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Are local group galaxies so improbable?

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ABSTRACT

Key words: galaxies: haloes, groups – cosmology: dark matter, observations

1 INTRODUCTION

cosmological scenario the local group the problem of locating the LG in the universe

The questions we want to address in this paper is: How common is the local group of galaxies in the cosmological context? what is the probability of generate a local group in the universe? under which physical conditions do we reproduce the properties of the local group?

2 METHODS

2.1 N-body simulations

In this work we study the evolution of galaxies in the local universe through the use of semi-analytic models of galaxy evolution. To properly constrain the study to the local group it is required to use then constrained simulations of the local universe. A constrained simulation of the local universe is a standard N-body simulation of the formation of structure in which observational constraints have been imposed in order to reproduce the large scale environment of the local universe (Martinez-Vaquero et al. 2009, Gottloeber et al. 2010, Doumler et al. 2012).

The constrained simulations used in this work are part of a suite of cosmological simulations part of the CLUES (Constrained Simulations of the Local Universe) project (Gottloeber et al. 2010). The observational constraints impose conditions on the large scale structure of the local universe on scales above a few mega parsec, however the small scales keep unconstrained and behave basically randomly. In order to overcome this problem, and to get a realisation that matches as close as possible not only the large scale environment but also the environment of the local group, many realisations are required of the same piece of the universe with the same constraints. From this set of realisations (200 in the case of the CLUES) a few have been selected to be potential candidates in which not only the large scale environment but also the small scale environment have been reproduced.

The criteria used to identify fiducial local group realisations are

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From a set of 200 low resolution simulations, three satisfy the criteria imposed. These three simulations are the re run at high resolution keeping the constrain on the large scale structure.

The final set of simulations we have used in this work is then a set of three simulations with a box size of 64 h^{-1} Mpc and sampled with 1024^3 particles giving a particle mass is 1.09^7 $h^{-1}\,\mathrm{M}_\odot$. The candidates to milky way and Andromeda galaxy in these simulations are resolved with more than XXXX particles. The starting redshift of the simulation was 50, and it was run with the cosmological Tree-PM code Gadget-2 (Springel 2005).

The use of the constrained simulations provide us with the unique opportunity to model the large and small scale environment of the local group, and pick candidate objects to host the milky way and Andromeda galaxy. Simultaneously, the realisation of simulations of dark matter only provide us with the opportunity to simulate a fairly large sample of galaxies. For each of the three simulations we have around XXX haloes, and XXX haloes in the mass range XXX to XXX. In general, combining the three data sets we have a total of 27000 haloes in the mass range of XXX to XXX, which provide us with a large statistical sample of MW type haloes.

Merger trees ....

2.2 Semi-analytic Modelling

description of galacticus and the recipes we use

Since the simulations we have performed are dark matter only, galaxy formation has to be modelled as an external process happening inside dark matter haloes. One of the advantages of using this semi-analytic approach is the opportunity to explore the parameter space and to find the parameter set that best reproduce the observed structure of the local group galaxies.

Instead of developing our own semi-analytic code we opted for the alternative to use a publicly available semi-analytic code for galaxy formation. The code we used in this work is GALACTICUS. A semi-analytic code developed by Andrew Benson (Benson 2011). GALACTICUS implements several physical processes and implements different approaches for each different process. Instead of exploring the many different possibilities of the code, we keep close to the "basic" usage of the code, used standard recipes to model the different physical processes.

In our simulations we have included many different physical phenomena: bla, bla, blahhh.

Each physical process is controlled by one or more parameters. From those processes we detail the most important ones, those are the ones we have decided to vary in order to explore the parameter space associated with the probability of having a local group.

2.2.1 *Galaxy mass growth*

One would expect that the accretion of cold gas in a dark matter halo depends on the growth rate of mass of the halo, but also on the available gas mass, the mass of the halo itself and the thermodynamical conditions of the gas. In GALACTICUS we use the *simple* method to model the accretion of cold gas like

$$\dot{M}_{\rm accr} = \{ \,(\,\Omega_b/\Omega_M)\dot{M}_{\rm halo}, \quad \text{if} \quad V_{\rm virial} > V_{\rm reioniz}$$

where Ω_b/Ω_M is the cosmic baryon fraction that basically controls the amount of available baryons and $V_{\rm reioniz}$ and $z_{\rm reioniz}$ are the free parameters that model cold gas accretion. If a halo has a low velocity (lower than the threshold $V_{\rm reioniz}$) is not massive enough to accrete and keep cold gas. Also, if the redshift is larger than $z_{\rm reioniz}$ the temperature of the gas should be high enough and no effective cooling should be present.

2.2.2 *star formation time scale*

We have used the standard Cole et al. 2000 star formation time scale. It is parameterized by a power law in the halo velocity

$$\tau_\star = \epsilon_\star^{-1} \tau_{\rm dyn} \left(\frac{V}{200{\rm km/s}} \right)^{\alpha_\star} \tag{2}$$

with free parameters $\epsilon_\star$ and $\alpha_\star$ that control the star formation efficiency and the shape on the velocity (or mass) dependence of the star formation time scale.

2.2.3 *supernova feedback*

Mass ejection from supernovae is modeled as

$$\dot{M}_{\rm outflow} = \left(\frac{V_{\rm outflow}}{V} \right)^{\alpha_{\rm outflow}} \frac{\dot{E}}{E_{\rm canonical}}, \tag{3}$$

where $V_{\rm outflow}$ is a threshold velocity for the galactic component. The larger the value of $V_{\rm outflow}$ the stronger the suppression of the outflow of mass. The second parameter is $\alpha_{\rm outflow}$, and as $\alpha_\star$ controls the mass dependence of the outflow. V, $\dot{E}$ and $E_{\rm canonical}$ are not constants, they are the velocity of the component, the rate of energy input from the stellar populations and the energy input by a stellar population normalised to $1{\rm M}_\odot$ after an infinite time.

2.2.4 *Minor/Mayor merger (η)*

We define a minor merger between a massive halo M_{Hm} and a low mass halo M_{Lm} if

$$\frac{M_{Lm}}{M_{Hm}} \leqslant \eta \tag{4}$$

in other case the merger will represent a major merger.

2.2.5 *Merger mass flow*

After a merger (minor or major) the mass of the galaxies must be redistributed in the remnant. The way the mass is redistributed in the remnant depends on the characteristics of the merger.

- If the merger is a major merger the structure of both galaxies is destroyed and all mass from both galaxies moves to the spheroid of the remnant central galaxy.
- In the case of a minor merger the mass of the satellite moves to the component that is indicated by the respective flag. $M_{\rm satel.,gas} \rightarrow$, where in our case gas and stars can move from the satellite to the disk or to the bulge of the central galaxy.

or $z > z_{\rm reioniz}$0, otherwise(1)

2.2.6 *galaxy structure: Spin and concentration parameter*

The structural properties of the galaxy depend partially on the structural properties of the dark matter halo. We used the approach included in GALACTICUS that allows to use the fitting formulas of Prada et al. 2011 to model the concentration parameter of halos as a function of mass and redshift while for the spin parameter used two prescriptions. The first one is the fitting formula from Bett et al. 2007. The second prescription assumes that the spin parameter follows a lognormal distribution with mean $\mu_\lambda = 0.031$ and variance $\sigma_\lambda = 0.57$ as computed from cosmological simulations by Muñoz-Cuartas et al. (2011).

2.3 Observational samples and definition of our local group

describe the data sample used to define the local group

We have already shown how we define the milky way and Andromeda galaxies in our simulations. Now we need to introduce an operational definition for these galaxies from the observational point of view. Clearly, MW and Andromeda are characterised by its observational properties. Considering the quantities we can reliably model using the semi-analytic approach. We will define, or characterise the milky way galaxy and Andromeda.

We decide to define the Milky Way and Andromeda galaxies through XXXXX, XXXXX, XXXXX, and XXXX because XXXXX, XXXXX and XXXX.

Disk stellar mass. The principal approach to estimate

Property	MW	Ref.	M31	Ref.
$M_{disk,\star}[10^{10}M_{\odot}]$	3.0	(1)	7.2	(2)
$M_{disk,gas}[10^{10}M_{\odot}]$	0.7	(3)	0.6	(4)
$M_{bulge,\star}[10^{10}M_{\odot}]$	$1-2$	(3)	3.2	(2)
V_{circ}[Km/s]	238	(5)	275 ± 5	(6)

Table 1. Observational estimations for different properties of the LG, where(1)**?**, (2) **?**, (3)**?**, (4) **?**, (5)**?**, (6)**?**.

the stellar mass in the disk of our galaxy is dynamical modelling. The work of **?** uses a parametric model that does not distinguish between the cold (gas) co component and the stars, their results for galaxy models that allow for exchange of angular momentum locate the total baryonic mass of the disk between $5-6\times10^{10}M_{\odot}$ for the MW and $7-9\times10M_{\odot}$ for M31. Later **?** use N-body realisations of self-consistent, equilibrium distributions of the dark matter and stellar components to address the same problem. Their models with good match to the observational data have stellar masses of $3.3-4.5\times10^{10}M_{\odot}$ for the Milky Way and $7-10\times10^{10}$ for Andromeda. (**?**) modeled the Andromeda strem using analytic bulge-disc-halo for M31, finding the best agreement for a disk mass of $8.4\times10^{10}M_{\odot}$. In this work we take $3.3-4.5\times10^{10}M_{\odot}$ for the Milky Way and $7-10\times10^{10}$ for M31.

Bulge stellar mass. **?** constrain the MW bulge stellar masss $1-1.2\times10^{10}$ $M_{\odot}$ while for M31 $1.9-2.4\times10^{10}$, for the same galaxy (**?**) find a bulge mass of $3.3\times10^{10}M_{\odot}$. The MW analytical model of model (**?**) finds a range of different values with average $\sim 0.510^{10}M_{\odot}$. In this work we pick $0.5-1.2\times10^{10}M_{\odot}$ for the MW and $1.9-3.3\times10^{10}M_{\odot}$ for M31.

Disk Gaseous mass. The abundance of gas in the Milky Way has been constrained through chemical evolution models. The set of observational constraints on these models most notably include the gas and star formation rate (SFR) profiles. The relevant observational data was compiled in (**?**) using from the original work in **??**, with a values of $6.0-8.0\times10^{9}M_{\odot}$, an update implementation of this chemical evolution model by (**?**) uses the same observations. In the case of M31 the best observational constraints come from the observations by (**?**) with the integrated mass of neutral gas corrected by (**?**), yielding a value of $5.2\times10^{9}M_{\odot}$, there is a systematic observational uncertainty of 5% originally quoted in (**?**), but due to opacity effects of the HI (**?**) the total value of gas can increase by a 19%. Therefore we keep a value of $5.0-6.0\times10^{9}$ for the mass of gas in the M31 disk and $6.0-8.0\times10^{9}M_{\odot}$ for the Milky Way.

2.4 Analysis strategy

Introduce the metric and technique used to quantify the distance and probability of MW.

Our goal is to determine quantitatively (instead of qualitatively) which is the probability to find a galaxy like the milky way and Andromeda in a given cosmological volume, as well as to see which are the values of the parameters in the model that maximise the probability of finding such a galaxies.

To do so we have already defined what a milky way would be, but we need to quantify how far are our models from such a definition, and from this distance, we can quantify the probability of finding milky way like galaxies in the nearby universe.

We define the distance between two galaxies (the defined MW and the model galaxy) through the distance measure

$$d = \sqrt{\sum_{i=1}^{N}\left(\frac{y_i - m_i}{\sigma_i}\right)^2} \quad (5)$$

The distance d indicates the actually the distance measure (or difference) between two points in a space defined by the parameter set m_i. the parameter set m_i is the set of values of quantities associated with the definition of our milky way and Andromeda galaxies, that is, stellar mass, circular velocity, XXXX, XXXX and XXXX. the values y_i are the values associated with those parameters for each model galaxy in our simulations. $sigma_i$ is the error associated with the estimated value of the observed parameter m_i which will be in any case larger than the uncertainty one can associate with the values of the parameters in the model galaxy.

One can clearly notice that so defined, d should follow a chi-square distribution, since it is defined in an equivalent way. Without loss of generality in our context this quantity can be associated to a measure distance more than the normal interpretation (Press et al. XXXX) of it as an estimation of goodness of fit. Another advantage is that so defined, assuming that the parameters m_i are independent, d should be distributed following a chi-square distribution, which will help us to interpret our results in a probabilistic way.

We then compute the value of the distance d from each model galaxy to the defined galaxies MW and Andromeda and trough it examine quantitatively the probability to find such an object in our simulations.

3 RESULTS

Now we present the results of our research. Since we are interested in to find Milky Way and Andromeda like galaxies, we will ignore all very massive and very low mass objects, and will focus only in a mass range around the estimated halo mass of those objects

3.1 Verification tests

We show that the SAM and our tress and simulations reproduce the trends.

A first test one should make is to see if our simulation, our post processing and merger tree constructions as well as the semi-analytic method are able to reproduce the basic observables on the distribution of galaxies.

To do so we have just run GALACTICUS on out three boxes and compute the colour magnitude diagram and the I-band Tully-Fisher fisher relation.

In Figure 1 we show the I-band Tully-Fisher relation. The data point are from Pizzano et al. (2007). The lines show the median value for the relation we obtain fro the runs R1,

Model	$z_{reioniz}$	$M_{\mathrm{satel.,gas}} \rightarrow$	η	$P(\lambda)$	μ_λ	σ_λ	$\alpha_{\mathrm{disk,outflow}}$	$\epsilon_{\mathrm{disk},\star}$
R1	9.0	bulge	0.3	Bett 2007			2.0	0.01
R2	7.0	bulge	0.3	Lognormal	0.031	0.57	2.0	0.01
R3	7.0	disk	0.3	Lognormal	0.031	0.57	2.0	0.01
E1	7.0	disk	0.3	Lognormal	0.031	0.57	2.0	0.02
E2	7.0	disk	0.3	Lognormal	0.031	0.57	2.0	0.035
E3	7.0	disk	0.3	Lognormal	0.031	0.57	2.0	0.05
E4	7.0	disk	0.3	Lognormal	0.031	0.57	2.0	0.075
E5	7.0	disk	0.3	Lognormal	0.031	0.57	2.0	0.1
A1	7.0	disk	0.3	Lognormal	0.031	0.57	1.5	0.01
A2	7.0	disk	0.3	Lognormal	0.031	0.57	2.5	0.01
A3	7.0	disk	0.3	Lognormal	0.031	0.57	3.0	0.01
D1	7.0	disk	0.2	Lognormal	0.031	0.57	2.0	0.01
D2	7.0	disk	0.4	Lognormal	0.031	0.57	2.0	0.01
B1	7.0	bulge	0.2	Lognormal	0.031	0.57	2.0	0.01
B2	7.0	bulge	0.4	Lognormal	0.031	0.57	2.0	0.01

Table 2. Set of four experiments intended to model the galaxies hosted in halos of mass range of $11.0 < log_{10} M_{\mathrm{DM}} < 13.0$.

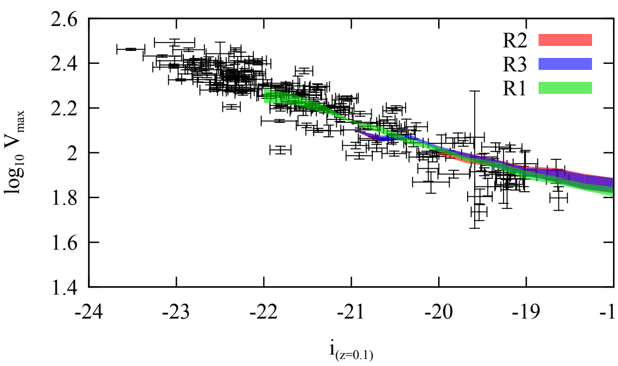

Figure 1. Tully-Fisher relation. The magnitudes where calculated without dust extinction and the parameters of the models can be seen at Table 3.2 as R1, R2 and R3. The error bars correspond to the results of **?**.

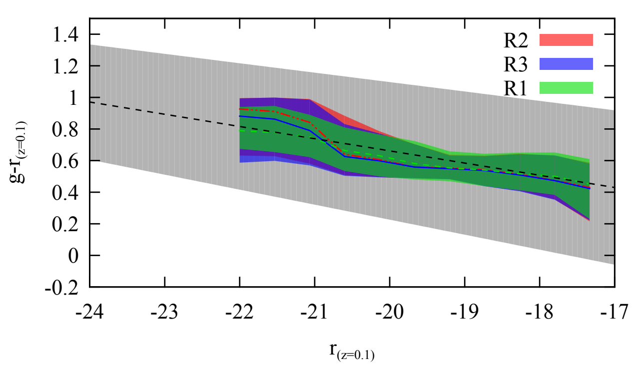

Figure 2. Colour magnitude relation. Magnitudes were calculated without extinction. This is the reference simulation presented in table 3.2 as R1, R2 and R3. The shaded region correspond to a scatter of 2σ from the work of **?**.

R2 and R3, where we have used the reference parameter values of GALACTICUS modifying only the redshift of reionization and the distribution of spin parameter. With the same simulations we have performed the comparison of the colour magnitude diagram obtained in our simulations with the data of the SDSS shown in Muñoz-Cuartas & Mueller 2012. The gray region shows the data from SDSS while the lines show the median values obtained from the model galaxies in our three boxes. As it can be seen, GALACTICUS can reproduce quite well obervables using our data, which give us confidence about the procedures implemented in the code and in the techniques we used to post analyse our N-body simulations.

3.2 Searching Local group galaxies

As it was shown in section 2.4 we look for galaxies similar to MW and Andromeda through the us of the distance measure 5. Figure 3 shows the distribution of values of d. As it can be seen, the distribution is peaked at a value of $log_{10}(d) \sim 0.4 to 0.5$ depending on the parameter set used to run the galaxy population. This clearly indicates that there is a large probability for a galaxy in our samples to be at a distance in parameter space of that value, meaning that the dominating population of galaxies (in the mass range explored in this work) is clearly not a MW or Andromeda-like galaxy. Considering that galaxies similar to LG galaxies are those with the lowest values of d, the distributions also show that being a LG galaxy is not so probable.

Indeed, in figure we show the associated estimated probability for a galaxy to be LG galaxy as a function of the model parameters for a given value of d for the smallest bins in d from figure 3. As it can be clearly seen $P(d)$ grows with d, as expected from figure, but the change depends strongly on the selection of the value of the model parameters. In particular, it can be seen that for a given value of d larger values of the $\alpha_{outflow}$ (runs A1, A2, A3, E5) parameter tend to maximise $P(d)$, that is, it is going to be more probable to have LG-like galaxies if a large value of $\alpha_{outflow}$ is used. It is also interesting to note how, for the largest d bin shown

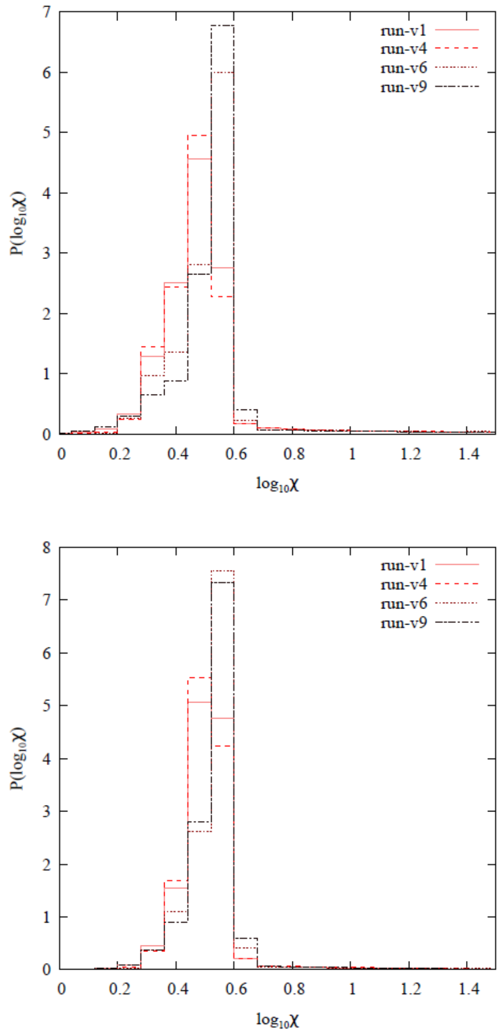

Figure 3. ...

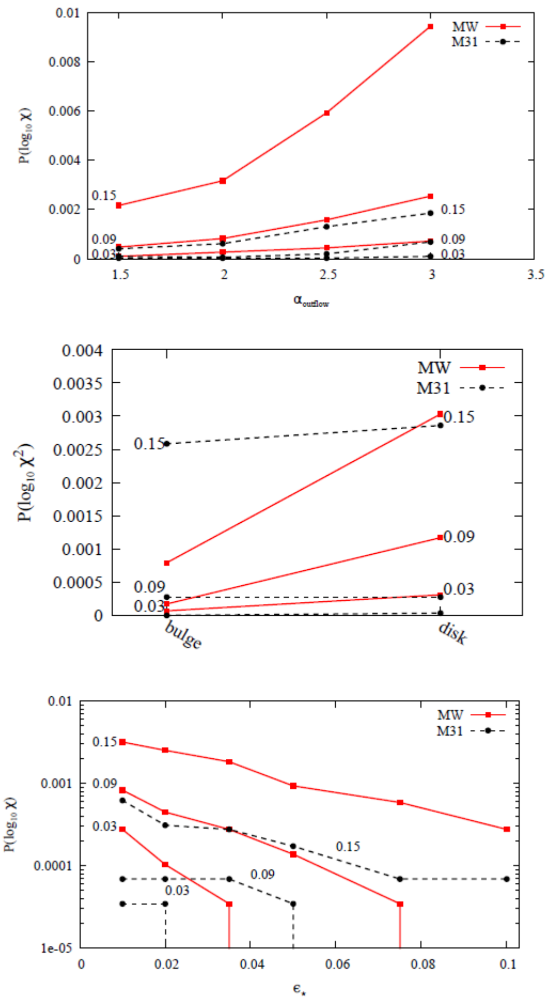

Figure 4. ...

in figure -top, the probability for a galaxy to be a MW-like is larger that the one for a galaxy to be a Andromeda-like galaxy, and the dependence on $\alpha_{outflow}$ is clearly stronger.

A similar behaviour can be seen for the same three d-bins when variating the place where the mass goes to after a merger (bulge or disk, runs D1 and B1). One can see that there is a clear dependence on the probability for a galaxy to be LG-like as a function of this parameter. In particular, choosing that after a merger mass flows to the disk instead of the spheroid maximises the probability for them to be LG-like galaxies. Again this dependence is stronger for the MW than for Andromeda.

A similar trend can be seen exploring the variation of the probability for a galaxy to be a LG-like as a function of the parameter $\epsilon_\star$ (runs E1, E2, E3, E4, E5). In this case the maximum value of $P(d)$ is obtained for the lowest values of $\epsilon_\star$, meaning that for the LG galaxies, it ts more convenient to model the star formation process with a low star formation efficiency.

In the three panels of figure can also be seen as a general trend that for a given d-bin, and a fixed value of the parameters, the probability for a galaxy to be a MW-like is larger than for them to be an Andromeda-like galaxy.

In general, according to the observational constraints, LG galaxies are favoured by model parameters given by $\alpha_{outflow} \sim 3$, $\epsilon_\star \sim 0.01$ and preferentially leaving the gas and stars in the disk after mergers.

One might ask that in general the model parameters that are well suited to fit the observations of the LG galaxies are not necessarily the ones that are required to describe the general statistical properties of the galaxy population. To explore the answer to this question wee explore now the behaviour of different galaxy properties in our halo samples and compare the results against observations.

Figure 5 shows a summary of the runs shown in table and his impact on variations on the parameters that characterise the galaxies in our definition: Stellar mass - halo mass fraction as a function of the stellar mass, gas mass to total ratio and bulge mass to total as a function of stellar mass. In general we see that in the halo mass regime explored in this work, the parameters that most affect the distributions are $\alpha_{outflow}$ and $\epsilon_\star$. Nevertheless it is intriguing that in the case of $\alpha_{outflow}$, the value that best fits the results reported in the literature (Moster et al. 2010) for the general trend in

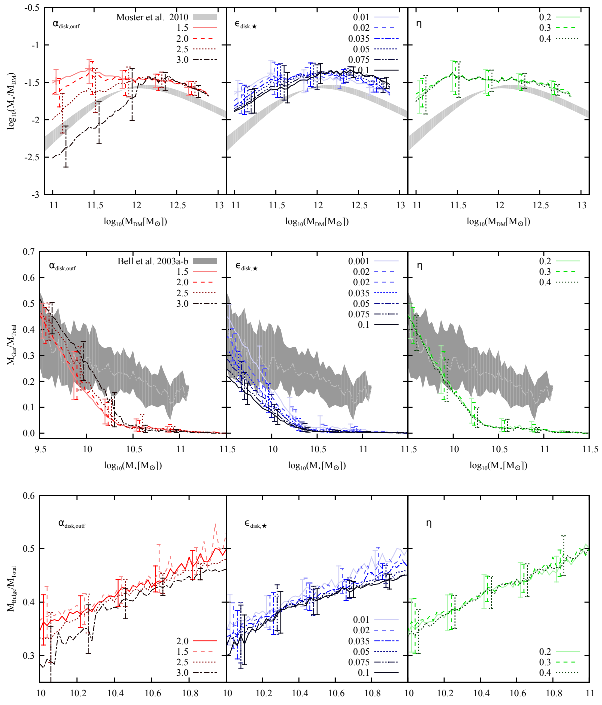

Figure 5. ...

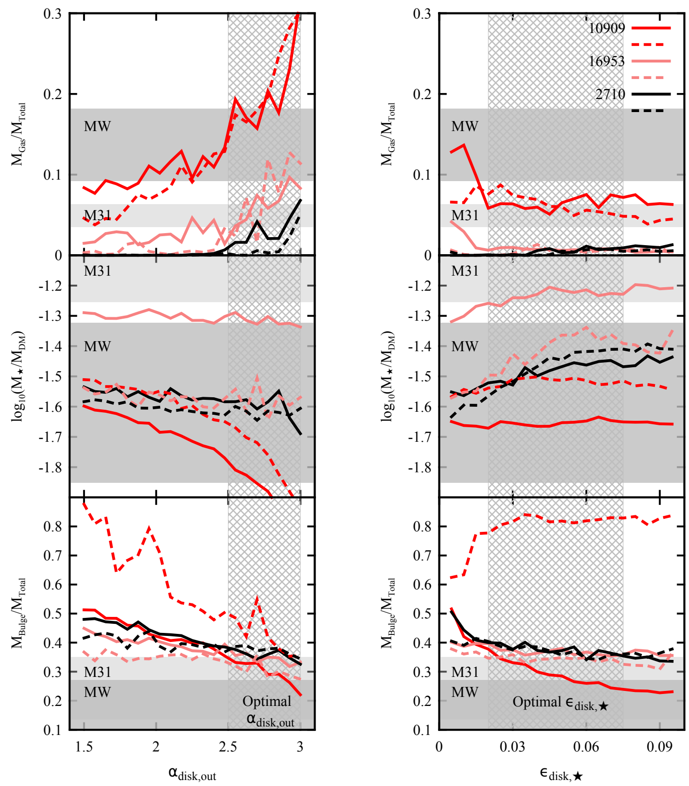

Figure 6. ...

the stellar-halo mass relation is $\alpha_{outflow} \sim 2.5-2.7$, but the value of $\alpha_{outflow} \sim 3$ clearly deviates from the expected at the low mass end. Nevertheless at the region of halo masses pf the order of $10^{12}h^{-1}\,\mathrm{M}_\odot$ it works quite well. The difference of the curves at lower halo masses should be due to ..... blah blah bla... (answer this point!).

The same stellar mass-halo mass relation is seen to be not so strongly affected -in general- by variations on $\epsilon_\star$. it can be seen that different values of $\epsilon_\star$ produce different stellar mass- halo mass relations, there are not really drastically different, conversely to what is observed with $\alpha_{outflow}$. For the specific case of the $\epsilon_\star$, again the value of $\epsilon_\star = 0.01$ produces the relations more strongly deviated at the low mass end of the relation, close to the halo mass we are interested in $10^{12}h^{-1}\,\mathrm{M}_\odot$, this value provides an acceptable match to the observations.

Finally, as it can be seen in the figure variations on the final end of the material after merger (bulge or disk) does not really affect the stellar mass-halo mass relation in a noticeable maner. We can however observe that in general the stellar mass-halo mass relation we produce (even with the reference parameter values) is in general relatively high.

Not so nice results are obtained for the gas to total mass ratio or the bulge to total mass ratio as a function of stellar mass. In general the scatter on the data is high enough to fit with almost all models on that mass regime below $10^{10.5}M_\odot$. In general we see again that $\epsilon_\star$ and $\alpha_{outflow}$ parameter are the ones that induce noticeable differences in the mean value for the relations. Large values of $\alpha_{outflow}$ produce slightly more gas rich galaxies and simultaneously low mass bulges, while low $\epsilon_\star$ values produce galaxies with slightly more mass in gas and simultaneously larger bulge mass. Variations on the final fate of the material after merger, bulge or disk, again produce no major difference on the relations for the models. Despite the differences observed in the different runs with different model parameters, all results are equally compatible with observations in the stellar mass regime below $10^{10}M_\odot$, although lower values of $\epsilon_\star$ produce mean quantities closer to observations.

After this exercise we see that in general the value parameters we obtain as those that maximise the probability of a galaxy to be a milky way are also well suited to describe statistical the observables and might represent a valid region in the volume of parameter space reproducing the properties of the galaxy distribution, implying that no fictitious assumption must be made to maximise the number of LG-like galaxies.

3.3 The LG candidates

Now we focus our attention on the candidates to MW and Andromeda galaxy in our constrained simulations and study how the properties of these galaxies change under variations of the model parameters. From the simulations we took the merger trees of these two galaxies and ran our models several times variating smoothly the values of the parameters $\epsilon_\star$ and $\alpha_{outflow}$ and check how the galaxy properties change under such variations. In order to account for the variance on the results, we have run, for each galaxy, for each value of the parameters 100 realisations of the same run and from that set we compute the median value of the galaxy properties that are presented in figure 6.

In Figure 6 we show the different galaxy properties: gas to total mass fraction, stellar to total mass fraction and bulge to total mass fraction all as a function of the values of the parameters $\epsilon_\star$ and $\alpha_{outflow}$ that we have seen are the ones that affect more strongly the properties of the distribution of galaxies. The different lines in that figure are associated to the different galaxy (MW or Andromeda) and to the different boxes, since we have three different realisations providing three pairs of candidates.

The horizontal shaded regions indicate the regions where the observations place the MW and Andromeda galaxies (CITATIONS). The width of the region is associated with the error bars of the measurements. The vertical semi-shaded areas indicate the regions in parameter space that we have found to be those that maximise the probability of a galaxy to be a LG-like galaxy. The interception of those two regions would place the region where our MW and Andromeda candidates are actually fitting our requirements.

A perfect MW or Andromeda galaxy model should be one for which the lines describing the dependence of the properties on the parameters intersects the regions of overlaping in all three properties. Nevertheless that is not the case for our simulations. According to figure 6-left none of the models are in agreement with the optimal parameter values. As it can be seen the LG-galaxies in our simulation 10909 fall in the region of optimal parameters for the gas mass fraction and.... ESTO ES CASPA.... ESTO HAY QUE REPETIRLO... QUI HAY ALGO MALO!

4 SUMMARY AND DISCUSSION

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