Assembly history of dark matter subhalo in ΛCDM

Lizhi Xie1,3 *, Liang Gao1,2
1Key laboratory for Computational Astrophysics, Partner Group of the Max Planck Institute for Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China
2Institute of Computational Cosmology, Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE
3INAF-Astronomical Observatory of Trieste, Via Riccardo Bazzoni, 2, 34124, Trieste, Italy

ABSTRACT

We make use of two suites of ultra-high resolution N-body simulations of individual dark matter haloes, the Phoenix and the Aquarius Projects, to investigate the systematics of subhalo assembly histories in host haloes differing by a factor of 1000 in mass. We find that the progenitors of the present day subhalo population are relatively more abundant in high mass haloes, in contrast to previous studies claiming a universal abundance independent of the mass of the host halo. This is mainly because these studies count progenitors that pass through the halo and are later re-accreted more than once. The fraction of these ‘wavering’ progenitors is larger in less massive haloes. The typical accretion time for all progenitors varies strongly with host halo mass: z ∼ 5 for the Galactic-scale Aquarius haloes and z ∼ 2.5 for the cluster-scale Phoenix haloes. Once progenitors start to orbit their parent haloes, they rapidly lose their original mass, but nevertheless more than 80 (70) percent of them survive to present day in the Phoenix (Aquarius) haloes. At given redshift, the fraction of subhaloes that survive is independent of the host halo mass, whilst the fraction of mass lost by subhaloes is larger in higher mass haloes. These systematics explain many similarities and differences between subhalo populations in haloes of different masses at the present day.

Key words:

1 INTRODUCTION

In the standard ΛCDM cosmology, dark matter subhaloes are a consequence of hierarchical clustering of dark matter haloes. During the hierarchical process, an accreted dark matter halo can survive as a self-bound subhalo orbiting its host (e.g. Tormen, Diaferio & Syer 1998; Ghigna et al. 2000, Springel et al. 2001; De Lucia et al. 2004; Gao et al. 2004, 2012; Diemand, Kuhlen & Madau 2007; Springel et al. 2008). In observations, subhaloes have been detected with gravitation lensing (Vegetti et al. 2012, Li et al. 2014) in recent years.

Thanks to great advances in high resolution cosmological simulations, the properties of subhaloes have been extensively investigated in recent years. Regardless of the wide variety of different definitions of ‘subhalo’ in cosmological simulations, numerical studies tend to agree on a number of basic properties of the subhalo populations in ΛCDM haloes. 1) Since tidal stripping of the subhaloes is efficient, particularly in the inner regions of the host halo, the subhalo population is a biased tracer of the dark matter distribution of its host. The distribution of subhaloes is substantially less concentrated than that of the underlying dark matter (e.g. Ghigna et al. 2000, Gao et al. 2004, Nagai & Kravtsov 2005). With the ultra-high resolution simulations of the Phoenix and the Aquarius projects, Gao et al. (2012) showed that the radial distribution of subhaloes is independent of subhalo and host halo mass. 2) The mass function of subhaloes follows a power-law relation dN(> Msub)/dMsub ∝ Msubα (Boylan-Kolchin et al. 2008, Gao et al. 2011) with a slope α varying from 1.9 to 2, depending on the subhalo finder employed (Onions et al. 2013). The subhalo mass function is found to be correlated with host halo mass, with more massive haloes tending to contain a greater abundance of subhaloes (Gao et al. 2004, 2011; Ishiyama et al. 2013). On average, the amplitude of the subhalo mass function of rich cluster-sized haloes is about 40 percent higher than that of Milky Way-like haloes (Gao et al. 2012). The subhalo mass function also correlates with other properties of the host halo, for instance concentration and formation time (Gao et al. 2004, 2011, Contini, De Lucia & Borgani 2012). In addition to numerical works, properties of subhalo populations have also been studied extensively with semi-analytic models (e.g. Taylor & Babul 2005, Zentner et al. 2005, Giocoli, Tormen & van den Bosch 2008, Yang et al. 2012, Jiang & van den Bosch 2014). Nevertheless, convincing and explicit explanations of the above trends in the subhalo mass function as a function of the properties of the host are still lacking.

Most previous studies on this subject have investigated sub-
halo populations at redshift $z = 0$. In this study, we complement such work by investigating the evolution of subhalo population. Specifically, we will study systematics in the assembly of subhaloes across cosmic time and in haloes of different masses. To this end, we make use of two ultra-high resolution $N$-body simulations of individual dark matter haloes from the Phoenix and Aquarius projects. The dark matter haloes simulated in these projects differ by a factor of 1000 in halo mass. Phoenix and Aquarius have very similar effective mass and force resolutions, using a similar number of particles. This facilitate an easy comparison between the two simulation sets.

Our paper is organized as follows. In Section 2, we briefly describe the numerical simulations used in this study. In Section 3 we present results for the progenitor populations of Phoenix and the Aquarius subhaloes (i.e. the subhalo populations before accretion). We contrast results for the evolution of subhaloes in the Phoenix and Aquarius simulations in Section 4. Section 5 summarizes our main findings.

2 SIMULATION

The numerical simulations used in this study comprise two sets of ultra-high resolution re-simulations of individual dark matter haloes from the Phoenix (Gao et al. 2012) and Aquarius Projects (Springel et al. 2008) of the Virgo consortium. In terms of the numerical resolution, these two projects represent the current state of the art in $N$-body simulations of rich clusters and Milky way-sized dark matter haloes, respectively. For the purpose of numerical convergence studies, both the Phoenix and the Aquarius suites include simulations from the same initial conditions with various levels of numerical resolution. In this study we use the level 2 resolution of each set. At the level 2 resolution, each of 9 Phoenix clusters and 6 Aquarius Galactic haloes contains about $10^5$ particles within its virial radius $R_{200}$. Here $R_{200}$ is defined as the radius at which the enclosed density is 200 times the critical density of the Universe. Hence, both simulation sets have identical effective mass and force resolution. Note that we use only the 7 Phoenix clusters for which there is no ambiguity in identifying the main branch of the merger tree of the most massive halo.

The Phoenix clusters and the Aquarius haloes were selected for resimulation from the Millennium simulation (Springel et al. 2005). The Millennium simulation assumes cosmological parameters consistent with first-year WMAP data: $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\Omega_{\Lambda} = 0.75$, $h = 0.73$, $\sigma_8 = 0.9$, $n = 1$. These parameters deviate from the latest CMB results, however the small differences are of no consequence for the topic addressed here. We refer readers to Gao et al. (2012) and Springel et al. (2008) for details of the Phoenix and the Aquarius simulation suites.

Dark matter haloes in our simulations are identified with standard friends-of-friends group algorithm with a linking length 0.2 times the mean interparticle separation (Davis et al. 1985). Based on an FOF group catalog, we identify locally overdense and self-bound subhaloes with SUBFIND (Springel, Yoshida & White 2001). The resulting subhalo catalog is used to construct merger trees tracking subhaloes between snapshots (e.g. Boylan-Kolchin et al. 2009).

3 THE UN-EVOLVED SUBHALO MASS FUNCTION

We first consider the distribution of subhalo masses measured at the time of their infall into the main halo. We refer to this distribution as the un-evolved subhalo (or the progenitor) mass function. We ask whether differences in subhalo abundance between cluster and galactic halos at the present day are imprinted at the time of infall. Previous studies on the subject have claimed that the un-evolved subhalo mass distribution follows a universal function independent of halo mass (see Giocoli, Tormen & van den Bosch (2008), Li & Mo (2009)). This is surprising, because the standard $\Lambda$CDM power spectrum is not scale free, and so it is not obvious that the un-evolved subhalo mass function should be identical in haloes of different scales.

We first identify a ‘main branch’ for the merger tree of each individual halo. Starting from the final halo at $z = 0$, we find its most massive progenitor in the preceding simulation snapshot. This procedure is repeated until the halo falls below the resolution limit of the simulation (32 dark matter particles for a FOF halo, in our definition). Next, we add a halo as a progenitor candidate if it is accreted into $r_{200}$ of the main branch halo at later time. The accretion time for a subhalo are defined as the time when it has its peak maximum circular velocity $V_{\text{max}}$ in its entire growth history. Correspondingly, its mass at the time of accretion is defined as the mass of the progenitor halo. This definition is used because the stellar mass of satellite galaxies are most tightly related to the peak $V_{\text{max}}$ (Kravtsov, Gnedin & Klypin 2004, Guo et al. 2010). Note that there is no unique definition of the accretion time of a subhalo. For example, some studies (Gao et al. 2004; Giocoli, Tormen & van den Bosch 2008, Li & Mo 2009) define the accretion time as the time when an individual halo becomes a subhalo of a larger FOF halo. Boylan-Kolchin et al. (2009) defined accretion as the time at which a progenitor halo achieves its maximum mass, which is similar to our definition.

The merging histories of dark haloes are generally quite complicated (Kravtsov et al. 2004). We consider two special cases below: 1) Ejected subhaloes: cases in which a halo crosses $r_{200}$ of a more massive halo but later becomes an isolated halo again. The ‘ejected’ subhalo population has been investigated by Ludlow et al. 2009; Wang, Mo & Jing 2009, Li et al. 2013. As these ‘ejected’ subhaloes are not part of the present-day subhalo population, we explicitly identify and exclude them from our analysis below. 2) Wavering subhaloes: cases in which halos pass into and out of the main branch more than once, as ‘ejected’ subhaloes, but in the end are either completely disrupted within the main branch or survive as one of its subhaloes at $z = 0$. We record such haloes at their first infall. Finally, we also add haloes that merged with other progenitors rather than the main branch. For these progenitors, we apply the same procedure as for the progenitors of the main branch, to make sure they are members of the final halo.

Our definition of the un-evolved subhalo mass function is somewhat different from Giocoli, Tormen & van den Bosch (2008) and Li & Mo (2009). In Giocoli, Tormen & van den Bosch (2008) and Li & Mo (2009), their merging tree is constructed from FOF haloes, while ours is constructed from spherical overdensities by restricting the progenitors to those accreted into $r_{200}$ of the main branch halo. There are also significant differences in the detailed tracking procedure. In Giocoli, Tormen & van den Bosch (2008), the authors only considered progenitors that merge directly with the main branch, and neglected the subhalo population that merge at an earlier stage in the hierarchy of those direct progenitors. This excludes a significant fraction of the progenitor population, since
subhaloes (and sub-subhaloes, etc.) brought in by direct progenitors
disperse into the main halo as their host is tidally stripped [Li & Mo
(2009)] improved this by considering the whole hierarchy of merg-
ers, as we do. However, we differ in our definition of progenitor
mass, and also in that we explicitly identify progenitors which re-
peatedly pass through the main progenitor and are later re-accreted.
As shown below, these also constitute a substantial fraction of the
total subhalo population.

In Figure 1, we plot the average fraction of ’wavering’ pro-
genitors in the 7 Phoenix and the 6 Aquarius haloes, as a function
of the progenitor mass (normalized to the host halo mass at $z = 0$).
For massive progenitors (mass greater than $1/1000$ of the host) the
fraction of ’wavering’ progenitors is small for both the Phoenix
and the Aquarius haloes. However, for progenitors of highermass
ratio, ’wavering’ progenitors make up a significant fraction of all
progenitors. About 35 per cent of progenitors have passed out of
the host halo and returned at least once. The fraction of such haloes
is even larger for Aquarius – about 50 per cent. The fraction ap-
pears to be independent of progenitor mass, except for the most
massive progenitors. We believe these ’wavering’ progenitors were
counted multiple times in the un-evolved subhalo mass functions
of Giocoli, Tormen & van den Bosch (2008) and Li & Mo (2009).
These repeatedly-accreted objects seem worthy of further study.

In Figure 1 we plot the average fraction of ’wavering’ pro-
genitors in the 7 Phoenix and the 6 Aquarius haloes, as a function
of the progenitor mass (normalized to the host halo mass at $z = 0$).
For massive progenitors (mass greater than $1/1000$ of the host) the
fraction of ’wavering’ progenitors is small for both the Phoenix
and the Aquarius haloes. However, for progenitors of highermass
ratio, ’wavering’ progenitors make up a significant fraction of all
progenitors. About 35 per cent of progenitors have passed out of
the host halo and returned at least once. The fraction of such haloes
is even larger for Aquarius – about 50 per cent. The fraction ap-
pears to be independent of progenitor mass, except for the most
massive progenitors. We believe these ’wavering’ progenitors were
counted multiple times in the un-evolved subhalo mass functions
of Giocoli, Tormen & van den Bosch (2008) and Li & Mo (2009).
These repeatedly-accreted objects seem worthy of further study.

In Figure 2 we plot our own un-evolved median subhalo mass
functions for the 7 Phoenix (red) and 6 Aquarius (black) sim-
ulations. Each cumulative mass function has been multiplied by
$M_{\text{sub}}/M_{\text{halo}}$ to remove the dominant mass dependence and make
the differences between the two more apparent. Clearly, the am-
plitude of the un-evolved subhalo mass function depends on the
halo mass, with the Phoenix clusters having 30 percent more pro-
genitors than the Aquarius Galactic haloes. This result is inconsis-
tent with Giocoli, Tormen & van den Bosch (2008) and Li & Mo
(2009), who claimed a universal form for the un-evolved subhalo mass functions
of the Phoenix and Aquarius haloes. These repeatedly-accreted objects seem worthy of further study.

In Figure 2 we plot our own un-evolved median subhalo mass
functions for the 7 Phoenix (red) and 6 Aquarius (black) sim-
ulations. Each cumulative mass function has been multiplied by
$M_{\text{sub}}/M_{\text{halo}}$ to remove the dominant mass dependence and make
the differences between the two more apparent. Clearly, the am-
plitude of the un-evolved subhalo mass function depends on the
halo mass, with the Phoenix clusters having 30 percent more pro-
genitors than the Aquarius Galactic haloes. This result is inconsis-
tent with Giocoli, Tormen & van den Bosch (2008) and Li & Mo
(2009), who claimed a universal form for the un-evolved subhalo mass functions
of the Phoenix and Aquarius haloes. These repeatedly-accreted objects seem worthy of further study.

4 THE ASSEMBLY HISTORY OF SUBHALO POPULATION

Above we studied the subhalo population at the time of their accretion. In this section, we will investigate the subsequent evolution of
these progenitors.

4.1 Accretion time distribution of progenitors

In the top panel of Figure 3, we show the accretion time distribution
of all progenitors as a function of their mass. The median mass function of each set. The vertical axis has been multiplied
by the progenitor-to-host mass ratio, to increase the dynamic range. Error bars show the full range of each sample. The un-evolved subhalo mass function of Li & Mo (2009) is shown by the blue dotted line.

Figure 1. The average fraction of ’wavering’ progenitors of 7 Phoenix (red line) and 6 Aquarius haloes (black line), as a function of progenitor mass. Wavering progenitors are those that pass through and are later re-accreted into the main branch.

Figure 2. Cumulative mass functions of un-evolved (solid lines) and present-day (dashed lines) subhalo populations in 7 cluster-scale haloes (Phoenix; red) and 6 Galactic-scale haloes (Aquarius; black). Lines show the median mass function of each set. The vertical axis has been multiplied by the progenitor-to-host mass ratio, to increase the dynamic range. Error bars show the full range of each sample. The un-evolved subhalo mass function of Li & Mo (2009) is shown by the blue dotted line.

For ease of reference, in Figure 3 we also plot the median of
the present-day subhalo mass function of the Phoenix and Aquarius
haloes. The difference in the amplitude of these subhalo mass func-
tions between the two simulation sets is about 40 per cent, larger
than the difference in the un-evolved subhalo mass functions. This
suggests that the evolution of subhaloes after their accretion is also
important for explaining the host halo mass dependence of the sub-
halo mass function. We analyse this evolution below.
its peak \( V_{\text{max}} \). Hereafter we quote the normalized mass for subhaloes and their progenitors, rather than the actual mass, in order to take out the host halo mass dependence. Error bars indicate the full range of each distribution. Both simulation sets produce a tight relation between accretion time and progenitor mass ratio, with less massive progenitors being accreted earlier on average than their more massive counterparts. Progenitors of subhaloes in Aquarius are typically accreted before redshift \( z \sim 5 \), and those in Phoenix before \( z \sim 2.5 \). The offset in the accretion time distribution between Phoenix and Aquarius may reflect the fact that the cluster haloes in Phoenix are themselves assembled later.

The bottom panel of Figure 3 shows accretion time distributions of subhaloes that survive to the present day, as a function of their mass ratio (lower axis). These follow the same trend as the progenitor population, with less massive subhaloes accreted earlier. As can be clearly seen, most present-day subhaloes of Galactic haloes were accreted before redshift \( z = 3 \), and those of cluster haloes, before redshift \( z = 1 \). This result is consistent with the study of Bovlan-Kolchin et al. (2009) who used a similar definition of the accretion time to ours, although we extend the result to lower subhalo mass. However, this result is inconsistent with earlier work by Gao et al. (2004) who found that most subhalo are accreted at \( z < 1 \). The discrepancy mainly lies in the definition of accretion time. In Gao et al. (2004), the accretion time of a subhalo was defined as the time it was last associated to a distinct FOF halo. As we demonstrated in the previous section, a large population of progenitors repeatedly pass through the main branch and are later re-accreted. In this work, the accretion time is defined at the time when a progenitor achieves its peak \( V_{\text{max}} \), which is substantially earlier than the reference time used by Gao et al. (2004).

### 4.2 The fate of accreted progenitors

After accretion, some progenitors will survive as subhaloes at the present day, and some will be completely destroyed by the tidal field. Below, we investigate the survival of progenitors. What fraction of them survive to the present day, in total and as a function of accretion redshift? How much mass is retained by surviving subhaloes? It is also interesting to study whether or not these quantities depend on the host halo mass.

We first consider the number and mass fraction of surviving progenitors accreted at two fixed redshifts, \( z = 2 \) and \( z = 4 \). Results are shown in Figure 4. Triangles represent the fraction of progenitors from each redshift that survive, and squares the mass fraction retained by surviving subhaloes. More than 90 per cent of progenitors with normalized mass \( \log(\frac{M_{\text{prog}}}{M_{\odot}}) > 10^{-5} \) at \( z = 2 \) survive to the present day, in both Phoenix and Aquarius haloes. The fraction of surviving subhaloes is independent of progenitor and host halo mass. The decline in the fraction of surviving haloes at the low mass end may be the result of finite numerical resolution. Even though the Phoenix and Aquarius haloes have similar fractions of surviving haloes, the retained mass fraction is quite different between the two simulations. Surviving subhaloes in the Aquarius haloes retain about 40 per cent of their mass at accretion, a factor of 2 larger than subhaloes in Phoenix. This suggests that the tidal stripping process is more efficient in clusters than in a galactic environment. Results for subhaloes accreted at \( z = 4 \) are qualitatively similar, albeit both the number surviving and mass fraction retained are slightly lower because of earlier infall. About 80 per cent of these subhaloes survive the tidal stripping process. About 20 – 30 percent of their original mass is retained.

In Figure 5, we plot the same quantities for all progenitors. The number of surviving progenitors depends strongly on mass for progenitors more massive than 1/1000 of the host halo mass at \( z = 0 \). The most massive subhaloes are more easily destroyed. This is expected, because the effect of dynamical friction is stronger for massive subhaloes and this accelerates tidal stripping. For progenitors having less than 1/1000 of their host halo’s mass, the fraction of survivors becomes largely independent of mass. Roughly 80 per cent of progenitors accreted into the Phoenix haloes survive to the present day. The survival fraction is only slightly lower for Aquarius haloes, about 70 per cent. Presumably, this results from the earlier accretion of subhaloes in Aquarius, as discussed above. The survival fraction falls towards the low mass end of the range we study, presumably as the result of the numerical resolution limit of our simulations.

Despite the noticeable differences in the number of surviving subhaloes between the two simulation sets, the fraction of mass retained by surviving subhaloes is quite similar in both simulations. While most accreted haloes survive to the present day, about 80 percent of their original mass is stripped. Although the typical accretion time is more recent for Phoenix subhaloes, they retain more-or-less the same fraction of their original mass as Aquarius subhaloes, reflecting the fact that the tidal disruption is stronger in...
Assembly history of dark matter subhalo in $\Lambda$CDM

Figure 4. The fraction of subhaloes accreted at redshifts $z = 2$ and $z = 4$ that survive to $z = 0$, and the fraction of mass they retain, both as a function of their mass at accretion. Solid lines correspond to subhaloes accreted at $z = 2$ and the dashed lines to those accreted at $z = 4$. Triangles and squares distinguish fractions of number and mass respectively. Red curves show results for Phoenix, the black curves for Aquarius.

Figure 5. The fraction of all subhaloes that survive to $z = 0$, and the fraction of mass they retain, both as a function of their mass at accretion. Triangles and squares distinguish fractions of number and mass respectively. Red curves show results for Phoenix, the black curves for Aquarius. Curves are medians for each simulation set; error bars indicate the range of each set.

Figure 6. The ratio between the present-day mass of subhaloes and their mass at accretion, as a function of halo-centric distance. Median profiles for Phoenix and Aquarius are shown in red and black respectively. Solid lines correspond to subhaloes with present mass $M_{\text{sub}}/M_h < 10^{-5}$ and dotted lines to subhaloes with present mass $M_{\text{sub}}/M_h > 10^{-5}$. Blue dashed lines show linear fits to each profile.

4.3 Radial dependence of the mass retained by subhaloes

Subhaloes orbiting within their host for a long time experience dynamical friction and tidal stripping, hence their orbits will typically have decayed relative to those of more recently accreted subhaloes of similar present-day mass. This is expected to result in a correlation between the radial position of a subhalo and its accretion time. Gao et al. (2004) showed that there is indeed a tight relation between the fraction of mass retained by subhaloes and their radial position (see also Nagai & Kravtsov (2005)). This relation can be tested by future galaxy–galaxy lensing observations (Li et al. 2013, 2014). With a factor of 1000 improvement in the mass resolution of our simulations, we revise the relation of Gao et al. (2004) as follows.

In Figure 6, we plot the median retained mass fraction of subhaloes against $r/r_{200}$. In order to investigate whether these radial profiles depend on present-day subhalo mass, we divide our subhalo populations into two sub-samples, $10^{-6} < M_{\text{sub}}/M_h < 10^{-5}$ and $10^{-5} < M_{\text{sub}}/M_h$, respectively. The error bars represent the full range of each sample. The strong radial dependence of retained mass fraction seems largely independent of subhalo mass. It depends only weakly on the host halo mass at larger radii, with large scatter. We derive a linear relation,

$$f(r/r_{200}) = 0.69r/r_{200} + 0.9$$

in the region $r/r_{200} < 0.6$ and extrapolate this to larger radii in Figure 6.

5 CONCLUSION

We take advantage of two sets of ultra high resolution $N$-body simulations, the Phoenix and Aquarius simulations, to explore systematic effects in the assembly history of subhaloes. Phoenix and Aquarius have the same effective mass and force resolution, which allows us to make direct comparisons of subhalo evolution between cluster and galaxy sized dark matter haloes.

We have adopted a detailed tracking procedure to follow the evolution of subhaloes from the time of their accretion to the present day. We find that a significant population of subhaloes in
our host haloes at the present day have passed through and later been re-accreted to the main progenitors more than once. The average fraction of these ‘multiply-accreted’ subhaloes varies with host halo mass, from 50 percent for the Aquarius haloes to 35 percent for the Phoenix haloes. We find that the number of accreted haloes which contribute to present day subhalo population systematically depends on the present-day host halo mass, in contrast to previous studies. The amplitude of the subhalo mass function at the time of accretion depends systematically on the final host halo mass, with cluster sized haloes on average having at least 30 percent more progenitors than Milky Way-mass haloes.

The median accretion time of progenitors depends on the host halo mass as well as the mass of the subhalo at accretion. Typically, most progenitors of the present day subhalo population are accreted before redshift \( z = 5 \) in Galactic-scale haloes and \( z = 2.5 \) in cluster-scale haloes. Less massive subhaloes at the present day are accreted earlier on average than more massive ones. At a fixed mass at accretion, the fraction of surviving subhaloes does not depend on the host halo mass, whereas the median mass fraction retained by survivors does correlate with host halo mass. Tidal stripping is more efficient in a cluster environment than around galaxies like the Milky Way. 80 percent of all accreted subhaloes are able to survive to the present day in clusters. The fraction of survivors in Galactic-scale haloes is only slightly lower, \( \sim 70 \) percent. Nevertheless, surviving subhaloes retain roughly 20 percent of their original mass, independent of host halo mass. The evolution of subhaloes after accretion leads to a host halo-centric radial dependence of the mass fraction retained by survivors. This relation seems to be largely independent of host halo mass and subhalo mass. We have provided a simple fit to this radial profile.

The systematic differences we have described in the evolution of subhaloes between cluster and Galaxy-sized hosts help greatly to explain discrepancies in the statistics of present-day subhalo populations at different scales which have been reported by previous studies of N-body simulations.

ACKNOWLEDGEMENTS

We are very grateful to Andrew Cooper for careful reading and correction of English for a version of the manuscript. We also acknowledge Prof. Simon D. White, Jie Wang, Ran Li and Lan Wang for simulating discussions. Phoenix and Aquarius are projects of the Virgo Consortium. Most simulations were carried out on the Lenovo Deepcomp7000 supercomputer of the super Computing Centre of Chinese Academy of Sciences, Beijing, China, and on Cosmology machine at the Institute for Computational Cosmology (ICC) at Durham. The Cosmology machine is part of the DiRAC facility jointly funded by STFC, the large facilities capital fund of BIS, and Durham University. LG acknowledges support from NSFC grants (Nos. 11133003 and 11425312), the Strategic Priority Research Program 'The Emergence of Cosmological Structure' of the Chinese Academy of Sciences (No. XDB09000000), MPG partner Group family.

REFERENCES

Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., Lemson G., 2009, MNRAS, 398, 1150
Contini E., De Lucia G., Borgani S., 2012, MNRAS, 420, 2978

Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, ApJ, 292, 371
De Lucia G., Kauffmann G., Springel V., White S. D. M., Lanzoni B., Stoehr F., Tormen G., Yoshida N., 2004, MNRAS, 348, 333
Diemand J., Kuhlen M., Madau P., 2007, ApJ, 667, 859
Gao L., Frenk C. S., Boylan-Kolchin M., Jenkins A., Springel V., White S. D. M., 2011, MNRAS, 410, 2309
Gao L., Navarro J. F., Frenk C. S., Jenkins A., Springel V., White S. D. M., 2012, MNRAS, 425, 2169
Gao L., White S. D. M., Jenkins A., Stoehr F., Springel V., 2004, MNRAS, 355, 819
Ghigna S., Moore B., Governato F., Lake G., Quinn T., Stadel J., 2000, ApJ, 544, 616
Giocoli C., Tormen G., van den Bosch F. C., 2008, MNRAS, 386, 2135
Guo Q., White S., Li C., Boylan-Kolchin M., 2010, MNRAS, 404, 1111
Ishiyama T. et al., 2013, ApJ, 767, 146
Jiang F., van den Bosch F. C., 2014, ArXiv e-prints
Kravtsov A. V., Berlind A. A., Wechsler R. H., Klypin A. A., Gottlöber S., Allgood B., Primack J. R., 2004, ApJ, 609, 35
Kravtsov A. V., Gnedin O. Y., Klypin A. A., 2004, ApJ, 609, 482
Li R., Mo H. J., Fan Z., Yang X., Bosch F. C. v. d., 2013, MNRAS, 430, 3359
Li R. et al., 2014, MNRAS, 438, 2864
Li Y., Mo H., 2009, ArXiv e-prints
Ludlow A. D., Navarro J. F., Springel V., Jenkins A., Frenk C. S., Helmi A., 2009, ApJ, 692, 931
Nagai D., Kravtsov A. V., 2005, ApJ, 618, 557
Onions J. et al., 2013, MNRAS, 429, 2739
Springel V. et al., 2008, MNRAS, 391, 1685
Springel V. et al., 2005, Nature, 435, 629
Springel V., White S. D. M., Tormen G., Kauffmann G., 2001, MNRAS, 328, 726
Springel V., Yoshida N., White S. D. M., 2001, NewA, 6, 79
Taylor J. E., Babul A., 2005, MNRAS, 364, 515
Tormen G., Diaferio A., Syer D., 1998, MNRAS, 299, 728
Vegetti S., Lagattuta D. J., McKean J. P., Auger M. W., Fassnacht C. D., Koopmans L. V. E., 2012, Nature, 481, 341
Wang H., Mo H. J., Jing Y. P., 2009, MNRAS, 396, 2249
Yang X., Mo H. J., van den Bosch F. C., Zhang Y., Han J., 2012, ApJ, 752, 41
Zentner A. R., Berlind A. A., Bullock J. S., Kravtsov A. V., Wechsler R. H., 2005, ApJ, 624, 505