Modeling Satellite Galaxies in Semi-analytical Models

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Abstract

Understanding the evolution of satellite halos is important in predicting the abundance of dark matter subhalos and satellite galaxies. However, in numerical simulations of structure formation, spurious disruptions can occur that make the halos of some galaxies no longer detectable. Those galaxies that have lost their host dark matter halo are called "orphan galaxies". In this work, we consider a semi-analytical model for the evolution of the orbits of orphan galaxies, which considers effects of both dynamical friction and tidal forces. We propose to use the two-point correlation function and the halo mass function of a high-resolution N-body simulation to constrain the free parameters of the model.

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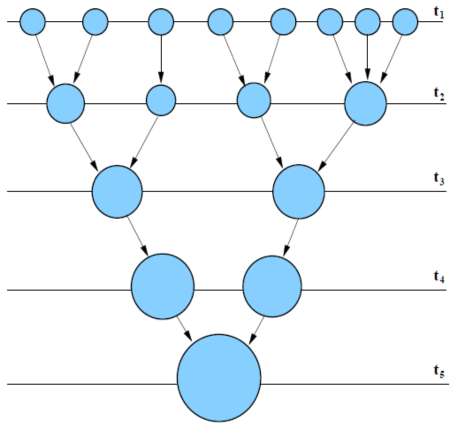
Introduction

Structure formation in the Universe is a hierarchical process, where the first galaxies are formed in the potential wells generated by dark matter halos. As the universe evolves, mergers between halos that host galaxies may occur; in that case the more massive galaxy occupy the center of the new halo while the less massive one becomes a satellite galaxy of the central galaxy. A satellite halo orbiting within its main system loses mass by tidal stripping and experiences dynamical friction, a net drag force that gradually shrink its orbit until it finally merges with the central.

However, in cosmological simulations, due to the mass resolution limit, it may happen that satellite halos are no longer identified before the merging of their respective galaxies. Satellite galaxies that lose their host halo before merging with its central galaxy are called "**orphans galaxies**".

In this work, we present an updated treatment for the orbits of orphan galaxies used in SAG [1] semi-analytical model of galaxy formation and evolution.

The model proposed includes semi-analytic expressions for the tidal stripping and dynamical friction mechanisms.



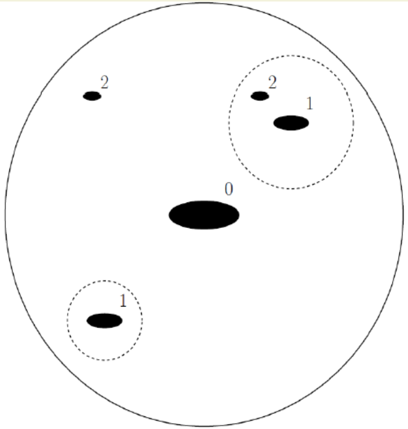


Figure 1. (*left*) shows the process of halo formation by hierarchical aggregation. The size of the circles indicates the mass of the halo. Credit: C. Baugh (*right*) scheme of different types of galaxies: central (0), satellites (1) and orphans (2). Dotted line circles indicate satellite halos.

Evolution of Orphan Galaxies I

To determine the orbit of an orphan galaxy, we consider each subhalo as a particle of the same mass moving in a smooth spherical potential generated by the host halo. To take into account the effect of the host halo over the satellite, at each instant we compute the effect of dynamical friction using Chandrasekhar's formula and we also take into account the loss of material by considering the tidal stripping effect. If, at any instant, the satellite-host distance is less than a fraction *f* of the host virial radius we considerate the satellite to be merged with its host.

The **dynamical friction** (DF) force $\mathbf{F}_{df}$ is given by Chandrasekhar's formula [2].

$$\mathbf{F}_{\mathrm{df}} = -\frac{4\pi G^2 M^2 \rho(r) \ln \Lambda}{V^2} \left[\mathrm{erf}(X) - \frac{2X}{\sqrt{X}} e^{-X^2} \right] \frac{\mathbf{V}}{V}$$

Following [3], we use the Hashimoto approximation for the Coulomb logarithm ln(Λ)

$$\ln \Lambda = \begin{cases} \ln(r/bR_{sat}) & r > bR_{sat} \\ 0 & r \leq bR_{sat} \end{cases}$$

where R_{sat} is the virial radius of the satellite halo and *b* is a free parameter.

Evolution of Orphan Galaxies II

We estimate the mass loss by **Tidal Stripping** (TS) as the mass outside the tidal radius $M_{sat}(> r_t)$. Since the rate at which the material located outside of r_t is removed is not clear, following [4] we introduce a free parameter α that controls the efficiency of TS i.e.

$$\frac{dM_{sat}}{dt} = -\alpha \frac{M_{sat}(> r_t)}{T_{orb}}$$

where the tidal radius r_t is given by the following expression

$$r_t = \left(\frac{GM_{sat}}{\omega^2 - d^2\Phi/dr^2} \right)^{1/3}$$

Proximity **criterion for mergers**: we consider a subhalo to be merged when the subhalo-host distance is smaller than a fraction f of the virial radius of the main system, i.e. if

$$r_{sat} < fR_{host}$$

Simulations

We use the MDPL2 and SMDPL halo catalogs from the MultiDark-Planck set of simulations, for more details see [5]. DM halos were identified with ROCKSTAR halo finder [6] and merger trees were constructed using CONSISTENT-TREES [7]. MDPL2 present a lack of low mass halos and lower clustering at low separations. These results show that these low mass halos which are not present in the MDPL2 due to the resolution limit of the simulation are responsible for the clustering difference with SMDPL (see upper row of Fig. 2). To compensate for this lack of satellite halos we introduce the orphans, and then compare the results to SMDPL.

Since running the model over the full MDPL2 simulation is computationally very expensive, we are interested in finding a MDPL2 box relatively small in volume but representative of the characteristics of the full simulation. The lower row of Fig. 2 shows (in black continuous line) the mean values of the halo mass function and two point correlation function computed over all subvolumes; error bars indicate the standard deviation. In red dashed line figure the “best box”. We selected this box by optimizing for masses higher than $10^{10.4}$ M_{sun}/h and for separations in the range [0.02, 1] Mpc/h.

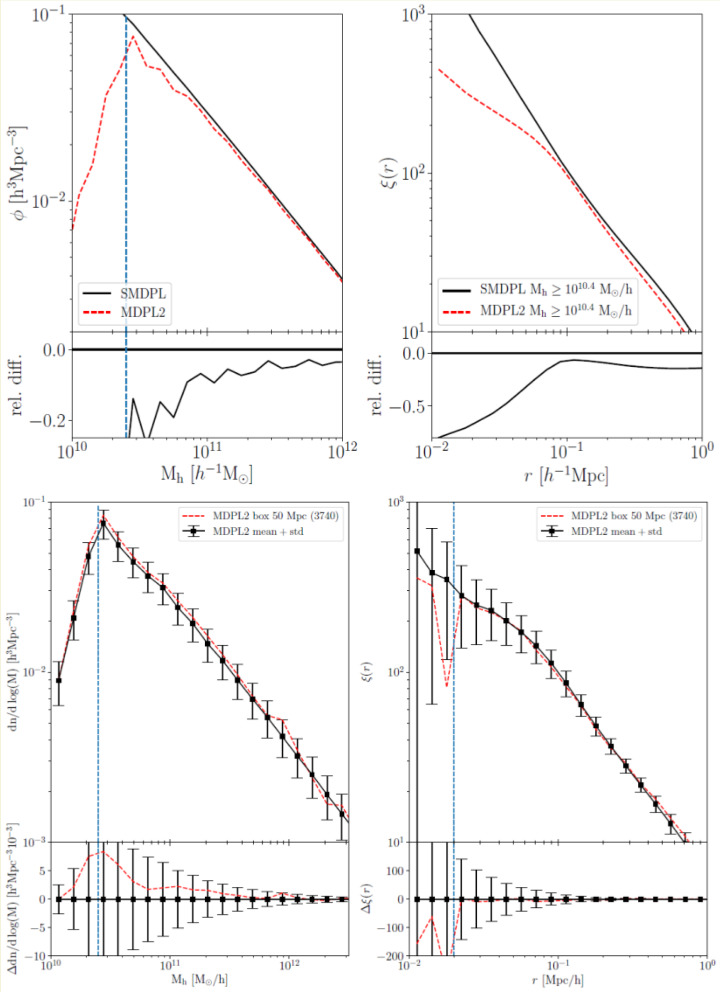


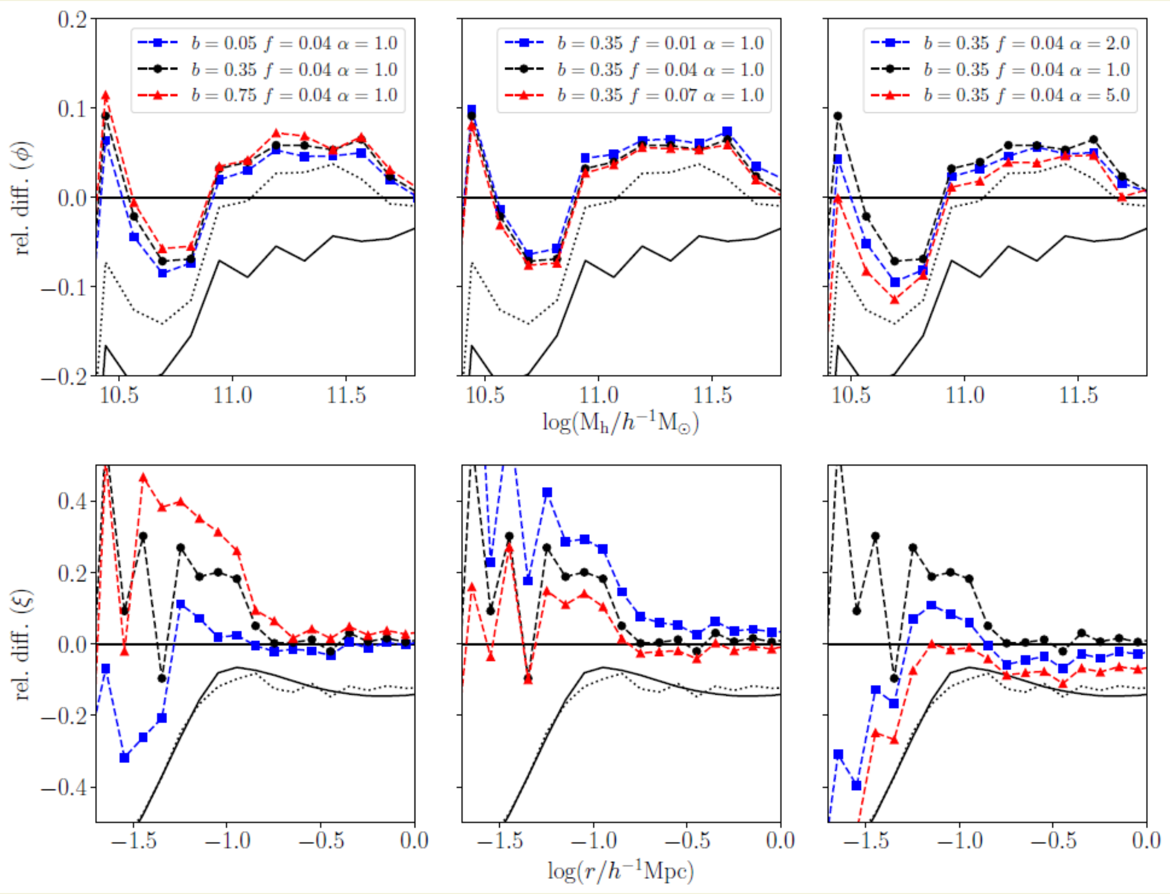
Figure 2. (*upper panel*) halo mass function and two point correlation function for full simulations. The vertical indicate the limit $10^{10.4}$ M_{sun}/h; (*lower panel*) halo mass function and two point correlation for the MDPL2 50 Mpc/h box. The vertical line in the clustering plot indicate the scale 0.2 Mpc/h.

Results

Fig 3. shows the result of running the model over the MDPL2 50 Mpc/h box for different parameter combinations. Here we plot relative differences taking SMDPL as a reference. From left to right we explore: *b*, *f* and *α*. The circle-dashed (black) line corresponds to the set (*b=0.35, f=0.04, α=1.0*).

As we can see varying the parameters have an impact on the correlation function (ξ) and halo mass function (φ). φ is more sensitive to the variation on the efficiency of TS (α). ξ seems to be sensitive to variation of the three parameters.

Figure 3. (*upper row*) halo mass function relative difference for different set of parameters; (*lower row*) relative difference for two point correlation function. The solid (black) line indicates the relative difference for MDPL2 full. The dotted (black) line indicates relative differences for MDPL2 50 Mpc/h. The dashed lines indices MDPL2+model for different parameter combinatios.



Conclusions

Clustering results show that low mass halos are responsible for the clustering difference between SMDPL and MDPL2. We propose to use the clustering of SMDPL as a constraint for the orphan galaxies orbit model in MDPL2.

Running the model over the complete simulation is very expensive, thus we have selected a MDPL2 50 Mpc/h box by optimizing the halo mass function for masses higher than $10^{10.4}$ M_{sun}/h and the correlation function for separations in the range [0.02, 1] Mpc/h.

The results from parameter exploration show that varying the parameters have an impact on halo mass function (φ) and on he clustering signal (ξ). φ is more sensitive to the variation on the efficiency of TS (α), but is less sensitive to the variation of the other parameters. ξ seems to be sensitive to variation of the three parameters.

Including clustering information can help to better define the parameters of the model and improve the clustering at small scales of semi-analytical models, such as SAG, by properly taking into account the orbits of orphan galaxies.

These are preliminary results to be published in Delfino et al. [8]

References

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