THE ABUNDANCE OF BULLET GROUPS IN ΛCDM

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ABSTRACT

We estimate the expected distribution of displacements between the two dominant dark matter (DM) peaks (DM–DM displacements) and between the DM and gaseous baryon peak (DM–gas displacements) in DM halos with masses larger than \(10^{13}\ h^{-1}\ M_\odot\). As a benchmark, we use the observation of SL2S J08544−0121, which is the lowest mass system \((1.0 \times 10^{14}\ h^{-1}\ M_\odot)\) observed so far, featuring a bi-modal DM distribution with a dislocated gas component. We find that \((50 \pm 10)\%\) of the DM halos with circular velocities in the range \(300−700\ km\ s^{-1}\) (groups) show DM–DM displacements equal to or larger than \(186 \pm 30\ h^{-1}\) kpc as observed in SL2S J08544−0121. For DM halos with circular velocities larger than \(700\ km\ s^{-1}\) (clusters) this fraction rises to \((70 \pm 10)\%\). Using the same simulation, we estimate the DM–gas displacements and find that \(0.1\%−1.0\%\) of the groups should present separations equal to or larger than \(87 \pm 14\ h^{-1}\) kpc, corresponding to our observational benchmark; for clusters, this fraction rises to \((7 \pm 3)\%\), consistent with previous studies of DM to baryon separations. Considering both constraints on the DM–DM and DM–gas displacements, we find that the number density of groups similar to SL2S J08544−0121 is \(\sim6.0 \times 10^{-7}\ Mpc^{-3}\), three times larger than the estimated value for clusters. These results open up the possibility for a new statistical test of ΛCDM by looking for DM–gas displacements in low mass clusters and groups.

Key words: dark matter – galaxies: clusters: individual (SL2S J08544−0121) – galaxies: interactions – methods: numerical

Online-only material: color figures

1. INTRODUCTION

The Bullet Cluster (1E0657-56) provided a new kind of observational evidence for the existence of dark matter (DM; Markevitch et al. 2004; Clowe et al. 2006). Since then, it has been used to test the cold dark matter (CDM) paradigm itself by quantifying different aspects such as the expected displacement between the dominant DM and baryonic component in a ΛCDM universe (Forero-Romero et al. 2010), the substructure velocity required to produce such displacement (Milosavljević et al. 2007; Springel & Farrar 2007; Mastroietti & Burkert 2008), and its abundance in large N-body cosmological simulations (Hayashi & White 2006; Lee & Komatsu 2010; Thompson & Navagime 2012). It has also been used to constrain the DM particle self-interaction cross-section and to explore possible extensions to the concordance cosmological model (Farrar & Rosen 2007; Lee & Baldi 2012).

Since then, other examples of bullet-like systems have been found: MACS J0025.4−1222 (Bradač et al. 2008), Abell 2744 (Merten et al. 2011), DLSCJ J0916.2+2951 (Dawson et al. 2012), ZwCl 1234.0+02916 (Dahle et al. 2013). Recently, Gastaldello et al. (2014) observed a DM–gas displacement of \(87 \pm 14\ h^{-1}\) kpc and a DM–DM separation of \(186 \pm 30\ h^{-1}\) kpc in SL2S J08544−0121, a low-mass cluster system with a total mass of \(2.4 \pm 0.6 \times 10^{14}\ M_\odot\) found in the Strong Lensing Legacy Survey (SL2S) sample (Cabanac et al. 2007; More et al. 2012).

Using a Sheth–Mo–Tormen mass function at \(z = 0\), one can estimate that systems around this mass are \(\sim65\) times more abundant than massive clusters in the mass range of the Bullet Cluster \(>10^{15}\ h^{-1}\ M_\odot\) (Sheth et al. 2001; Murray et al. 2013). This should open up the possibility of finding bullet-like groups in large numbers to test ΛCDM. However, a larger abundance of small mass systems has to be weighted by the probability of being in a merger and presenting a large displacement between the DM and gaseous components. These two conditions (merger rates and maximum possible displacement) are functions of DM halo mass in ΛCDM cosmologies. A detailed statistical study to estimate the DM–gas displacements of bullets has been performed for clusters (Forero-Romero et al. 2010) but not for lower mass systems.

In this Letter, we extend such a study for systems in the group mass scale. We measure the abundance of DM systems with a multi-modal morphology (large DM–DM displacements) and estimate the amount of systems with a bullet-like configuration (large DM–gas displacements). To this end, we use a high resolution \(N\)-body cosmological simulation (Bolshoi) that allows us to find multi-modal DM distributions in hosts with circular velocities larger than \(300\ km\ s^{-1}\) \((\sim1.0 \times 10^{13}\ h^{-1}\ M_\odot)\).

This Letter is organized as follows. In Section 2, we present the simulation and the halo catalogs. We continue in Section 3 with the geometry of the problem at hand and the measurement setup. In Section 4, we present our results and observational perspectives to finally conclude in Section 5.

2. SIMULATION, HALO CATALOGS, AND PAIRS

We use the Bolshoi run, a cosmological DM-only simulation over a cubic volume of \(250\ h^{-1}\ Mpc\) comoving on a side (Klypin et al. 2011). The simulation uses the ART code (Kravtsov et al. 1997) to follow the evolution of a DM density field from \(z = 80\) to \(z = 0\), sampled with \(2048^{3}\) particles. The cosmology used corresponds to the spatially flat concordance model with the following parameters: the density parameter for matter (DM and 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 slope of the primordial power spectrum, $n = 0.95$, and the amplitude of mass density fluctuations (at redshift $z = 0$), $\sigma_8 = 0.82$. These cosmological parameters are consistent with the 9 yr Wilkinson Microwave Anisotropy Probe results (Hinshaw et al. 2013). A detailed presentation of the simulation can be found in Klypin et al. (2011).

This results in a mass resolution of $1.35 \times 10^8 M_\odot h^{-1}$ for each computational particle. The completeness limit in this simulation is set for halos with 100 particles, corresponding to a mass of $1.35 \times 10^{10} h^{-1} M_\odot$ or a maximum circular velocity, $V_c$, of 50 km s$^{-1}$.

We use DM halo catalogs, constructed using the bound density maxima (BDM) algorithm (Klypin & Holtzman 1997; Klypin et al. 1999). To define the radius of a halo we use a density threshold of 360 times the mean density of the universe. An important feature of BDM is that it allows us to detect sub-halos inside larger virialized structures.

All the raw data used in this Letter are available through the MultiDark Database$^3$ (Riebe et al. 2013). Furthermore, in order to facilitate the reproducibility and reuse of our results, we have made available all the data and the source codes available in a public repository.$^6$

To construct our main halo sample, we follow three steps. First, we select all the host halos (i.e., halos that are not inside a larger halo) with circular velocities $V_c \geq 50$ km s$^{-1}$.

Second, as the sub-halo crosses the center of the host halo, $R_{\text{vir}}$. Another useful quantity computed in the simulation is the distance between the minimum of potential of the host halo and its center of mass (computed from all the particles inside the $R_{\text{vir}}$), $X_{\text{off}} = |\mathbf{r}_{\text{min}} - \mathbf{r}_{\text{cm}}|/R_{\text{vir}}$, which serves as a measurement of how much the host halo is perturbed.

In this Letter, we work with two quantities that could be inferred from observations of bullet-like systems. The projected distance between two dominant DM clumps, $d_{\text{2D}}$, and the projected distance between the DM and the gas clumps, $d_{\text{bar}}$. The projection is computed along the $z$ axis for all halos at all redshifts.

From the simulation point of view, the first quantity can be translated into the two-dimensional (2D) projected values of $|\mathbf{r}|$ and its value relative to the virial radius $D_{\text{eff}} = |\mathbf{r}|/R_{\text{vir}}$. The second quantity, the projected DM–gas distance, is not directly available from a DM-only simulation, but can be estimated from the data.

We also use the physical quantities described above to discriminate three main stages in a bullet-like encounter with $|\mu| \sim 1$. First, when the sub-halo crosses the virial radius of the host halo, starting a head-on collision, $D_{\text{eff}} \sim 1$ and $\mu \sim 1$. Second, as the sub-halo crosses the center of the host halo $D_{\text{eff}} < 1.0$ and $\mu \sim 1$ for the first time. Third, as the sub-halo reaches apogee and comes back to the center of the halo $D_{\text{eff}} < 1.0$ and $\mu \sim -1$.

4. RESULTS

4.1. DM–DM Displacements

Figure 1 presents the integrated probability distribution for the DM–DM displacements, $d_{\text{2D}}$. The left panel shows the displacement in physical units and the right panel as a fraction of the virial radius of the host halo. The panel with the projected 2D physical displacements also shows a vertical stripe with the estimated displacement for the bullet group reported by Gastaldello et al. (2014).

In the group sample, we see that a fraction of 40%–60% should present a displacement equal to the estimate for SL2S J08544−0121; in the cluster sample, this fraction increases to 70%–80%. The uncertainties in these estimates are derived from the uncertainties in the displacement measurement for SL2S J08544−0121. This fraction is naturally higher in more massive systems because they are larger in size. Normalizing

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Table 1: Absolute Number of Objects in the Groups and Clusters Sampled at all Redshifts for Different Selection Criteria

|                  | Groups | Clusters |
|------------------|--------|----------|
|                  | $z = 0$| $z = 0.25$| $z = 0.5$| $z = 1.0$| $z = 0$| $z = 0.25$| $z = 0.5$| $z = 1.0$|
| Full Sample      | 9641   | 9984     | 10244   | 10190   | 400    | 363     | 310     | 192     |
| $64 < d_{2D} h^{-1} \text{kpc} < 350$ | 6188   | 6422     | 6635    | 6933    | 151    | 141     | 120     | 99      |
| $(64 < d_{2D} h^{-1} \text{kpc} < 350)$ & $(d_{2D} h^{-1} \text{kpc} > 87)$ | 14     | 25       | 44      | 35      | 8       | 9       | 13      | 8       |

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$^3$ www.multidark.org

$^6$ https://github.com/Fernandez-Trincado/Bullet_Groups-2014
Figure 1. Integrated probability distribution for the displacement between the center of the host halo and its dominant sub-halo at all redshifts \(z = 0, 0.25, 0.5, \) and \(1.0.\) The left panel shows the results in terms of the physical displacements, while the right panel shows the displacements normalized by the virial radius of the host halo. The continuous (dashed) line corresponds to the halos in the cluster (group) sample. The vertical lines show the mean value and uncertainties (186 ± 30 km s\(^{-1}\)) in the separation between the two dark matter clumps estimated in Gastaldello et al. (2014) for the SL2S J08544−0121. Between 40% and 60% of the groups show a displacement equal to or larger than this observational benchmark. This fraction rises to 60% and 80% in clusters.

(A color version of this figure is available in the online journal.)

Figure 2. 2D histograms in the plane, \(\mu – D_{\text{off}},\) describing the geometry of the bullet encounter. The left panel corresponds to clusters and the right panel to groups. The weak redshift evolution of the structure in these planes allows us to include halos at all redshifts to construct these figures. The three rectangles (continuous, dashed, and dot-dashed) roughly delimit stages of interest in a head-on collision (initial infall, first crossing until apogee, return after apogee) as described in Section 4.2.

the displacements by the virial radius, right panel of Figure 1, we see that the distributions are similar for the two samples at all redshifts.

4.2. Collision Geometries

Figure 2 presents the geometry of the interactions using the variables \(\mu\) and \(D_{\text{off}}.\) The first evident feature is that most of the configurations have head-on encounters, \(|\mu| > 0.9 (\theta \leq 30^\circ),\) while only a minority with \(|\mu| < 0.9\) can be described as having grazing trajectories.

For pairs on radial trajectories, there are three regions of interest in this plane that correspond to the three merging stages described at the end of Section 4.2, assuming that the sub-halo merges (or falls below the BDM detection threshold) right at its second pass through the center of the host halo (Poole et al. 2006). These regions are shown as three different rectangles in Figure 2.

The first region (continuous rectangle) has \(\mu < -0.9\) and \(D_{\text{off}} > 0.6,\) which locates the systems where a head-on collision has just started. The second region (dashed rectangle) has \(\mu > 0.9\) and \(D_{\text{off}} < 0.6.\) At this stage, the collision continues after the first crossing of the host’s center. The low number of halos with radial infalling velocities and displacements, \(D_{\text{off}} > 0.6,\) suggests that this is the maximum range of radii for the apogee. The third region (dot-dashed rectangle) corresponds to \(\mu < -0.9\) and \(D_{\text{off}} < 0.6\) which is the secondary infall after apogee.

In the next subsection, we use the information in this collision sequence to estimate the expected DM–gas displacement.

4.3. DM–Gas Displacements

The results we have derived so far apply to multi-modal systems and their expected separation between the two dominant DM clumps. However, a non-zero DM–DM displacement does not imply a non-zero DM–gas displacement. We now estimate these displacements from the available information in our DM-only simulation.

Our estimates are based on the different kinds of trajectories and collision stages described in previous sections. To begin, we consider that systems with \(|\mu| < 0.9,\) describing grazing trajectories, have a DM–gas displacement equal to zero. In systems with head-on collisions, \(|\mu| > 0.9,\) the systems with \(\mu < -0.9\) and large displacements \(D_{\text{off}} > 0.6,\) most probably describe the beginning of the interaction and should have
DM–gas displacements equal to zero as well. In all other cases, the DM–gas displacement should be different from zero with DM–gas displacements equal to zero as well. In all other cases, clusters (groups). The continuous black line marked as Figure 3. The Astrophysical Journal Letters h

Figure 3. Integrated probability distribution for the estimated DM–gas displacements in the group and cluster samples. Continuous (dashed) lines correspond to clusters (groups). The continuous black line marked as $P_{2D}$ shows the statistics reported by Forero-Romero et al. (2010) for a cosmological simulation including DM and gas. The vertical lines correspond to the mean value and uncertainty of the displacement measured for SL2S J08544−0121. (A color version of this figure is available in the online journal.)

4.4. Toward a Statistical Comparison Against Observations

Recently, Foëx et al. (2013) presented an analysis of 80 galaxy groups in the SL2S sample. From the light distribution, only 34 objects (~42%) have regular isophotes, 33 had elongated isophotes (hints of a merging system), and 13 (~16%) had a clear bimodal light distribution; SL2S J08544−0121 is one of these 13 systems.

The bimodal objects are defined to have at least a clear second luminosity peak within 350 $h^{-1}$ kpc from the main halo, as traced by the strong lensing system. The lowest separation in those systems is 64 $h^{-1}$ kpc and the average is 145 ± 52 $h^{-1}$ kpc.

We now make a comparison of these fractions against the results of our simulations. The results are summarized in Table 1. The first row indicates the total number of halos in each sample at each redshift. The second row shows the number of objects with DM–DM displacements $46 h^{-1}$ kpc $< d_{2D} < 350 h^{-1}$ kpc. The last row indicates the number of objects in the previous subsample with DM–gas displacements $d_{2D}^{\text{bar}} > 87 h^{-1}$ kpc.

Considering that the statistics for the cluster sample are dominated by objects in the mass range of the SL2S J08544−0121, we make a comparison against this sample. Table 1 shows that ~40% of the clusters are expected to have large DM–DM displacements, which is a factor of ~2 larger than the observational estimate by Foëx et al. (2013). However, roughly ~7% of these systems present a displacement equal to or larger than the observed in the SL2S J08544−0121, a fraction that is compatible with the 1/13 ~ 0.07 fraction in the SL2S sample from which SL2S J08544−0121 was drawn.

This rough comparison shows that our estimates for the relative number of bullet systems (large DM–gas displacements) with respect to multi-modal systems (large DM–DM displacements) is compatible with observations. A proper comparison must take into account all the observational uncertainties, biases and mixtures between our two populations (groups and clusters at different redshifts) to derive a stronger bound from the simulation, something that is beyond the scope of this Letter.

Nevertheless, comparing the absolute number of systems with characteristics similar to SL2S J08544−0121 in the group sample (last row of Table 1), we predict that its number density is ~6.0 $\times 10^{-7}$ Mpc$^{-3}$, three times larger than the expected number density of SL2S J08544−0121 systems in the cluster sample.

5. CONCLUSIONS

In this Letter, we estimated the fraction of galaxy groups and clusters in a ΛCDM cosmology that could present observational features associated with a bullet-like event. This is motivated by the recent observational results of Gastaldello et al. (2014) where a system (SL2S J08544−0121) on the mass range $1 \times 10^{14} h^{-1} M_\odot$ and velocity dispersion 650 km s$^{-1}$ was reported to feature a displacement between its baryonic (gas) and DM components.

We computed the distribution of projected displacements between the dominant DM clumps in two kinds of systems; groups with circular velocities 300 km s$^{-1} < V_c < 700$ km s$^{-1}$ ($1.0 \times 10^{13} h^{-1} M_\odot < M_{\text{vir}} < 8.0 \times 10^{12} h^{-1} M_\odot$) and clusters with $V_c > 700$ km s$^{-1}$ ($M_{\text{vir}} > 8.0 \times 10^{13} h^{-1} M_\odot$). We reported these results at four different redshifts $z = 0.0, 0.25, 0.5, 1$. Our results are based on large DM-only $N$-body cosmological simulation with a resolution that allows us to study bullet-like configurations in the mass range of galaxy groups for the first time.

Our main result is that a fraction of 40%–60% of the halos in the group sample presents DM–DM displacement equal to or larger than the observed displacement for SL2S J08544−0121. For halos in the cluster sample, this fraction increases to...
60%–80%. We also derived an estimate for the DM–baryon displacement. In the group sample, 0.1%–1.0% of the halos show a displacement equal to or larger than the measurements of SL2S J08544–0121 by Gastaldello et al. (2014); in the cluster sample, this fraction rises from 4%–10%.

For the case of SL2S J08544–0121 a fair comparison is achieved against our cluster sample which has statistics dominated by objects of similar mass. In a rough comparison, using the observational criteria (Foëx et al. 2013; Gastaldello et al. 2014), we find that the relative number of bullet-like systems (large DM–gas displacement) with respect to a general sample of multi-modal systems (large DM–DM displacements) is consistent with observations; both are in the range of ~7%.

Using the same criteria, we find that in the simulation there are ∼6.0 × 10^{-7} Mpc^{-3} groups similar to SL2S J08544–0121. This number density is three times larger than the computed value for clusters. This opens up a new observational possibility with surveys such as SL2S that target a large number of groups and estimate their multi-modal nature from lensing analysis (Foëx et al. 2013). An approach that can be further exploited with upcoming lensing surveys (e.g., with the Euclid satellite) and pushes for X-ray surveys with higher sensibility: chances to find bullets are larger in systems with lower X-ray luminosities.

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