

## BULLET GROUPS AS A TEST OF $\Lambda$ CDM

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### ABSTRACT

We estimate the expected distribution of displacements between the two dominant dark matter peaks in halos within a mass range corresponding to galaxy groups. We find that the probability of finding a system similar with displacements of  $\sim 400 \text{ kpc h}^{-1}$  is between 40% for  $z=0$  and 60% for  $z=1$  and  $\Lambda$ CDM standard model, which correspond to the observational constraint the object SL2S J08544-0121 that is a gravitational lens found in the SL2S and located at  $z=0.35$ . Given the larger abundance of groups with respect to clusters, finding multi-modal groups and baryonic-dark matter displacements.

*Subject headings:* cosmology: theory – dark matter

### 1. INTRODUCTION

The Bullet Cluster provided a new kind of observational evidence of the existence of dark matter. Quantifying the displacement between dark matter and the dominant baryonic component (hot X-ray emitting gas) has been used to test the CDM paradigm itself by quantifying the substructure velocity required to produce such displacement and also by estimating the expected abundance of such events in the Universe.

Since that time there are other observations of other Bullet-like systems [...].

Recently (Gastaldello et al. 2014) observed baryonic-DM displacement of  $124 \pm 20 \text{ kpc}$  in a group-like system with a total mass  $2.4 \pm 0.6 \times 10^{14} M_{\odot}$ . Systems of this mass are  $\sim 10$  times more massive than cluster systems in the mass range  $> 10^{15} h^{-1} M_{\odot}$ , this opens up the possibility of observationally finding bullet groups in a fair amount to impose constraints on  $\Lambda$ CDM. This greater abundance has to be weighted by the fraction of systems that present large displacements. Such study has been performed for clusters but not for lower mass systems.

In this Letter we present prediction for the abundance of group-like systems that might show a DM-baryon displacement. To this end we use a N-body cosmological simulation with such a resolution that allows us to identify multimodal dark matter clumps in the circular velocity range  $300 - 1000 \text{ km s}^{-1}$ .

This paper is organized as the follows. In Section 2 we present the simulation and the halo catalogs used in this work. We continue in Section 3 with the geometry of the problem at hand and the measurements setup. Next in Section 4 we present our results to finish with a discussion and conclusion in Sections 5 and 6.

### 2. SIMULATION AND HALO CATALOGS

We use the Bolshoi Run, a cosmological DM only simulation over a cubic volume of 250 comoving  $h^{-1} \text{Mpc}$  on a side. The simulation uses the ART code to follow the evolution of a dark matter density field sampled with  $2024^3$  from  $z = 80$  to  $z = 0$  [...]. The cosmology used corresponds to the spatially flat concordance model with the following parameters: the density parameter for

matter (dark matter+baryons)  $\Omega_m = 0.27$ , the density parameter for baryonic matter  $\Omega_b = 0.0469$ , the density parameter for dark energy  $\Omega_{\Lambda} = 0.73$ , the Hubble parameter  $h = 0.7$ , the normalization of the Power spectrum  $n = 0.95$  and the amplitude of mass density fluctuation (at redshift  $z=0$ )  $\sigma_8 = 0.82$ . The number of particles used for each of the DM component was  $2048^3$ , resulting in a mass resolution of  $1.35 \times 10^8 M_{\odot} h^{-1}$ . Klypin et al. (2011).

### 3. BULLET GEOMETRY AND MEASUREMENT SETUP

The configuration of the BGs in the simulations is shown in Figure 1. There we depict a host and its most massive sub-halo from in a particular case found at  $z=0$ . The arrows show the position and the velocity vectors sub-halo in a frame of reference where the main halo is at rest; thus  $\vec{v} = \vec{v}_{sub} - \vec{v}_{halo}$  and  $\vec{r} = \vec{r}_{sub} - \vec{r}_{halo}$ . The angle between these two vectors characterized by,

$$\mu \equiv \cos(\theta) = \frac{\vec{v} \cdot \vec{r}}{\|\vec{v}\| \|\vec{r}\|} \quad (1)$$

encodes the geometry of the collision, i.e. cases of  $|\mu| \approx 1$  can be considered as head-on collisions while  $|\mu| \approx 0$  describe a grazing trajectory.

The bullet-like encounter can be instantaneously described by quantities the following quantities the circular velocity of the host and the sub-halo,  $V_{c,host}$  and  $V_{c,sub}$ ; the size of the host halo  $R_{vir}$ ; the relative position and velocity of the substructure,  $\vec{v}$  and  $\vec{r}$ ; and the angle between the position and velocity  $\mu$ .

Using these quantities one can describe three main stages in a Bullet-like collision. First, the sub-halo crosses the virial radius of the host halo in a head-on fashion,  $|\vec{r}|/R_{vir} \approx 1$  and  $\mu \approx < 0.0$ . Second, as the sub-halo crosses for the first time the center of the host halo  $|\vec{r}|/R_{vir} < 1.0$  and  $\mu > 0.0$ . Third, as the sub-halo reaches apogee and comes back to the center of the halo  $|\vec{r}|/R_{vir} < 1.0$  and  $\mu < 0.0$ .

the mass ranges and number of host halos and substructures are summary in the Table 1. Of all the possible configurations that can be presented in Figure 1, we are interested in estimate in the simulation the number

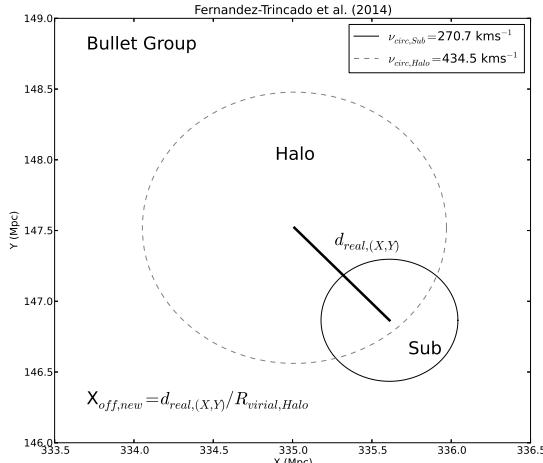


FIG. 1.— Configuration for a host halo (dashed circle) and substructure (black circle) in the sample.

of Bullet Groups that may be present in an Universe of  $250 h^{-1}\text{Mpc}$ . For this we selected of the simulations all the substructures whose velocities indicate a movement out of the host halo. Each halo in this sample has a quantity called  $X_{off}$  that corresponds to the distance halo center (the minimum of the gravitational potential) to the center of mass normalized by the virial radius ( $R_{vir}$ ). Values of  $X_{off}$  equal to zero indicate relaxed halos, while  $X_{off} > 0$  indicates the existence of perturbed halos which can be considered candidates to be Bullet Groups and this ditribution is shown in a scatter plot in the Figure 2 and the distribution of  $\nu_{circ,Halo}/\nu_{circ,Sub}$  is shown in Figure 3, both figures for different z.

#### 4. RESULTS

##### 4.1. Cumulative Probability Distributions

We selected four snapshot of the simulation for four different redshifts ( $z=0$ ,  $z=0.25$ ,  $z=0.5$  and  $z=1$ ) based in the distribution of redshift in the Figure 1 by Verdugo & Foex (2014), and for each sample in redshift we selected the host halo with circular velocities greater than  $300 \text{ km s}^{-1}$  and was split in two principal groups: The first group correspond to host halo with circular velocities between  $300 \text{ km s}^{-1}$  to  $700 \text{ km s}^{-1}$  with mass in the range of  $10^{12} M_\odot$  to  $10^{14} M_\odot$  in the range of mass of the Bullet Groups, and second group correspond to host halo with circular velocities greater than  $700 \text{ km s}^{-1}$  with mass  $\geq 10^{14} M_\odot$ , in the range of mass of the Bullet Clusters, in the Table 1 is shown the two groups selected in this

work. For each group, we classified the corresponding substructures most massive and associated with the corresponding host halo. In this work, we estimate the expected distribution of displacements ( $d_{real,(X,Y)}$ ) in the projection 2-D that can estimated by observations, these displacements correspond to the separation between the minimal potential of the host halo and the minimal potential of the substructure, both are dark matter distributions.

In order to explore the distribution of displacements expected in the observational, we define a new parameter given by:

$$\frac{v_{circ,sub}}{v_{circ,halo}} = 0.5 \quad (2)$$

Figure 4 shows the scatter plot of the parameter  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right)$  vs the displacement ( $d_{2d,(X,Y)}$ ) between the host halo and the substructure and for different redshifts. This parameter is consistent with the observations. The red star simbol in the Figure 4 is equal to 0.54 corresponding to the fraction in velocity dispersion in the line-of-sigth of the group SL2S SJ08544-0121 ( $\sigma_{host,halo} = 341^{+43}_{-109} \text{ km s}^{-1}$  and  $\sigma_{substructure} = 185^{+30}_{-62}$ ), reported by Muñoz et al. (2013). Based in the parameter  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right) > 0.5$ , we estimate the expected distribution of displacements and this is shown in the Figure 5 for the two groups classified in this work.

##### 4.2. Number expected of Bullet Groups in the sample

In order to estimate the number of Bullet Groups expected in the Bolshoi Cosmological Simulation, we define the configuration of this system as one where the substructure is coming out of the host halo ( $\cos(\theta) > 0.5$ ). For this we make the scalar product between the velocity vector and position vector that defines the separation between the host halo and the substructure, as shown below:

#### 5. DISCUSSION

#### 6. CONCLUSIONS

#### ACKNOWLEDGEMENTS

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Sample	Minimum $V_c$ km s $^{-1}$	Maximum $V_c$ km s $^{-1}$	# Halos $z = 0$	# Halos $z = 0.25$	# Halos $z = 0.5$	# Halos $z = 1$
Host	300 km s $^{-1}$	XX	400	362	310	192
Sub-structure	75 km s $^{-1}$	XX	XX	XX	XX	XX

TABLE 1  
CIRCULAR VELOCITY RANGES FOR THE HALOS AND SUBHALOS AT DIFFERENT REDSHIFTS.

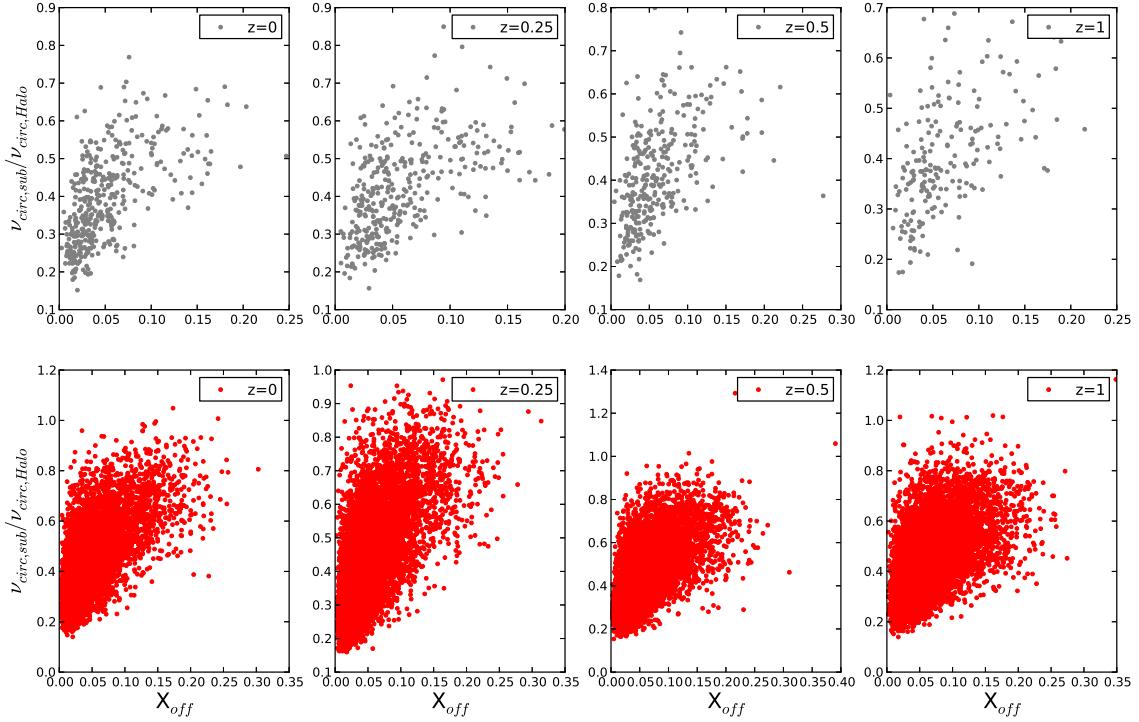


FIG. 2.— Scatter plot for  $X_{off}$  as function of the relation between velocities of substructures and the host halos and for different  $z$ . The top panel is represented to the sample with  $v > 700$  km s $^{-1}$  and down panel is represented for  $v < 700$  km s $^{-1}$

FIG. 3.— Integrated distributions of  $|\vec{v}|/V_{c,\text{host}}$  at all  $z$ . The left panel correponds to the sample with  $V_{c,\text{host}} > 700$  km s $^{-1}$  and right panel correpond to the sample with  $V_{c,\text{host}} < 700$  km s $^{-1}$ .

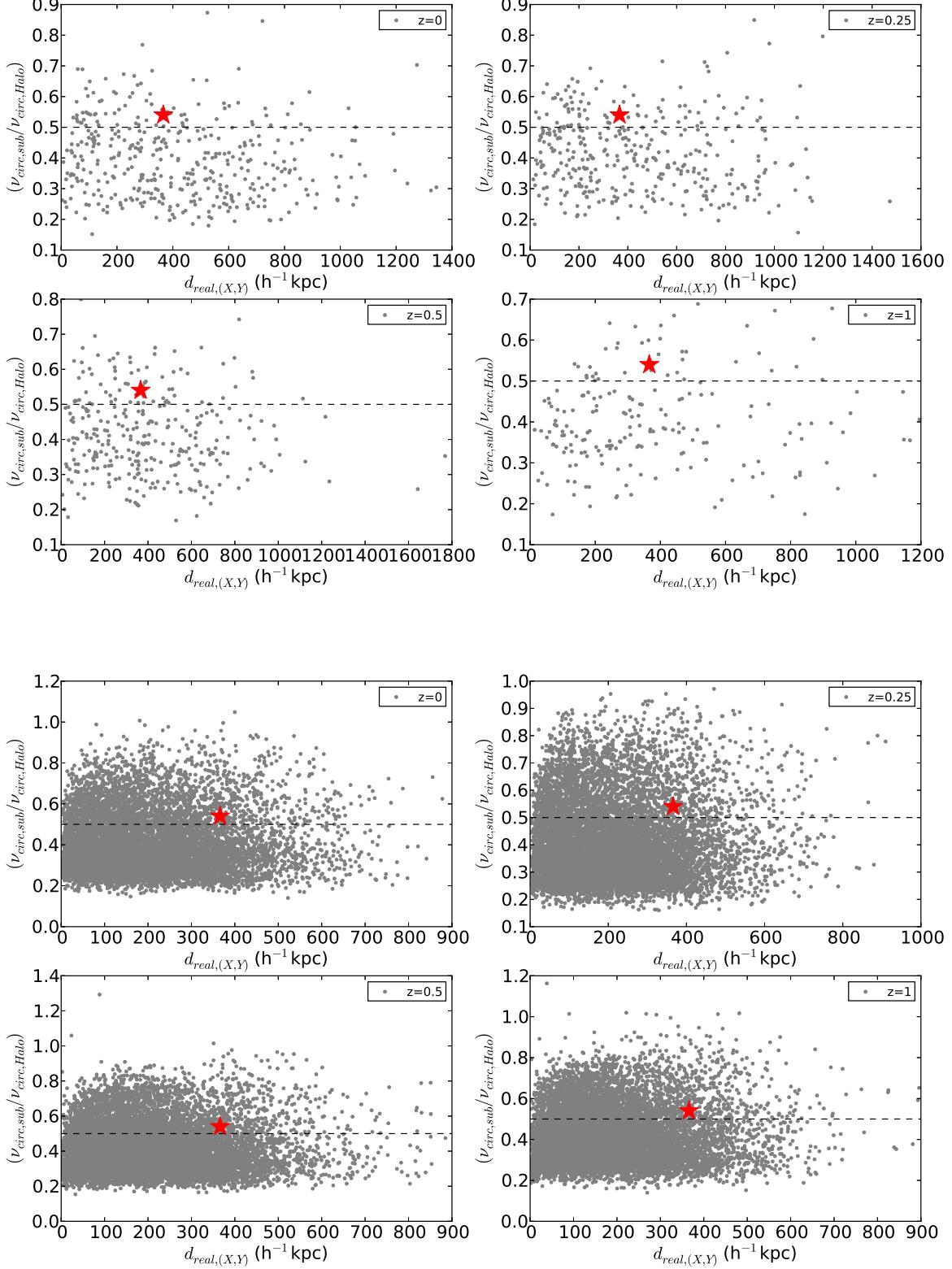


FIG. 4.— Scatter  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right)$  vs  $d_{real,(X,Y)}$  for different redshifts. The horizontal dashed line correspond to  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right) = 0.5$  and the red star symbol correspond to  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right) = 0.54$  for SL2S SJ08544-0121 in Muñoz et al. (2013). The four top panels are the sample with circular velocities  $> 700 \text{ km s}^{-1}$  and the four down panels are the sample with circular velocities between  $300 \text{ km s}^{-1}$  to  $700 \text{ km s}^{-1}$ .

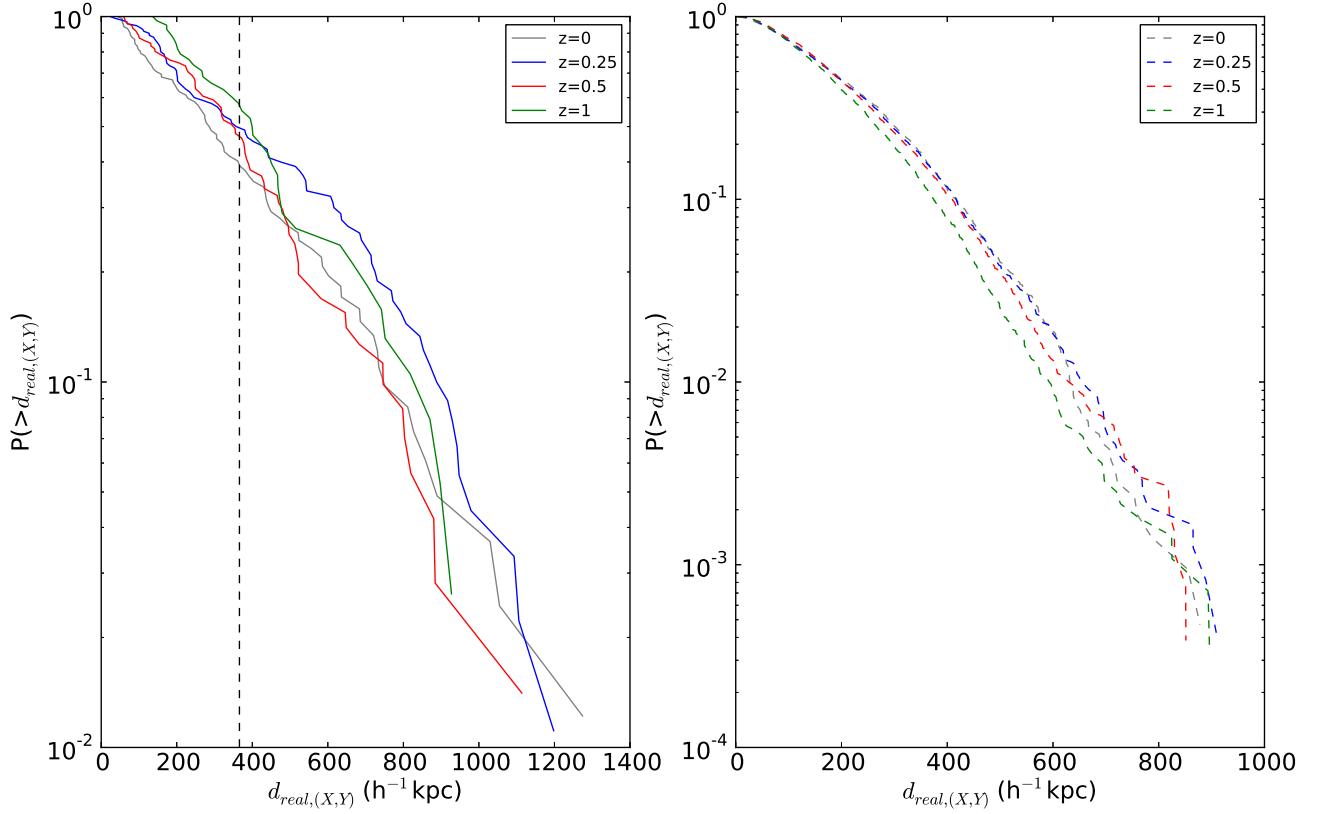


FIG. 5.— Cumulative distribution ( $P(>d_{2d,(X,Y)})$ ) of displacements for the projection (X,Y). **Left panel:** Sample with  $v_{max} > 700 \text{ kms}^{-1}$  for different redshifts. The vertical dashed line, correspond to the separation between dark matter to dark matter estimate in this work as the double of separation between the collisional gas and dark matter of  $124 \pm 20 \text{ kpc}$  reported by Gastaldello et al. (2014) for the group SL2S J08544-0121. **Right panel:** Sample with  $300 \text{ kms}^{-1} < v_{max} < 700 \text{ kms}^{-1}$  for different redshifts.

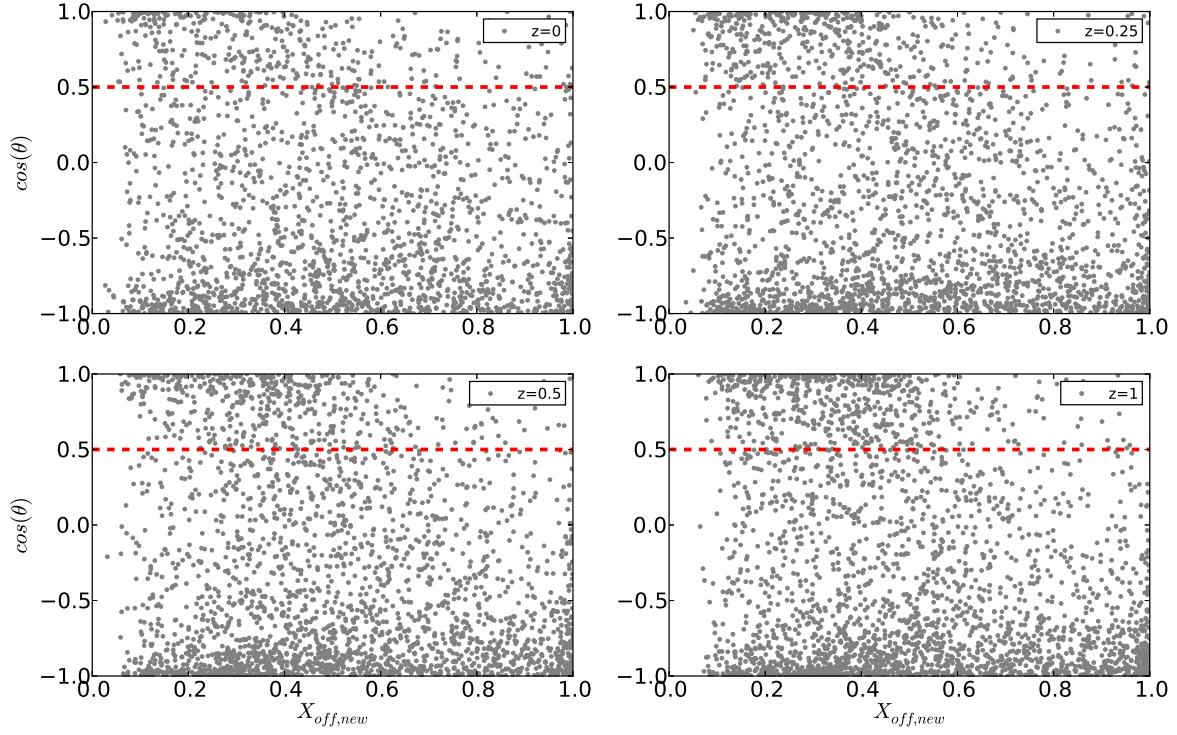


FIG. 6.— Scatter of  $\cos(\theta)$  vs  $X_{off,new}$ . The red dashed line correpond to the limit for  $\cos(\theta) > 0.5$ , where the substructure is emerging from the host halo and  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right) \geq 0.5$ , circular velocities  $< 700 \text{ kms}^{-1}$  and different redshifts.

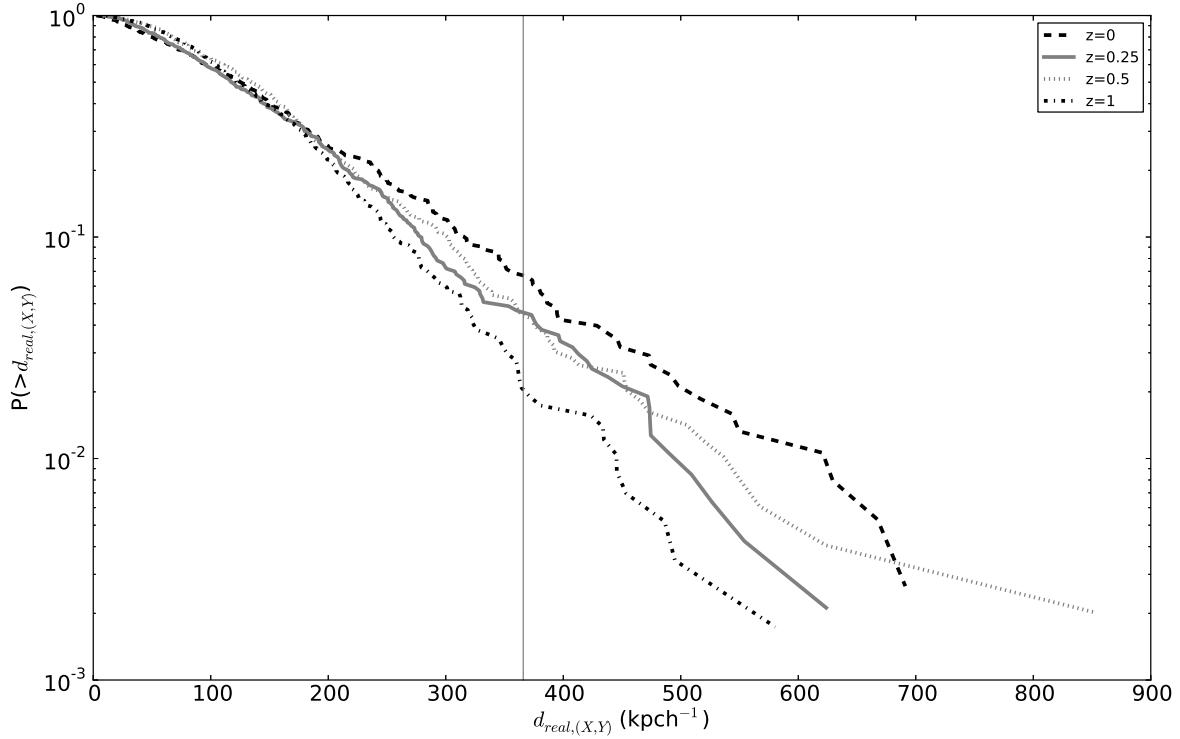


FIG. 7.— Cumulative distribution of  $d_{real,(X,Y)}$  for  $\cos(\theta) > 0.5$ ,  $\left(\frac{v_{circ,sub}}{v_{circ,halo}}\right) \geq 0.5$ , circular velocities  $< 700$   $\text{km s}^{-1}$  and different redshifts.