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RECONSTRUCTING FORMATION AND EVOLUTION OF COMPACT DWARF CANDIDATES IN CLUSTERS OF GALAXIES

N. MARTINOVIĆ[1], M. MIĆIĆ[1], A. MITRAŠINOVIĆ[1], S. MILOŠEVIĆ[2] and M. SMOLE[1]
[1]*Astronomical Observatory, Volgina 7, 11060, Belgrade 38, Serbia*
E–mail: nmartinovic@aob..rs

[2]*Department of Astronomy and Astrophysics,*
Mathematical Faculty, University of Belgrade, Serbia

Abstract. We present results from recently published paper in which we have identified a possible solution for the question of formation and evolution of compact dwarf galaxies in clusters of galaxies. We will present a process, involving halo catalogue and particle data, used to reconstruct formation and evolution histories from Illustris-1 cosmological simulation for objects which were not found in merger tree data. This has lead to the discovery of two channels for formation of compact objects in vicinity of the simulation's most massive cluster galaxies.

1. INTRODUCTION

In recent years discovery of the new classes of compact dwarfs, which are populating the link between dwarf ellipticals (dEs) and globular clusters (GCs) in the galaxy mass-size diagram stirred new interest for their evolution and formation. Here we present results from the recently published paper (Martinović and Micic, 2017) and PhD thesis.

Results were obtained from the Illustris-1 simulation, a cosmological hydrodynamical simulation with a complete model for galaxy formation physics (Vogelsberger et al. 2014). For the identification of the gravitationally bound substructures SUBFIND algorithm was used (Springel et al, 2001). Merger tree was generated with the SUBLINK code (Rodriguez et al. 2015). It should be noted that these results would not be possible without public release of the data and ingenious API system for retrieval of specific informations from each of the results (Nelson et al. 2015).

2. SELECTION OF DATA AND METHOD OF ANALYSIS

Our interest was to look for the compact dwarf galaxy candidates in the vicinity (inside of 106 kpc) of the most massive galaxies in clusters at $z = 0$ in Illustris-1 simulation. This parameter space was inspired by results of Zhang and Bell (2017) paper.

For that purpose (identification of compact dwarf candidates), we have used the data from the group catalogue of the Illustris-1 simulation, which gave us information about identified halos at $z = 0$. Considering that compact dwarf galaxies are near the reliable resolution limit of the Illustris-1 simulation, idea was to ensure that we indeed have a significant population. To avoid resolution limit we have searched for halos which have at least the stellar mass of $\sim 10^8 M_\odot$ and total mass less than $\sim 10^{11} M_\odot$ (all found objects are represented with several hundreds of particles). To keep the search confined only to compact objects, we have also used upper limit for the half-mass radius lower than 1.4 kpc (1 kpc/h). As our interest was inspired by Zhang and Bell (2017) paper (as previously stated) we have searched only for objects inside of 106 kpc from most massive galaxies in clusters at $z = 0$. Operating near the resolution limit of the simulation most likely reduced number of compact objects found. This might be seen on Fig. 1, where we have plotted our compact objects against Norris et al. (2014) dwarf population data. From the Fig. 1 it is obvious that these objects (compact dwarfs) populate parameter space which goes well below the resolution limit of the Illustris-1 simulation (shown by position of our objects).

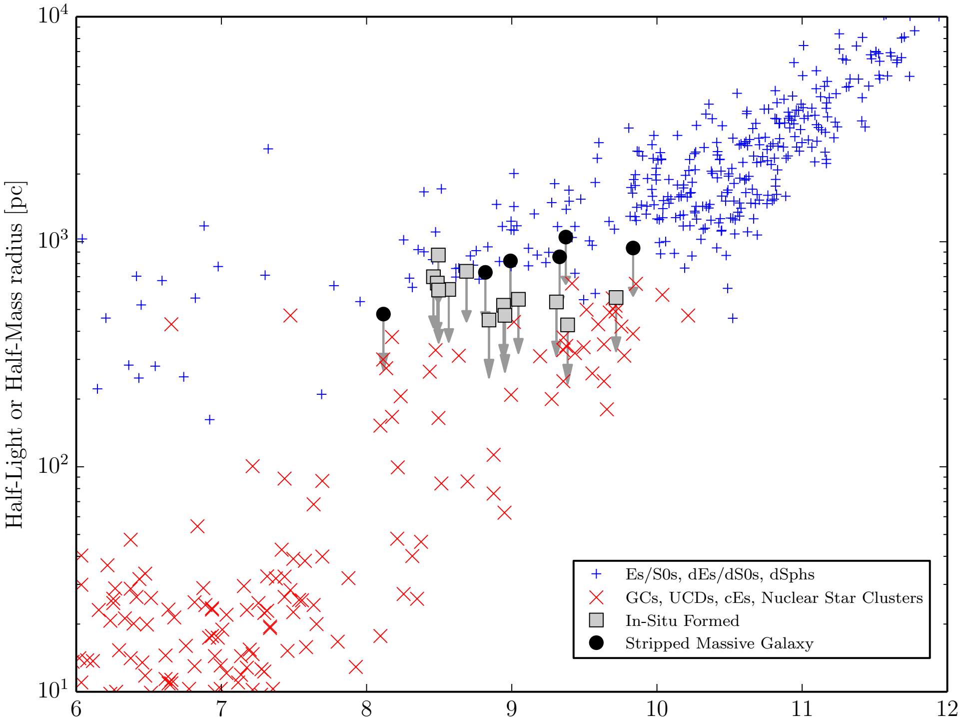

Figure 1: Galaxy mass-size diagram for compact dwarf galaxies. Blue pluses and red crosses are data points from (Norris, 2014) presented with half-light radius. Overplotted are candidate compact dwarfs at $z = 0$ from Illustris-1 presented with 2D projected half-mass radius (averaged over 1000 projections). Black circles represent objects which are remnants of tidally stripped Milky Way mass galaxies, while gray squares represent remnants of dwarf-like objects formed inside clusters of galaxies. Arrows convey that for these populations half-light radius is smaller than half-mass radius. Taken from Martinović and Micic (2017).

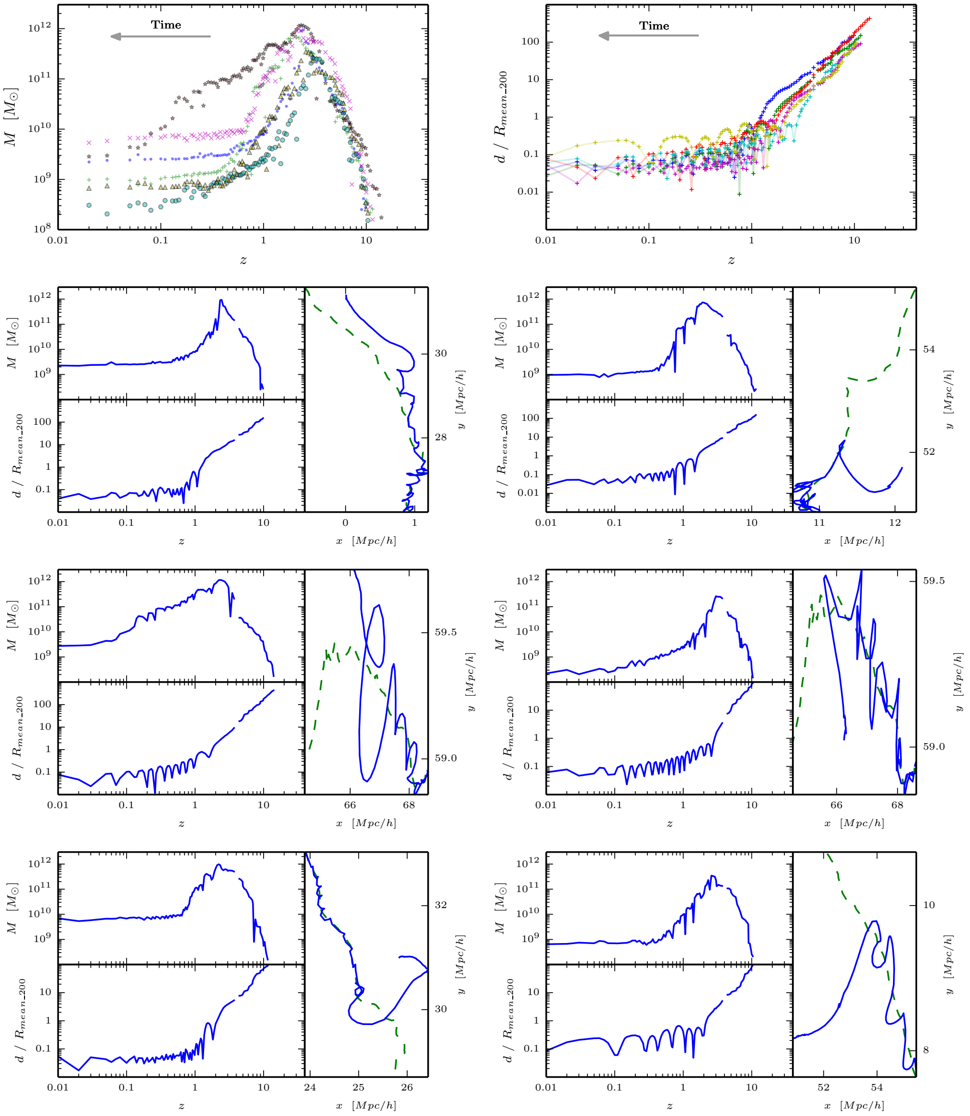

Figure 2: External formation population. Evolution of mass and distance of compact dwarfs from the center of the cluster, relative to the cluster's R_{mean_200} in a same snapshot. Top row represents the total mass and distance evolution, combined for all candidates. Candidates start loosing mass as they enter the cluster at redshift $z \sim 2$. By redshift $z \sim 1$ they are already deep inside the cluster as compact dwarf galaxies. Each of the compact dwarf candidates is featured on its own set of mass and distance evolution plots for clear overview. Additional orbit in x-y plane is outlined for easier visualization, where blue line represents motion of dwarf candidate and green dashed line motion of most massive galaxy inside of cluster of galaxies. Taken from Martinović and Micic (2017).

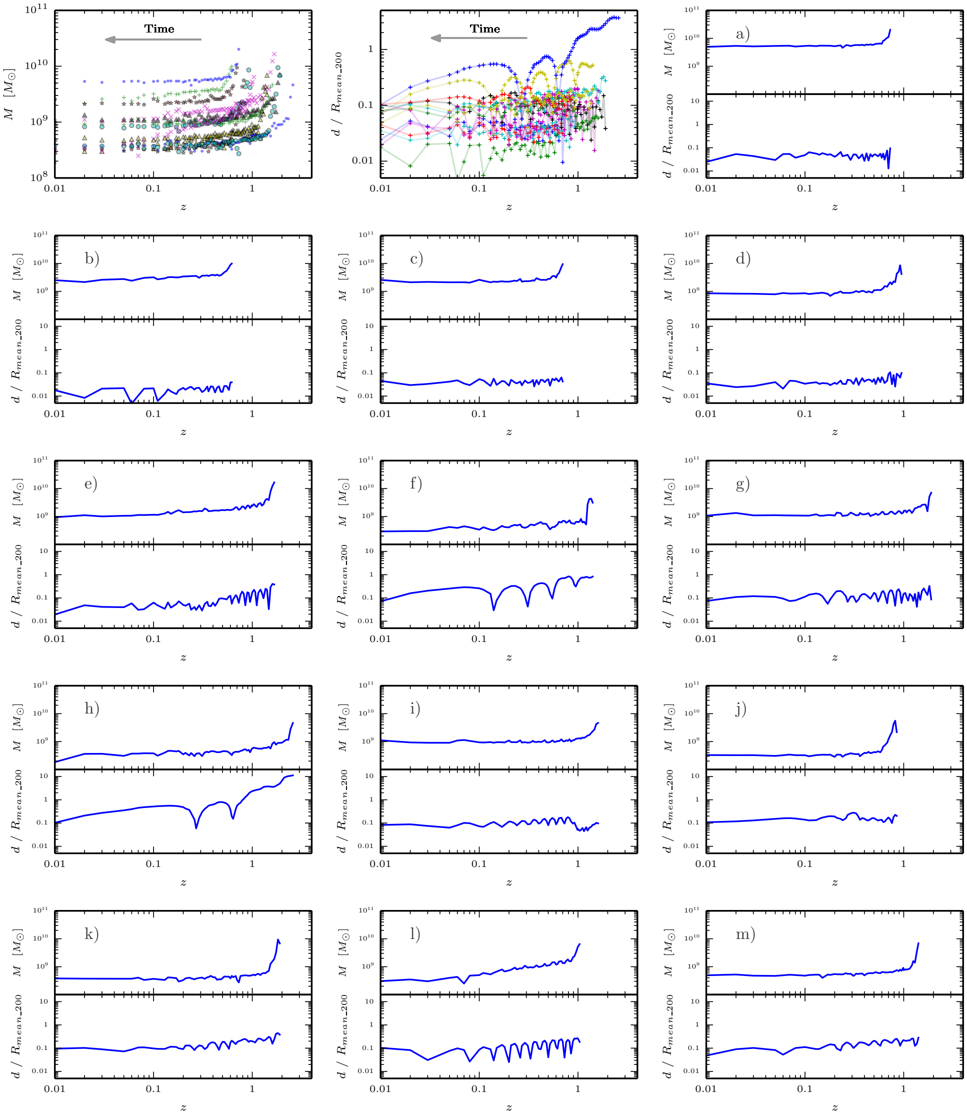

Figure 3: In-situ cluster formed population. Evolution of mass and distance of compact dwarfs from the center of the cluster, relative to the cluster's R_{mean_200} in a same snapshot. Similar as in Fig. 2, first two plots of top row represent the total mass and distance evolution, combined for all candidates. Here we can see that galaxies in this population form within clusters and have less dramatic mass evolution than external population presented in Fig. 2. Each of the compact dwarf candidates is featured on its own set of mass and distance evolution plots for clear overview. Orbit outline is omitted here because of additional area it would necessitate.

As noted in Martinović and Micic (2017) we have found 22 objects that satisfy our criteria. Next came the search for evolutionary paths for those objects with idea that it may reveal to us a preferred path or channel of their formation. For retrieving that data we have relied extensively on snapshots or more precisely on temporal data that is a part of each numerical simulation. Considering that Illustris team also released complete merger tree for Illustris-1 simulation initial search for evolutionary paths of our objects was searched within it.

We have chosen several objects randomly and for them initial search in merger tree yielded no information about connection between halos that were identified in previous snapshots, that is, there was no found evolutionary paths for identified objects. At that point, we were ready to dismiss our objects as numerical artifacts or products of recent dynamical mergers or processes within clusters (considering that they were all close to the major halos within clusters). But interestingly, after running the analysis for all objects within merger tree, for two of them there was significant evolutionary informations going far toward the start of the simulation. This gave us clue that missing merger tree data was consequence of the analysis itself that lead to the creation of the merger tree for the whole simulation (more than 4 million halos identified at $z = 0$). This was most likely because analysis had to incorporate as broad range of scenarios as possible thus sacrificing very specific cases as these turned out to be.

Ultimately we have reconstructed the history of each object manually. For that purpose we have relied on full snapshot information provided by the Illutris team and on the ingenious API system which enabled us to probe specific snapshot data without the need to retrieve terabytes of snapshots. As noted in Martinović and Micic (2017) we have extracted particle IDs and position and velocities for each object. Idea was to look for progenitor information in previous snapshot and to repeat the process as long as possible (toward the start of the simulation).

To constrict the search on manageable number of candidates for progenitors (and to limit the load on API) from the position and velocity data we have predicted where would object be located in previous snapshot after which we would retrieve all the objects in vicinity of that location (cutting out small box where object should have been located previously and finding the objects within it). Then we used initial particle IDs and compared them to particle IDs of the identified objects in the previous snapshot. To speed the process up, initial location probability box was smaller (with sides of 100 kpc/h) and we checked only particle IDs of stellar component (as most of our objects at $z = 0$ had majority of particles of that type). If there was a match, percentage of the found particles was checked. If it was high enough (at least 80% of same particle types) analysis for that snapshot was stopped. Object with matching particle data would be flagged as progenitor and the whole process was repeated for the next snapshot, where now particle IDs of the flagged progenitor were used as primer. Thus iteratively we would search for progenitors in each snapshot, by repeating that process until the start of the simulation.

If in a certain snapshot no progenitor was identified, additional analysis was performed. It consisted of checking other particle IDs in those objects - first dark matter particles, and then gas particles. If no significant number of particles of any type was found (at least 10%), then we would repeat the whole process but for a slightly larger probability box. Box was enlarged until it reached 400 kpc/h around estimated location. After no progenitor objects were found even in a very large box for all particle IDs, then we would flagged that we have retrieved furthest information as possible for the object.

If matching particles were found but with matching percentage between 10% and 80% we would manually stop and analysed all of the particle IDs for the object to decide if that object is a progenitor and how to proceed further (case by case basis). In merger situations (though not many were found until early in the simulation) we would choose main progenitor branch which we declared as progenitor with greatest particle matching percentage (usually above 50% of matching particle IDs).

The whole process was tested against the main progenitor branch within merger tree of two objects which had evolutionary informations and it yielded the same results. Curiously, if during analysis we came upon objects with matching dark matter particles in adjacent snapshots (during random phase of searching for progenitors) that would usually coincide with a link between those objects in merger tree data which exists for few snapshots, thus showing that Illustris team analysis relying heavily on dark matter particles. Considering that objects on $z = 0$ had few dark matter particles, that might explain why they were omitted from merger tree to begin with.

Ultimately from 22 initially selected objects, 3 were dismissed with no progenitor history (probably numerical artefacts) and 19 have been identified to have significant evolutionary data. Their parameters are given in the Table 1. which was taken from the (Martinović and Micic, 2017).

3. RESULTS AND CONCLUSION

After successfully retrieving the evolutionary history of the 19 obtained compact dwarfs in vicinity of most massive galaxies of clusters at $z = 0$ in Illustris simulation it became obvious that there were two channels for their creation.

First channel of formation was the channel which identified a population of compact dwarfs whose formation comes from the tidal stripping of the Milky Way mass galaxies that have been created outside of the clusters and which lost most of their material during spiraling toward cluster center (Figure 1.). This was more exciting to us because dynamics of galaxies of these sizes is not sensitive to simulations underlaying physics.

Second channel was formation which comes from the gas clouds which are located inside clusters with no dark matter component at earlier redshifts, the so called in-situ formation channel (Figure 2.). Although there are explanations for their creation (see Martinović and Micic, 2017) prevalence of this mode of formation might be sensitive to hydrodynamics incorporated in the simulation core and it remains to be seen how sensitive this mode of creation is to the slight differences of an implemented underlaying hydrodynamical model.

In total, 19 compact dwarf candidates from 14 clusters were identified. Around 30% of candidates (in central parts of the clusters) have been formed by tidal stripping of Milky Way mass galaxies spiraling into the cluster, while around 70% are in-situ cluster formed from dwarf like progenitors. These result are consistent with the observational results presented by Zhang and Bell (2017). For further discussion of the results we refer the reader to the paper of Martinović and Micic (2017).

Table 1: Parameters for compact dwarf galaxy candidates from Illustris-1 simulation at $z = 0$: label on plot (if applicable), distance to the most massive cluster galaxy (*kpc*), total mass (given in log), total stellar mass (given in log), maximum stellar mass of the candidate during its existence (given in log), maximum total mass of the candidate during its existence (given in log), stellar half-mass radius (*pc*), a 2D projected stellar half-mass radius (*pc*) (averaged over 1000 projections), minimal retrieved 2D projected stellar half-mass radius (*pc*) and maximum retrieved 2D projected stellar half-mass radius (*pc*). Above the horizontal line are parameters for external population and below the line for the in-situ population. Taken from Martinović and Micic (2017).

Label	d	$\log(M_\odot)$ ($z = 0$ total)	$\log(M_\odot)$ ($z = 0$ stellar)	$\log(M_\odot)$ (max stellar)	$\log(M_\odot)$ (max total)	R	R_{proj}	R_{min}	R_{max}
	45	9.3	9.3	10.3	12.0	1136	857	778	928
	91	9.0	9.0	10.5	11.9	1074	822	757	892
	99	9.4	9.3	10.8	12.1	1395	1049	1016	1078
	21	8.1	8.1	10.0	11.4	656	477	419	527
	92	9.8	9.8	10.8	12.0	1257	938	888	994
	73	8.8	8.8	9.9	11.5	943	731	626	855
a)	71	9.7	9.7	9.8	10.3	739	565	374	685
b)	32	9.4	9.4	9.7	10.0	558	427	338	479
c)	76	9.3	9.3	9.6	10.0	692	540	332	636
d)	71	8.8	8.8	9.4	9.9	587	449	432	463
e)	83	8.9	8.9	9.6	10.2	679	522	411	615
f)	80	8.5	8.5	9.0	9.6	895	699	567	778
g)	64	9.0	9.0	9.4	9.9	730	555	479	634
h)	85	8.6	8.6	9.2	9.7	808	614	538	688
i)	76	9.0	8.9	9.3	9.7	618	471	452	493
j)	104	8.5	8.5	8.9	9.7	1125	873	813	926
k)	88	8.5	8.5	8.9	10.0	847	655	563	741
l)	93	8.5	8.5	9.3	9.8	787	610	516	669
m)	58	8.7	8.7	9.1	9.8	967	739	548	855

It also needs to be noted that these results would not be possible without public data release of Illustris simulations and without manually reconstructing the evolutionary paths. In the era of big data we need to be aware that broadest analysis applied to full scope of data might overlook important peculiar results.

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