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DARK MATTER DISTRIBUTION IN CLUSTER GALAXIES

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Abstract. Galaxy clusters are large structures of the Universe, and they are formed and grow through the accretion of smaller structures such as groups or isolated galaxies. In this scenario, during their infall into the core of a cluster, satellite galaxies are submitted to a number of interactions with their host, both on the level of dark and baryonic matter. In particular, both observations and numerical simulations suggest that part of the dark matter composing their haloes can be stripped by the host tidal forces. We present our weak lensing measurement of the Stellar-to-Halo Mass Relation for satellite galaxies in the redMaPPer clusters, using shear data fro the CS82, CFHTLenS and DES-SV surveys. To help interpret these results we then discuss our analysis of the evolution of subhaloes in the Illustris hydrodynamical simulation.

Keywords: galaxy clusters, galaxy evolution, weak lensing, numerical simulations

1 Introduction

In the ΛCDM model of the Universe, structures are formed in a hierarchical way, which means that small objects, such as galaxies and their dark matter haloes will merge over time to form larger and larger structures. In this scenario, galaxy clusters, which are the largest gravitationally bound structures in the Universe, form and grow through the accretion of individual galaxies or smaller groups.

During this accretion process, when an isolated halo becomes a subhalo of a host, there are different interactions taking place between them, both at the level of baryonic and dark matter. For the baryonic part, different effects such as ram pressure stripping, harassment or mergers will tend to suppress star formation in satellite galaxies and form a population of massive and passive red galaxies. Then, the gravitational interaction between the dark matter in the cluster and in the subhalo creates dynamical friction, which slows down the subhaloes and makes them spiral down towards the centre. Because of this effect, subhaloes that are closer to the centre of their host cluster will on average be the ones that started their accretion earlier. Finally, the gravitational potential of the cluster can exert tidal forces on the subhalo, and these forces may strip part of the dark matter from the subhalo and distribute it into the cluster halo.

In this work we examine how the dark matter of a satellite galaxy is affected during infall. In Sect. 2, we summarize our measurement of the Stellar-to-Halo Mass Relation (hereafter SHMR) for the satellite galaxies of the redMaPPer clusters, using galaxy-galaxy weak lensing. More details can be found in Niemiec et al. (2017) (Paper I). In Sect. 3 we measure the SHMR for central and satellite galaxies in the Illustris simulation, and examine the processes that drive the shift in the SHMR, as described in Niemiec et al. (2019), thereafter referred to as Paper II. The cosmology used throughout is a flat ΛCDM universe consistent with the *Wilkinson Microwave Anisotropy Probe* 9-year data release (WMAP9, Hinshaw et al. 2013, : $\Omega_{\rm m,0} = 0.2726$, $\Omega_{\Lambda,0} = 0.7274$, $\Omega_{\rm b,0} = 0.0456$, $\sigma_8 = 0.809, n_{\rm s} = 0.963$ and $H_0 = 70.4 {\rm km\,s^{-1}}$). The notation log() refers to the base 10 logarithm.

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2 SHMR for redMaPPer satellite galaxies

To measure the evolution of the dark matter content of cluster galaxies, we first need an observable to describe the stage of accretion of the satellite, as in observations we cannot directly follow the infall of one subhalo. We use the projected distance between the satellite and the centre of the cluster, as it has been shown to correlate on average with the redshift of infall. We split satellite galaxies into two groups: the satellites in the inner part of the clusters, and the one in the outer part, saying that the galaxies close to the centre of the cluster have started their accretion process before the ones in the outskirts. Then, we need to know that we are comparing galaxies that were similar before accretion, and classify them according to their stellar mass, as a proxi for halo mass before infall. And finally we need to know the subhalo mass of the satellite galaxies, and we measure this using gravitational lensing. To summarize, we measure the SHMR for satellite galaxies, and see how this relation evolves between the satellites in the inner part of clusters and the satellites in the outer part.

As the lensing signal produced by a single galaxy has a very low amplitude compared to the intrinsic ellipticity of the background galaxies, it is impossible to significantly measure the lensing profile (and thus the mass) for each cluster galaxy. Stacking the lensing signals produced by a large number of galaxies is therefore necessary to increase the signal-to-noise ratio. To increase our lens galaxy sample, we use the satellite galaxies of many different clusters, and namely the clusters from the redMaPPer catalogue (Rykoff et al. 2014, 2016). We use the part of the catalogue that overlaps with three lensing surveys, CS82 (Moraes et al. 2014), CFHTLenS (Heymans et al. 2012) and DES-SV (Flaugher 2005; Flaugher et al. 2015; Dark Energy Survey Collaboration et al. 2016). We classify the satellite galaxies according to two parameters: the projected distance to the centre of their host, splitting them between the inner part of the clusters ($0.1 < R_{\rm s} < 0.55\ h^{-1}$Mpc) and the outer part ($0.55 < R_{\rm s} < 1\ h^{-1}$Mpc); and the stellar mass, splitting galaxies in three bins: $10 < \log(M_\star/M_\odot) < 10.5$, $10.5 < \log(M_\star/M_\odot) < 11$ and $11 < \log(M_\star/M_\odot) < 11.5$.

We measured the stacked lensing signal for each of the 6 satellite galaxy samples thus obtained, and fit a halo model to extract the mean subhalo mass for each sample (see Paper I for details on this procedure). The left panel of Fig. 2 shows the best-fit stellar-to-halo mass relation for the satellite galaxies in the redMaPPer cluster that we measured. The blue points present the galaxies in the inner parts of the clusters, and the red points the galaxies in the outer part. The black solid line is the stellar to halo mass relation computed from abundance matching in Moster et al. (2013) for central or field galaxies. For the galaxies in the outskirts of clusters the SHMR is consistent with the one for centrals, which is what could be expected as these galaxies just started their accretion process and were therefore not much affected by the dense cluster environment. On the contrary, for a given stellar mass, the dark matter mass of galaxies in the inner part of clusters is shifted towards lower value compared the galaxies from the outer part, which is consistent with tidal stripping of the dark matter in the subhaloes.

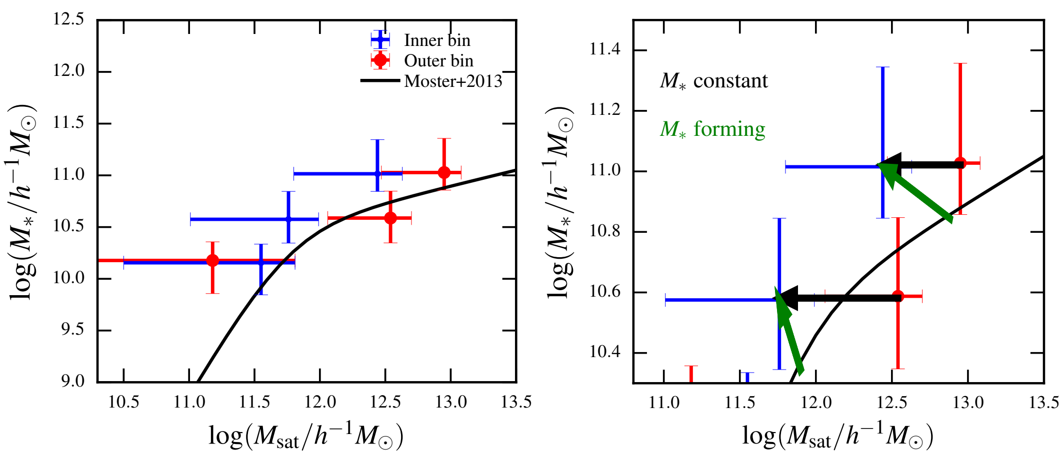

Fig. 1. Left: SHMR for the redMaPPer satellite galaxies, in blue for galaxies in the inner part of clusters, and in red for galaxies in the outer part. **Right:** same as the left panel, but with two extreme evolutionary paths that can explain the SHMR shift between the galaxy in the inner and outer parts of the clusters: the green arrows represent the evolution at constant stellar mass (only dark matter stripping), and the green arrows represent the evolution where the galaxies are forming stars with the same star formation rates as for galaxies in the field. The two figures are adapted from Paper I.

The difference between the SHMR for satellite galaxies in the inner and outer part of clusters can be explained by different evolutionary processes. The first considered scenario is when all the satellite galaxies are quenched: the galaxies then lose part of their dark matter by tidal stripping and keep a constant stellar mass (black arrows in the right panel of Fig. 2). However, it is also possible that at least part of the cluster galaxies continue to form stars during part of their infall. To quantify this scenario, we estimate the amount of stars that could have been formed during accretion, using star formation rates computed in Buat et al. (2008) for central galaxies at the estimated time of accretion for the galaxies that are located in the inner part of their hosts. We then estimate the corresponding subhalo masses before accretion using the SHMR from Moster et al. (2013). This evolutionary path is represented with green arrows in the right panel of Fig. 2, and corresponds to a co-evolution of the dark and baryonic parts of satellite galaxies.

These two scenarios are extreme cases, with either no stellar evolution at all (black arrows), or stellar formation as the same rate as blue star-forming galaxies, and the true evolution should be somewhere between the two. To gain a better understanding of the stellar and dark matter mass evolution of cluster galaxies, we examine the evolution of satellite galaxies in the Illustris simulation, as described in the next section.

3 Subhalo/satellite galaxy evolution in the Illustris simulation

We use the publicly available Illustris simulation* (Vogelsberger et al. 2014a,b), and specifically its most resolved run Illustris-1, where the dark matter particle mass is $m_{\rm DM} = 6.3 \times 10^6 M_\odot$, and the effective baryonic resolution is $m_{\rm b} = 1.3 \times 10^6 M_\odot$. We select the three most massive haloes at redshift $z = 0$ in the Illustris-1 run, with $M_{200} > 10^{14} h^{-1} M_\odot$ that will represent our sample of "cluster-like" haloes.

We first measure the SHMR for central and satellite galaxies in the simulation. We focus on redshift $z = 0.35$ as it corresponds to the mean redshift of the redMaPPer satellite galaxies that we examined in Sect. 2. The left panel of Fig. 2 present the SHMR for all the central galaxies in the simulation, while the right panel shows the SHMR for the satellite galaxies in the three cluster-like haloes. The blue dots show the the SHMR for each galaxy, while the black crosses represent the median relation in stellar mass bins. We find that at a given stellar, the satellite SHMR is shifter towards lower halo mass compared to the central SHMR, with $M_{\rm sub}(M_\star)/M_{\rm h}(M_\star) \sim 0.3$.

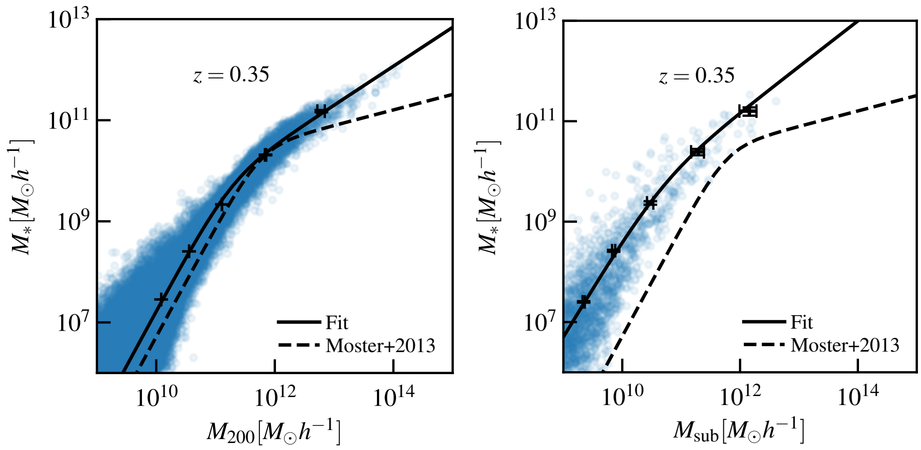

Fig. 2. Left: SHMR for central galaxies at $z = 0.35$. **Right:** SHMR for the satellite galaxies of the 3 cluster-like haloes at $z = 0.35$. The solid black line shows the best-fit relation and the dashed line shows the relation from Moster et al. (2013) as reference. Both figures are adapted from Paper II.

To understand what drives the difference in SHMR between satellite and central galaxies, we then examine the time evolution of different satellite/subhalo properties. We select the satellite galaxies of the three cluster-like haloes that have $M_{\rm sub} > 10^{10} h^{-1} M_\odot$, to ensure that the subhaloes are sufficiently resolved above the mass resolution of the simulation. Using the publicly available merger trees of the simulation, we then follow the

*http://www.illustris-project.org

evolution of these galaxies starting from accretion. The accretion time is defined as the time when the satellites enter for the first time the shell of radius $R_{\rm acc} = 2 \times R_{200}$.

Left panel of Fig. 3 shows the evolution of the satellite cluster-centric distance normalized by the virial radius at accretion, the subhalo mass normalized by the mass at accretion, and the satellite stellar mass normalized by its value at accretion, respectively from top to bottom panel. The three columns represent the three cluster-like host haloes. The black lines represent the evolutions for each individual subhaloes, while the red tick and thin lines represent respectively the median evolution and the 16th and 84th percentiles.

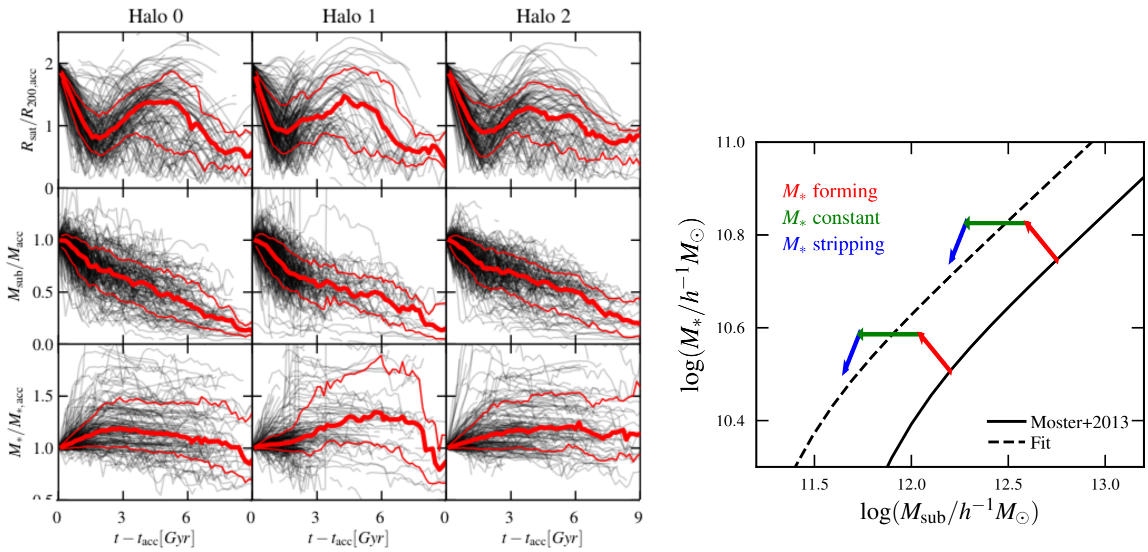

Fig. 3. Left: time evolution of subhalo/satellite galaxy properties since accretion: cluster-centric distance, subhalo mass and stellar mass, from top to bottom. The masses are normalized by their values at the time of accretion. **Right:** summary of the SHMR evolution for satellite galaxies. Three phases can be identified in the process: dark matter stripping + star-formation (red arrows), dark matter stripping at constant stellar mass (green arrows) and dark + stellar matter stripping (blue arrows).

The median evolution of the subhalo mass shows a continuous decrease over time, starting very soon after the subhaloes infall at $2 \times R_{200}$. The mass loss appears to be faster during the first infall into the cluster, with a rate of 20% of the mass at accretion lost per Gyr, and then drops to 6% of the mass at accretion per Gyr. The satellite galaxy stellar mass has a different evolution: it keeps increasing for ~ 2 Gyr after accretion, showing that on average galaxies still have ongoing star formation.

The evolution of the satellite galaxies and their subhaloes can then be summarized as presented on the right panel of Fig. 3: during the first phase, that corresponds roughly to the first infall, the subhaloes start to lose mass by tidal stripping, while the galaxy continues to form stars (red arrows); star-formation is then stopped, and the subhalo mass continue to decrease at fixed stellar mass (green arrows); finally, when only 30% of the initial dark matter mass remains, the galaxy itself can start to be affected by stripping, and the average stellar mass starts to decrease as well (blue arrows). Overall, the total mass evolution is dominated by the subhalo mass loss, and during infall the ratio of stellar to dark matter mass goes from 0.03 to 0.3.

4 Conclusions

We have examined the Stellar-to-Halo mass relation for cluster galaxies. We first measured the SHMR for the satellite galaxies in the redMaPPer clusters, using galaxy-galaxy weak lensing, with shear catalogues coming from the CS82, CFHTLenS and DES-SV surveys. Our measurements suggest that at given stellar mass, the SHMR if shifted towards lower halo masses for galaxies living in the inner parts of their host clusters, which is consistent with tidal stripping of the dark matter. The error bars on the measurements are large, but oncoming large scale surveys such as Euclid will allow to reduce the statistical uncertainties and put tighter observational constraints on the subhalo mass evolution.

We then examined the mechanisms that drive the SHMR shift using the Illustris hydrodynamical simulation. We found that while dark matter stripping is the dominant process that modifies the SHMR, satellite galaxies continue to form stars during infall, and become on average quenched ~ 2 Gyr after accretion. Future work on simulations will allow to determine what systematic errors affect the observational measurements, and measure the expected subhalo lensing signal in different dark matter scenarios.

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