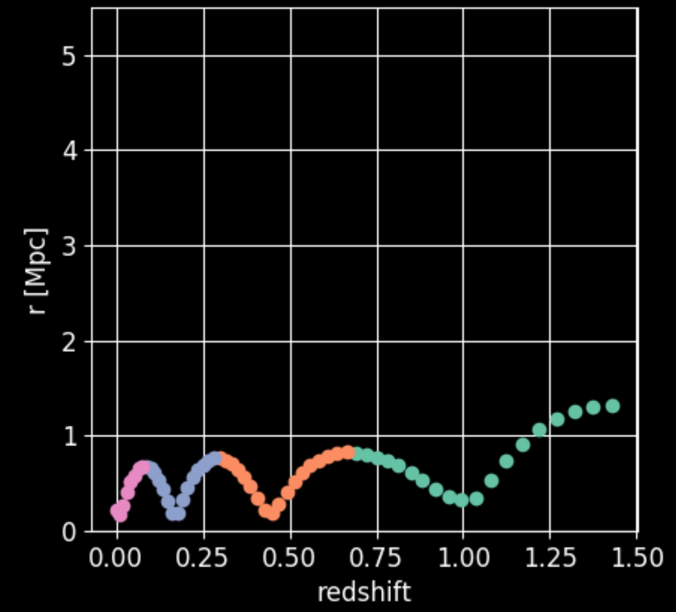
$$v_r(z_{\text{prev}}) \geq 0 \text{ and } v_r(z) \leq 0,$$

record $p = p_{\text{prev}} + 1$, else p_{prev}.

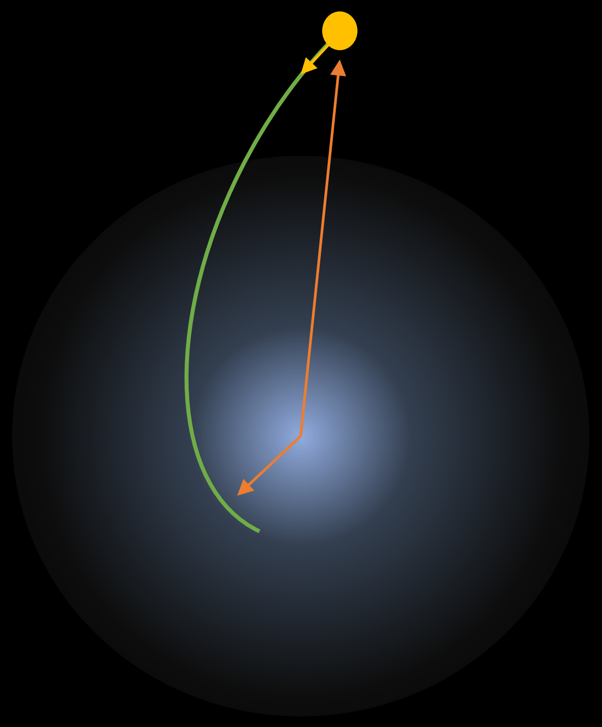
3. Repeat this procedure until $z = 0$.

-> We get lists of p-values for each particles.





Difference from Diemer's SPARTA



The motion of particles in a subhalo

1. Large motion in the main halo
2. Small motion in the subhalo.

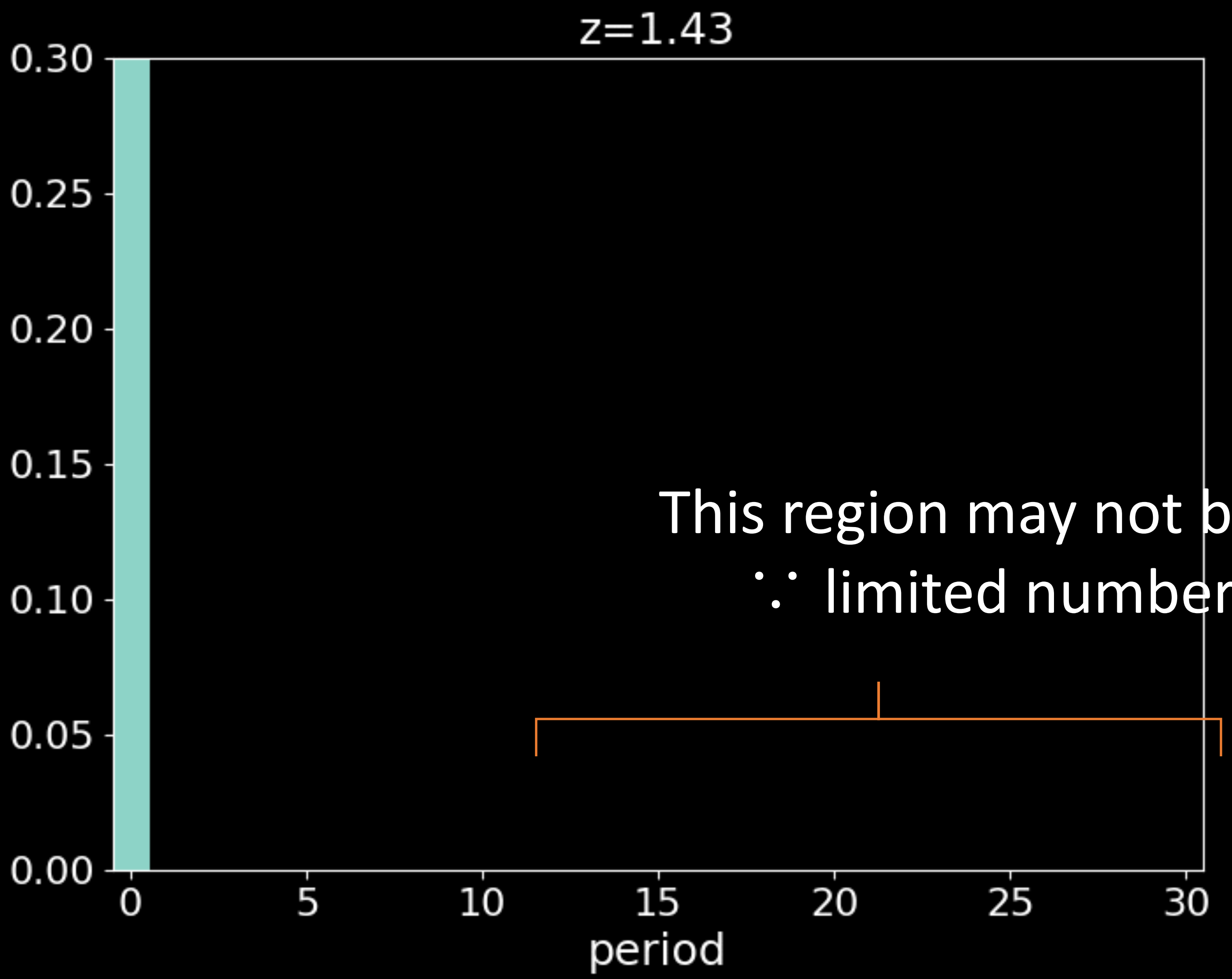
-> we require that a particle must experience

$$\boldsymbol{r}(z_1) \cdot \boldsymbol{r}(z_2) < 0$$

between adjacent apocenters.

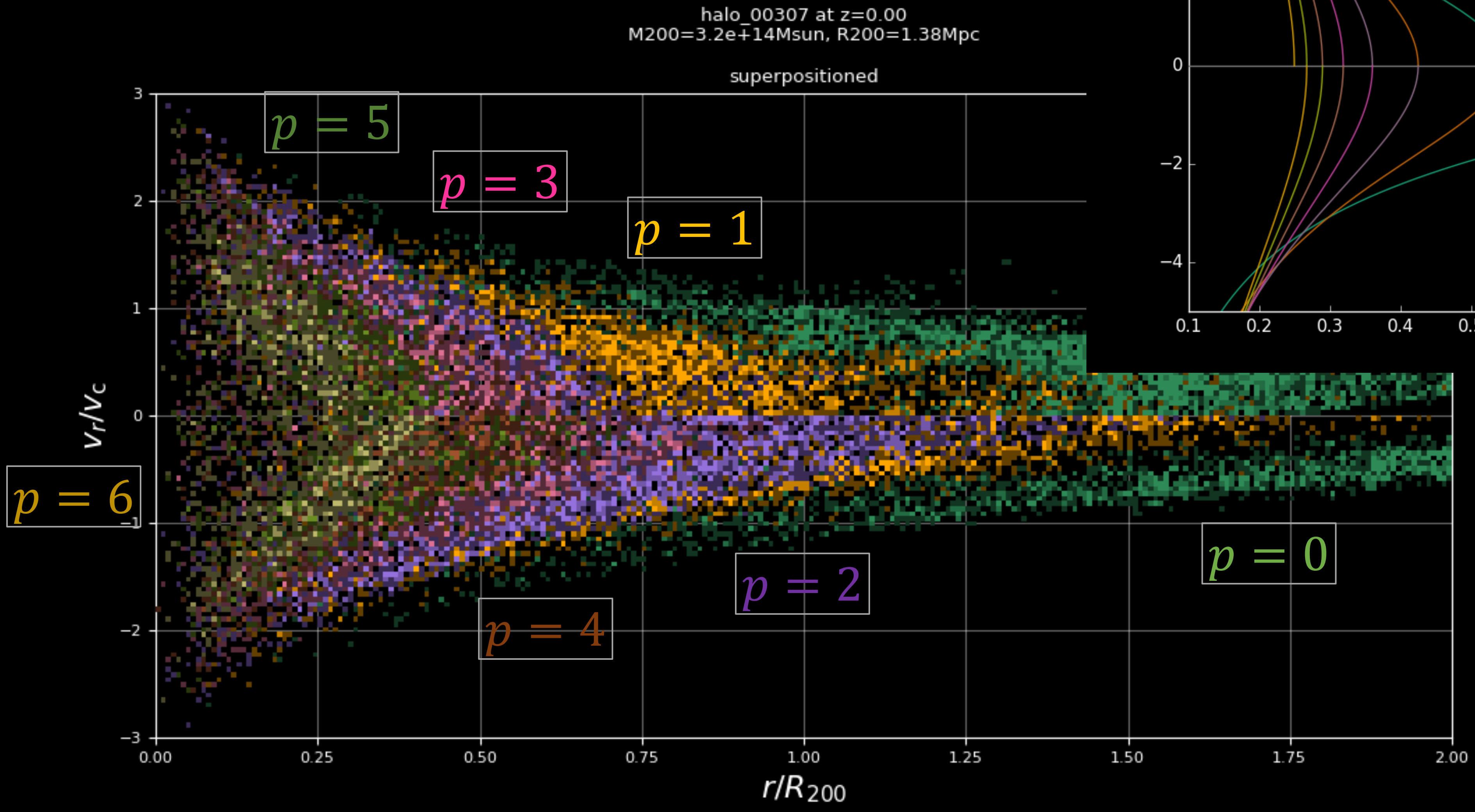
This is an important difference from Diemer's SPARTA, which deals with subhalos as ONE object and particles belonging to them are NOT decomposed.

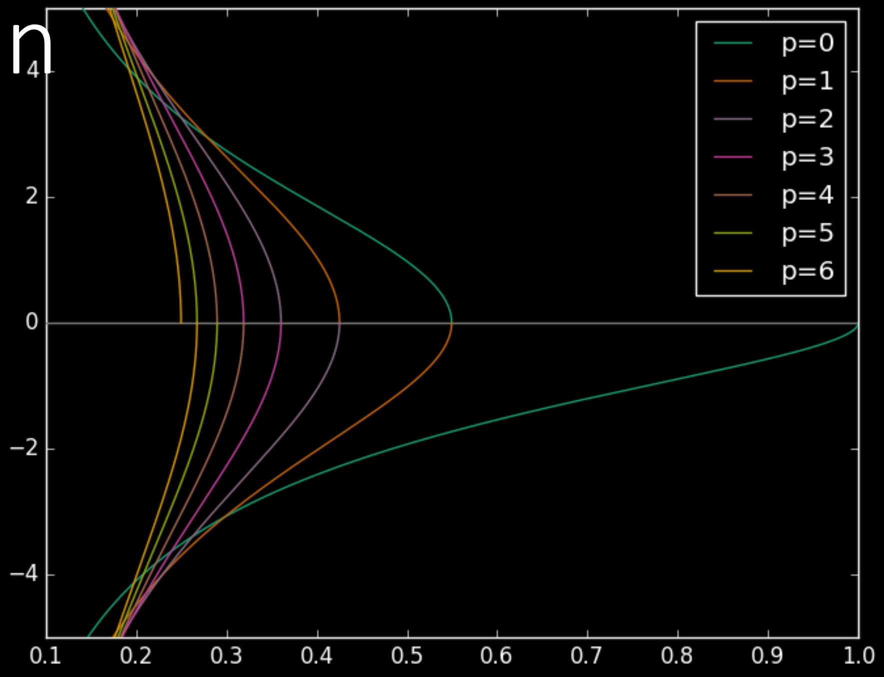
Result: Period Distribution



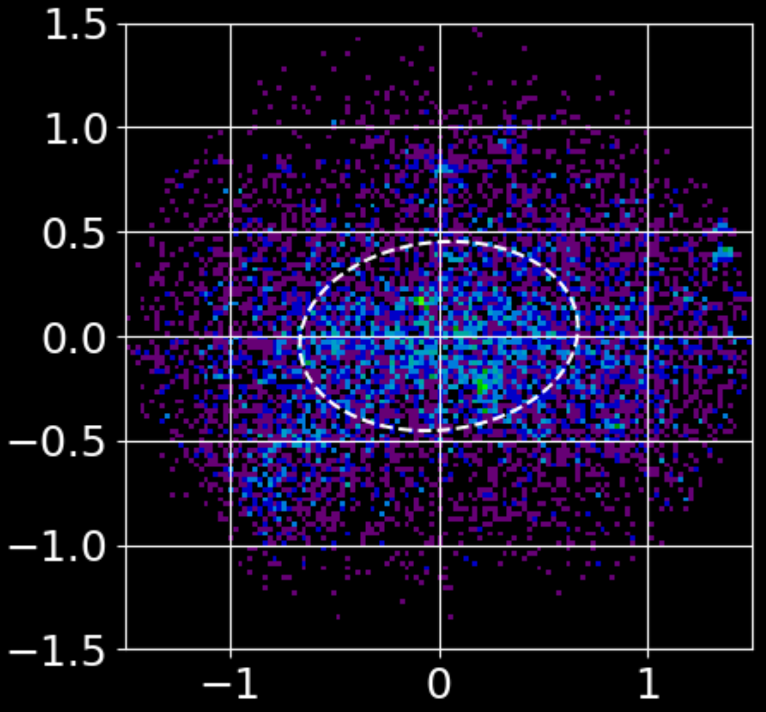
This region may not be correct values.
∵ limited number of snapshots

Result: Phase-shell Decomposition





Inertial tensor & Halo shape



Inertial tensor of phase-shell p is given by

$$I_{ij}^{(p)} = \frac{1}{N_p} \sum_{p_a = p} x_i^{(a)} x_j^{(a)} \,.$$

$x_i^{(a)}$: position of the particle a relative to the C.M.

p_a : period of the particle a

Jing & Y. Suto (2002), D. Suto et al. (2016), etc.

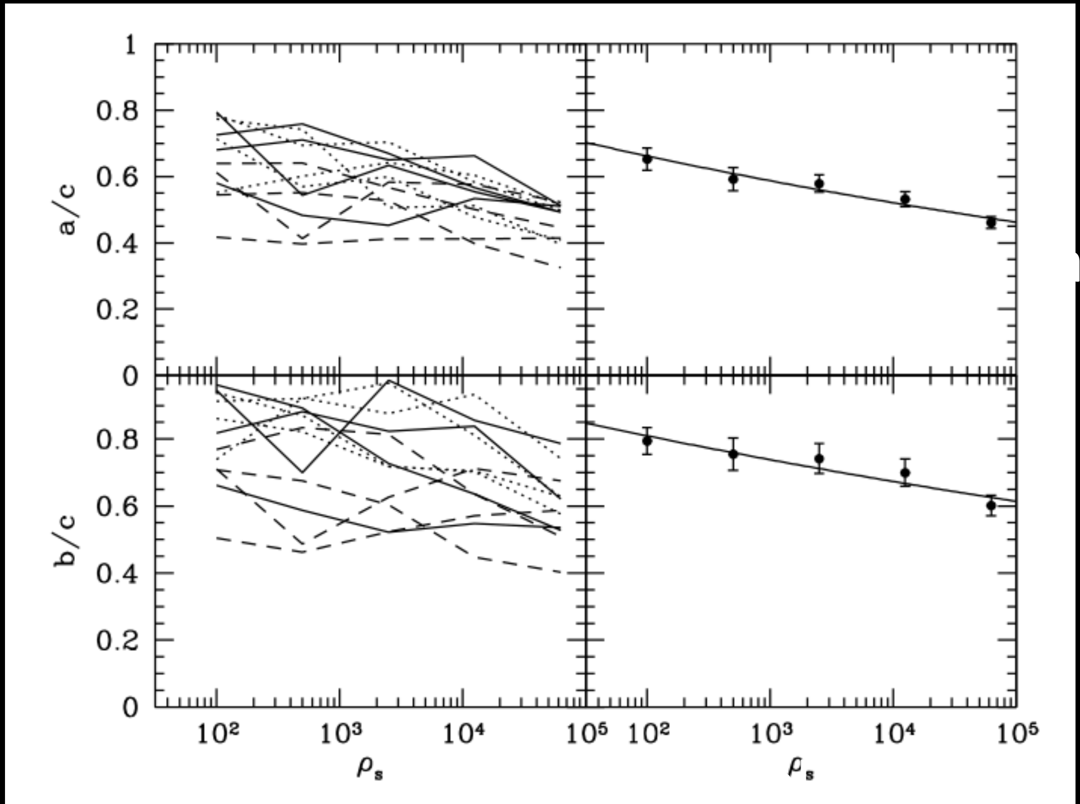
Average radius R_p is given by

$$R_p = \sqrt{\frac{1}{3} \mathrm{tr}\left(I_{ij}\right)} = \left(\frac{a^2 + b^2 + c^2}{3}\right)^{1/2}$$

Eigenvalues of I_{ij} gives axis lengths a, b, c.

$$I_{ij} \sim \begin{pmatrix} a^2 & & \\ & b^2 & \\ & & c^2 \end{pmatrix}$$

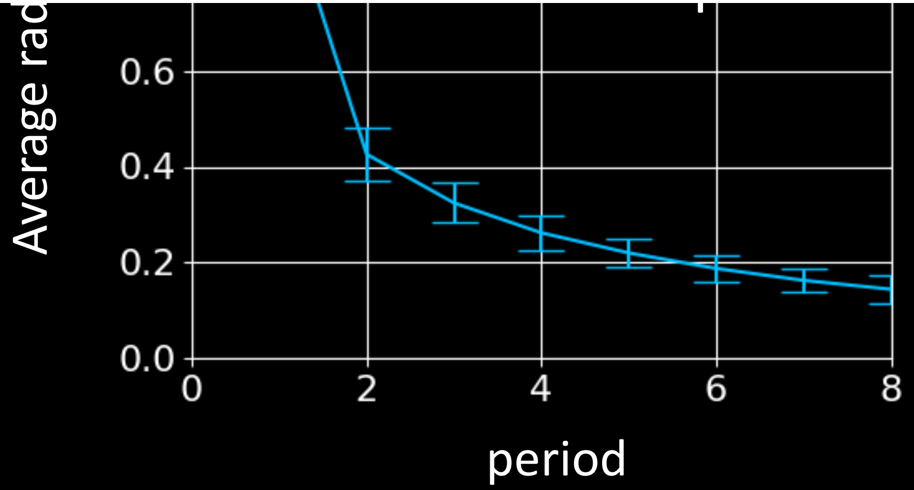
Jing & Suto (2002): isodensity sphere

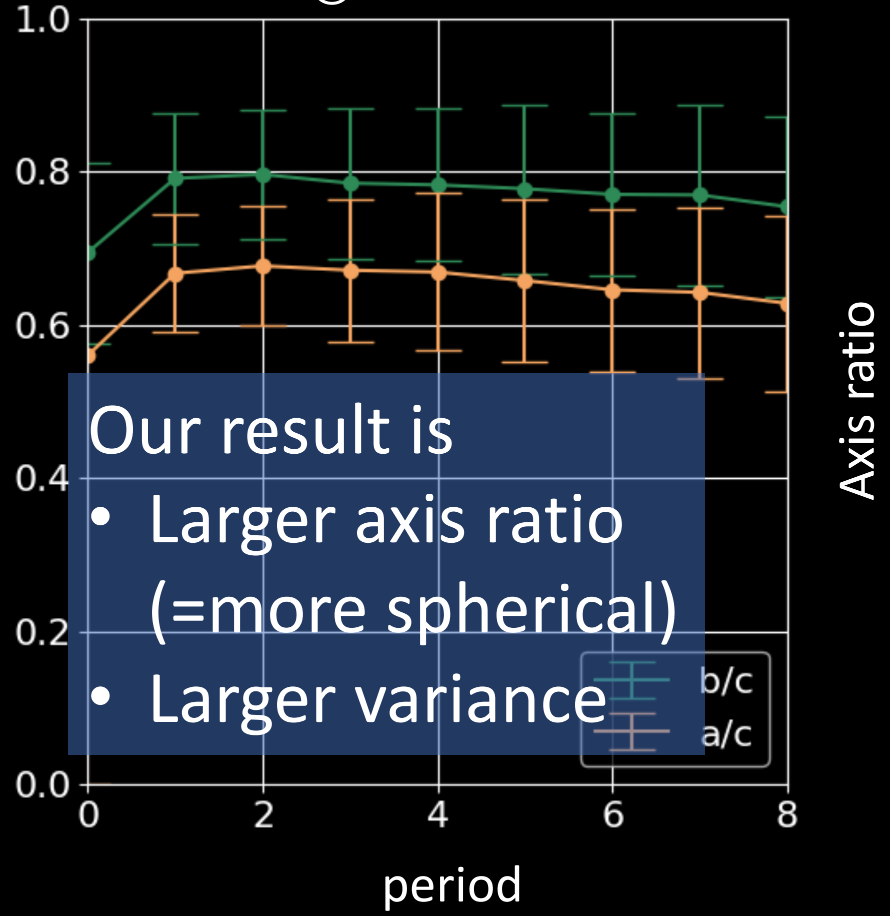


tio for 139 halos,

$3.2\times10^{14}M_{\odot}$

Our approach can quantify more outer region.



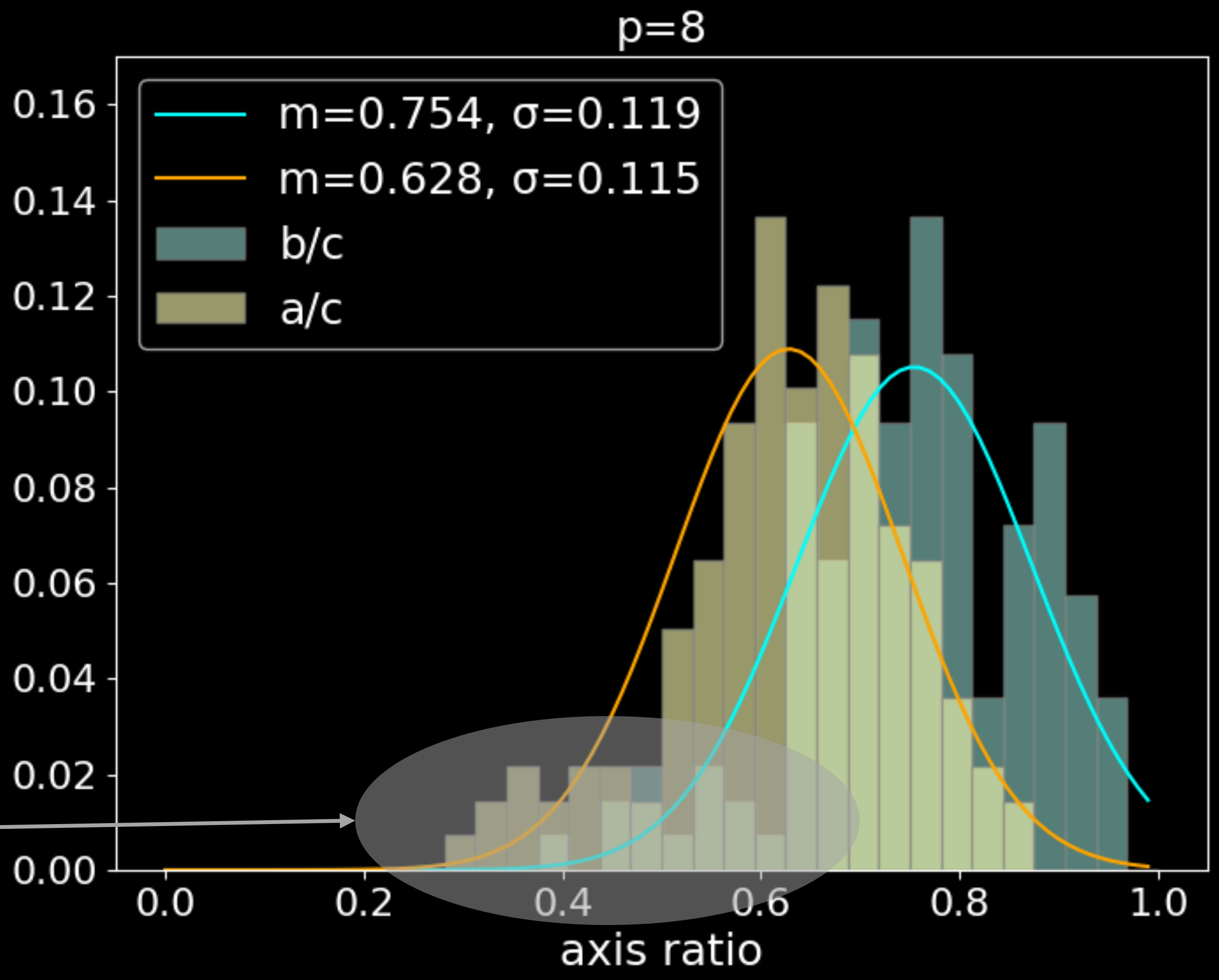


Our result is
- Larger axis ratio (=more spherical)
- Larger variance

preliminary

Discussion: Axis Ratio

preliminary



Peculiar tail: This may be due to major merger.

To-do list

- mass accretion history
  - Relation of R_{sp} to accretion history is interesting. (Diemer & Kravtsov 2014)
  - How does it effect on other quantities?

- Splashback mass

$$\sum_{i,j} I_{ij}^{(\mathrm{sp})} x_i x_j \leq 1$$

- (Non-spherical) density profile & obervability of inner shells
  - "Second splashback" shell may be destroyed by spherical average.

Summary

- Splashback radius of a halo

- My work: classify particles by the number of apocenter-passages.
  - $p = 1$ particles define a "splashback shell".
  - Higher-p particles define "inner shells."

- Halo structures:
  - Shell radius, axis ratio, density profile, …

- Future work: application to the observations.

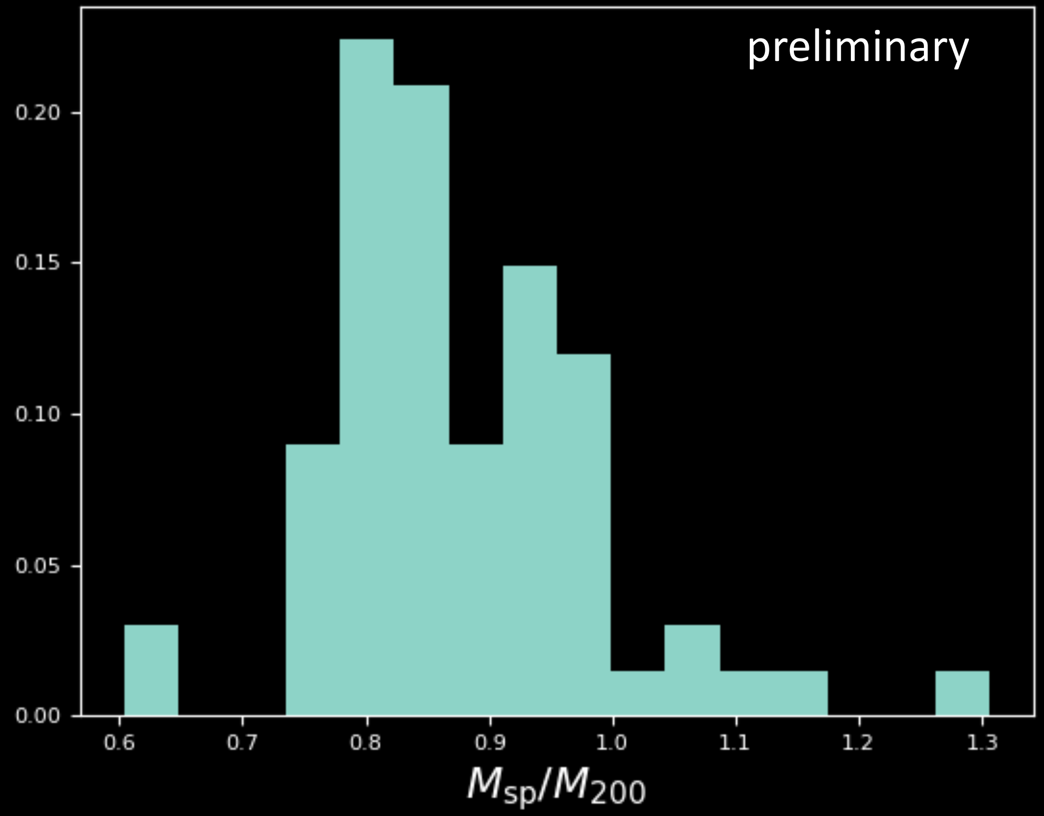
Calculation of period

```
if ( flag== 0 ) and ( np.dot(r0,r1) >= 0 ):
        period.append(period[-1])
else:
        flag = 1
        vr0 = np.dot( r0, v0 )
        vr1 = np.dot( r1, v1 )
        if ( vr0 > 0 ) and ( vr1 <= 0 ):
                period.append(period[-1]+1)
                flag = 0
                direction[id] = x1
        else:
                period.append(period[-1])
```

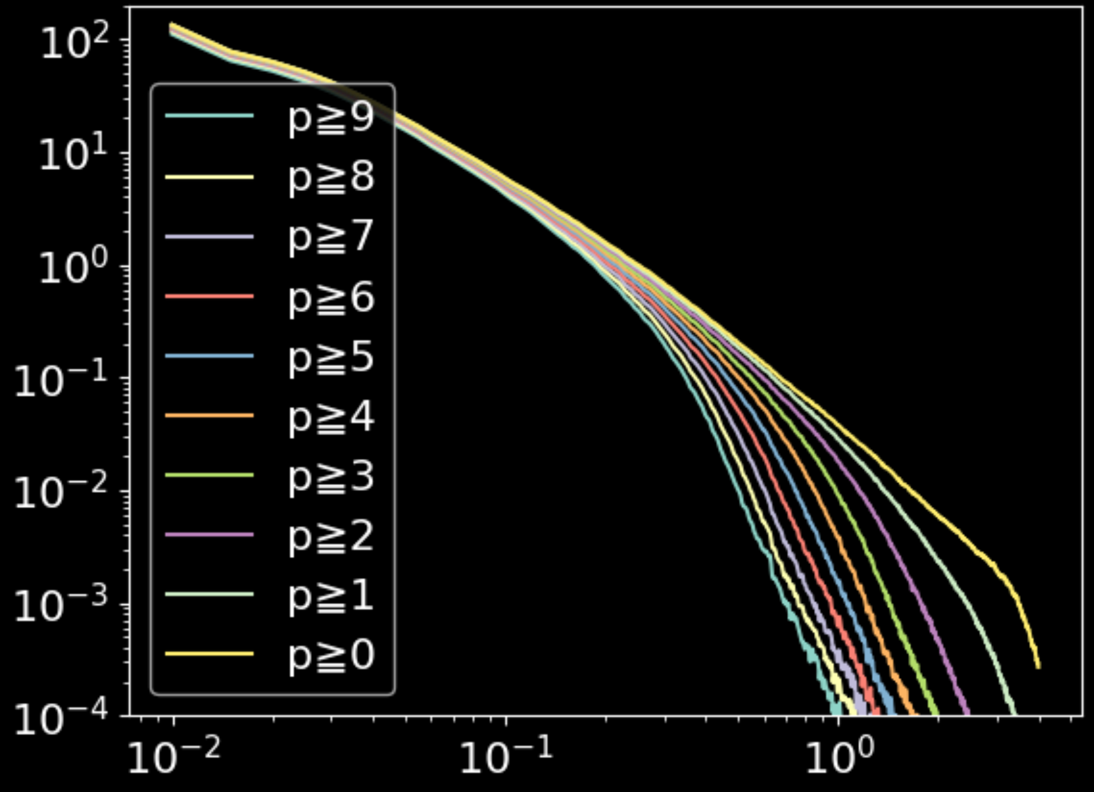
Halo Mass

Non-spherical splashback mass:

$$\sum_{i,j} I_{ij}^{(\mathrm{sp})} x_i x_j \leq 1$$



Result: Density Profile



halo_00188 z=0.0
9≦p<30