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High resolution simulations of the Local Group in the CLUES project

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Abstract

Constrained simulations with different resolution, cosmological models and dark matter components were carried out within the CLUES project. They allowed us to study some important properties for both the Local Group (LG) and its environment. We have studied the evolution and structure of the main galactic haloes in the Local Group and their galaxies as well as the substructures in these haloes. We paid special attention to the missing satellite problem in the standard Cold Dark Matter scenario and studied whether the possible biases between dark and luminous components could alleviate or even solve this problem.

1 Introduction

The CLUES project [1] is an international collaboration whose main propose is to construct a numerical laboratory for the scientific community to be able to compare observational data of the nearby Universe with the cosmological models prediction for the formation of our local environment.

To this end we have constructed cosmological initial conditions which include constraints coming from the observed present day mass and velocity distributions around us, that are then linearly extrapolated back in time using linear perturbation theory and by the spherical top-hat model. In this way we can simulate the formation of LG-like dark matter halos in an environment similar to the real one, with the Virgo and the Local Supercluster properly simulated at their correct position and mass. Thus, with this technique, we have at

[1] http://www.clues-project.org

our disposal an invaluable tool to investigate many aspects of dark halo and galaxy formation and to relate them with the particularities of the local environment. In the past years, the CLUES project has produced already a considerable database of numerical simulations, both dissipational and dissipationless, in different computational volumes, cosmological parameters, dark matter candidates and resolutions.

We will review some of the most recent results from the CLUES simulations. Different realizations were carried out assuming both WMAP3 [15, 7] cosmological parameter values. The WMAP3 simulations were done in two different dark matter cosmological models, namely the standard Cold Dark Matter (CDM) and in the Warm Dark Matter (WDM). We perform a detailed comparison on the substructure abundance and distribution of dark matter haloes in the local volume. Moreover, CDM with baryonic physic simulations were carried out in order to study the galaxies and the influence of the baryons in the dark matter component.

The CLUES project has been awarded with computing time in several large scale supercomputing facilities through the DEISA Extreme Computing Initiative, the Constrained Simulation project at LRZ, Munich and the MareNostrum Numerical Cosmology Project at BSC (Spain).

2 Simulations

We used the PMTree-SPH MPI code GADGET2 [16] to simulate the evolution of a cosmological box with side length of $L_{\rm box} = 64\,h^{-1}$ Mpc.

First, a constrained density field on a grid of 256^3 mesh points was obtained applying the [3] algorithm for generating constrained realizations of Gaussian random fields. As observational constraints, we have used the radial velocities of galaxies drawn from the MARK III catalogue [20], Surface Brightness Fluctuation Survey [18] and the local volume galaxy catalogue [5] as well as the positions of nearby X-ray selected clusters of galaxies [13]. The algorithm has been described in detail in [21, 8, 6]. With this algorithm to calculate the initial conditions, the resulting simulation contains the main features which characterize the Local Universe.

Within this box we identified (in a lower resolution run utilizing 1024^3 particles) the position of a model local group that closely resembles the real Local Group. This Local Group has then been re-sampled with 64 times higher mass resolution in a region of $2\,h^{-1}$Mpc about its centre giving a nominal resolution equivalent to 4096^3 particles giving a mass resolution of $m_{\rm DM} = 2.1 \times 10^5\,h^{-1}$ $M_\odot$ for the dark matter and $m_{\rm gas} = 4.42 \times 10^4\,h^{-1}$ $M_\odot$ for the gas particles (for more details see [2]).

For the gas dynamical SPH simulation, we used the model of [17]: the interstellar medium (ISM) is modelled as a two phase medium composed of hot ambient gas and cold gas clouds in pressure equilibrium. The thermodynamic properties of the gas are computed in the presence of a uniform but evolving ultra-violet cosmic background generated from QSOs and AGNs and switched on at $z = 6$. Cooling rates are calculated from a mixture of a primordial plasma composition. No metal dependent cooling is assumed, although the gas is metal enriched due to supernovae explosions. Molecular cooling below 10^4 K is also

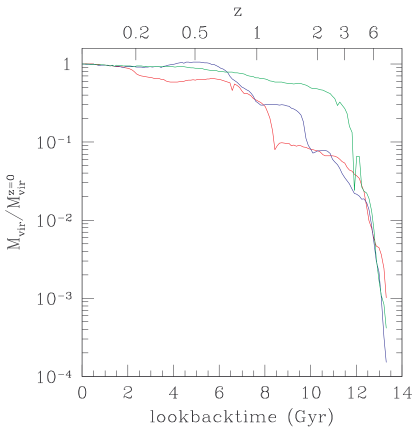

Figure 1: Mass evolution of the three main members in the WMAP3 Pure CDM simulation.

ignored. Cold gas cloud formation by thermal instability, star formation, the evaporation of gas clouds, and the heating of ambient gas by supernova driven winds are assumed to all occur simultaneously.

For the WDM simulations, we assumed two candidates for Warm Dark Matter with masses of individual particles corresponding to $M_{\mathrm{WDM}} = 3$ keV and $M_{\mathrm{WDM}} = 1$ keV. The WDM power spectrum was computed by re-scaling the CDM power spectrum using a fitting function by [19] that approximates the transfer function associated to the free streaming effect of WDM particles. The effects of thermal velocities in the smear-out of primordial density perturbations has been neglected in our computations since they are not likely to affect the results for the mass range we are reaching here.

3 Results

In this section, we summarize some of the most important results that have been obtained from the CLUES simulations.

Different properties of the Local Volume (a sphere of around 10 Mpc centred in the Local Group) was initially analysed using the full box (low resolution) simulations. From the study of the dynamics [10] and the local Hubble flow [4, 11] in this volume some important conclusions were derived: the importance of the unbounded matter in the Local Volume, the importance of the effects on the environment against the presence of a Λ term, the absence of a manifestation of the Dark Energy in the local Universe, and the reformulation of the problem of the coldness of the local Hubble flow in terms of the problem of the local density.

In our high resolution simulations, we find two (in the WMAP5 realization) or three (in the WMAP3 ones) main haloes, that we have called M31, MW and M33 from the most to the least massive ones.

In Fig.1 the mass accretion history of the three main haloes in WMAP3 Pure CDM simulation is shown. We observe that M31 and MW have suffered several major mergers in their histories. Moreover M31 present a very current one. On the other hand, M33 is more relaxed, has had a more gradual evolution, and was formed earlier than M31 and MW. Studying the formation of these objects, we have seen that M31 and MW are approaching to each other in mainly radial trajectories with no previous interaction between them.

The simulation with CDM and baryons has also been analysed to study the properties of the galaxies within the main haloes. In the three cases, we do find spiral galaxies that are compatible with the observational ones. They fit very well to the Tully-Fisher relations for spirals. However our galaxies are less massive than the real Milky Way. Nevertheless we have to keep in mind that our goal was not to reproduce exactly the Milky Way galaxy, but to obtain galaxies with similar properties generated in a similar environment than our own galaxy.

From the mass and maximum circular velocity profiles, we have seen that the contribution of the gas in the centres of the galaxies is much lower than the stars contribution. This is due to the model we used implements a high star formation and strong feedback. The contribution of excessive number of stars and the simple chemical evolution model is also responsible of obtaining higher metalicities than the observed ones.

Other properties related with angular momenta and shapes were studied. We have seen that the angular momenta of the different components (dark matter, gas and stars) are aligned within the disk region. The dark matter angular momentum within the virial radius follow the same direction than the smallest inertial axis in M31 and MW haloes. Moreover, the dark matter ellipsoid is more spherical than the gas and the stars ones. We have observed that a recent major merger affects the external part of M31: the disk is perpendicular to the direction of the major inertial axis in this halo (like [9] obtained fitting observational data to a triaxial halo model), but parallel in MW and M33.

The dark matter density profiles change with the presence of baryons. In fact, baryons create a deeper potential well that produces a higher concentration of dark matter in the centre of the haloes as compared with the results from collisionless simulations. The inner density profiles can be fitted as a power law with slopes 1.8 (1.3), 1.7 (1.2) and 1.5 (1.1) for M31, MW and M33 in the Pure CDM (and CDM with baryons) simulation respectively. We checked that the adiabatic contraction model [1] overestimates the dark matter concentration. We have also seen that the presence of the baryonic component produces more spherical dark matter haloes.

The so-called missing satellite problem, i.e. finding higher number of small subhaloes in CDM simulations than in observations, appears in our CDM simulations as well. In Fig.2, the cumulative number of substructures as a function of their maximum circular velocity are shown. One can observe that the missing satellite problem is alleviated if we only take those subhalos which have had star formation. Therefore there are plenty of dark subhaloes without galaxies within them, since UV photoionization avoids gas to cool down and form stars in these small haloes. On the contrary, in Fig.3, we see that using WDM instead of a CDM model considerably alleviates the problem as well. But this time, the reduction is too much (in the WDM 1 keV case), even without considering the biases between luminous galaxies and dark WDM subhaloes.

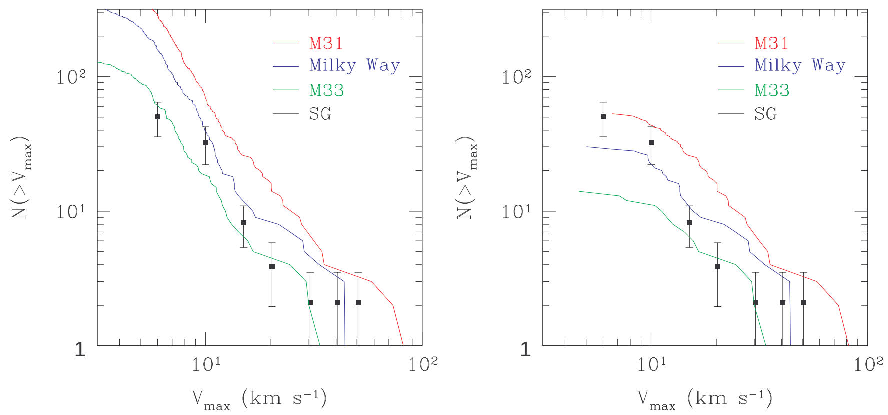

Figure 2: Comparison of the cumulative function of subhalos as a function of their maximum circular velocity. The *left* panel correspond to taking all subhalos and *right* panel shows the abundance of subhalos in which star formation has taken place. The data points correspond to the observed Milky Way satellites [14].

4 Conclusions

A numerical laboratory to study the evolution of Local Group like systems has been performed by the CLUES project. Spiral galaxies are obtained with similar observational properties to those in the Local Group. It has been shown that the two main Local Group members have had independent evolutions. Some other properties has been analysed, getting results compatible with previous observational and numerical studies.

Getting a statistical collection of high resolution Local Group like objects is necessary in order to disentangle generic and particular characteristics of Wilky Way like haloes. Moreover, combining WDM model with baryonic physic is needed to determine if the missing satellite problem is only produced by an observational bias or it comes from the particle physics model itself.

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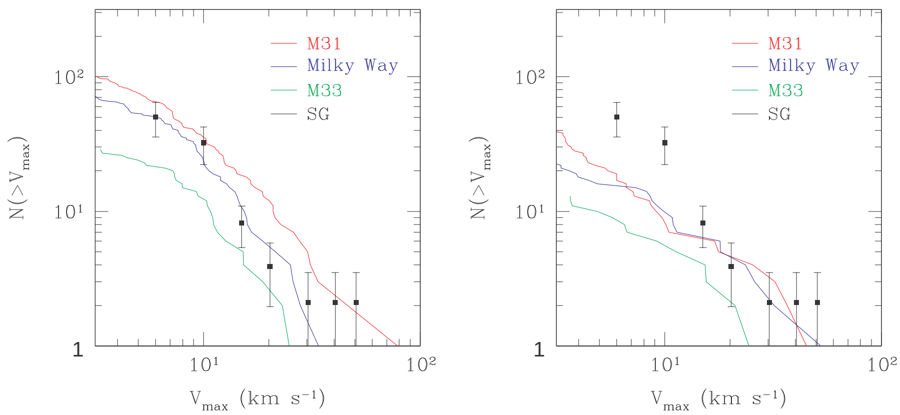

Figure 3: Same as in Fig.2 but this time we compare the abundace of subhalos in 2 different WDM simulations assuming a particle mass of 3 keV (*left*) and 1 keV (*right.*)

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