Study of Galaxy Evolution in Simulations of Formation of Large Scale Structure in the Universe

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Title: Study of Galaxy Evolution in Simulations of Formation of Large Scale Structure in the Universe.
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Classification: Theoretical work.

1 Project Description.

1.1 Problem Proposition

Commonly the large scale structure of the universe has been intensely studied in two different fashions, theoretical and observational. There are a lot of observational data that togheter with other data produced by large simulations of formation of structures in the universe can be used to constrain the characteristics of cosmological models, and delineate the process that galaxies follow to evolve.

Nowadays there are two different theoretical (numerical approximations both of them) approximations to study the process of galaxies formation and evolution:

The first one uses numerical simulations of dark matter and baryons in joint evolution and interaction and by means of numerical procedures to approximate the evolution of baryons (radiative procesess basically) and therefore galaxy evolution (Hernquist & Springel 2003, Scannapieco et.al. 2006). In this approximation *all physical process* are taken into account, gravitational and radiative procesess are computed directly on the fly in simulations in a robust but very expensive procedure.

The second one uses only dark matter simulations, and therefore, follows the evolution of dark matter structures and in proportion to the gravitational potential of structures formed, to approximate the physical properties of galaxies in these halos following semi-analytic recipes that can be used to trace the characteristics of galaxies in such simulations. This approximation relates the properties of galaxies with his "parent" halos in a way that galaxy properties are computed directly from halo properties (Hatton et.al. 2003, Cole et.al. 1994, Cole et.al. 2000, Kang et.al., 2005). In this case the simulation proceeds only to compute the dynamical evolution of dark matter, and baryons are *put in to* halos in the analysis procedure.

The question to be solved in this project is how to follow the evolution of galaxies (dark matter and baryons) in N-body simulations through a set of simple questions:

- How is the assembly of dark matter structures?.
- Whath is the better way to model the cooling of baryons in these dark matter halos?
- How can be modelled the star formation process in galaxies?
- Finally, obtain a good agreement of observations with our analysis of the N-body simulations.

1.2 Objectives

1.2.1 General Objective

The principal objective of this work is to study the evolution of galaxies in ΛCDM cosmologies through N-body simulations matching results with observations.

1.2.2 Specific Objectives

- To build a computational toolbox to analyse cosmological N-body simulations and extract from them results about galaxy evolution.
- To study galaxy evolution using N-body simulations through semi-analytical recipes and cosmological gas dynamics simulations.
- To study the properties of star formation process in galaxies in the early Universe.

2 Theoretical Background

Evolution of galaxies in the universe is a complex process bound to evolution of dark mater structures, this process only can be followed in a clear analytic way in the early times of the life of the universe using linear theory, nevertheless, for later cosmic times (or smaller redshifts) non-linear gravitational process dominate the growth of structures in the universe (Longair 1998), such a process must be followed using computational techniques that allow us to sample the dark matter distribution of the universe, and with this, to follow the statistical properties of the evolving structures.

Recent cosmological models, describe the evolution of the universe parameterising its matter-energy content. Matter-energy content dominates the geometrical properties of the universe, and therefore its gravitational and dynamical evolution in a way described by general relativity. Recent models describe the universe like an universe that in early times is radiation dominated, while in present cosmic times is dominated by a strange energy density filling the universe like a whole, the dark energy. In current parameterisations, the matter-energy content of the universe is quantified using the omega parameter $\Omega = \rho/\rho_c$ where $\rho_c = 3H_0^2/8\pi G$. $\Omega_m = 0.24$ is the relative mass content, when the matter content is distributed in two distinct components, the dark matter $\Omega_{dm} = 0.2$ and baryons $\Omega_b = 0.04$. The remainder cosmological parameters are the dark energy density $\Omega_\Lambda = 0.76$, the total density of the universe $\Omega_0 = 1$, the Hubble parameter $h = 0.73$, the spectral index of the initial power spectrum of perturbations $n = 1$ and the variance in counts of galaxies $\sigma_8 = 0.77$ (Spergel et.al 2006).

The most recent studies, shows that apparently the evolution of structures in the universe is hierarchical, i.e, structures at small scales form first, and through gravitational interaction process this proto-halos undergo mergers to form more massive structures. Such a hierarchical process is recognised like the ΛCDM cosmology, in that the dark matter distribution is cold, that is, massive particles with low velocity dispersion.

In the past decade simulations have shown the properties of dark matter substructures, and also, implementation of procedures to track the evolution of baryons forming galaxies in such simulations, exhibit many correlations with observational data. We will describe in some detail some basics characteristics of cosmological simulations and analysis of galaxy formation and properties.

Initial conditions.

Basically initial conditions for cosmological N-body simulations must solve a small number of constrains, in an enormous difference with initial conditions to simulate, for example, galaxies. Initial conditions to simulate structure formations must satisfy the characteristics of distribution of galaxies in some volume of the universe, such volume is filled with mass in a proportion as indicated by the matter-energy content (accordingly to the accepted cosmological model that is being implemented). In such case, dark matter must be distributed in a way that the correlation function must correspond to the correlation function associated to the redshif at which we will begin the simulation. Correlation function $\xi(r)$ is defined as the probability to find a galaxy at distance r from a galaxy selected at random over the sample, it has been shown that this function can be fitted with a power-law (Longar 1998)

$$\xi(r) = \left(\frac{r}{r_0}\right)^{\gamma} \tag{1}$$

on physical scales from about $100h^{-1}$ kpc to $10h^{-1}$ Mpc where the scale $r_0 = 5h^{-1}$ Mpc and $\gamma = 1.8$. Because the correlation function changes with time, sometimes is better to describe the evolution or growth of structures in the universe as a function of density fluctuations that mathematically can be modelled as density waves, and in such a way that can be also described in a reciprocal space associated to the wave number. In this space, the power spectrum is directly related with principal modes associated with density distribution, such that if we compute the power spectrum we can relate this to the correlation function through

$$P(k) = 4\pi \int \xi(r) \frac{\sin(kr)}{kr} r^2 dr \tag{2}$$

Once we know this, we can proceed applying a recipe to build initial conditions using the Zeldovich approximation (Padmanabhan 2002, Klipin 2000) in a cubic box of side L. Zeldovich approximation is one that allow us to build a commoving density field x from an homogeneous density field q using the transfer function and the growth rate at a given cosmic time a through the relations

$$x = q - \alpha \sum_k D_k(t) S_k(q) \qquad\qquad p = -\alpha a^2 \sum_k D_k(t) \left(\frac{\dot{D}_k(t)}{D_k(t)}\right) S_k(q) \tag{3}$$

where x is the commoving coordinate, q is the initial position associated to the homogeneous density field, p is the momentum of particles, $D(t)$ is the linear growth function of structures, given by

$$D(a) = \frac{5}{2}\Omega_m \left[\Omega_m^{4/7} - \Omega_\Lambda + \left(1 + \frac{\Omega_m}{2}\right)\left(1 + \frac{\Omega_\Lambda}{70}\right)\right]^{-1} \tag{4}$$

and his derivative

$$\dot{D}(a) = \frac{\Omega_m H_0^2}{2\dot{a}a_0}\left[5 - \frac{3D(a)}{a} - \frac{2\Omega_k D(a)}{\Omega_m}\right] \tag{5}$$

where $S_k(q)$ is a displacement vector related with the velocity potential that can be computed as

$$S_k(q) = \sum_{k_{x,y,z}=kmin}^{-kmax} ikC_k \exp\left(i\vec{k}\cdot\vec{q}\right) \tag{6}$$

with $C_k = a_k - ib_k$, and a_k and b_k constants sampled from normal Gaussians

$$a_k = \sqrt{P(k)}\frac{Gauss(0,1)}{k^2} \qquad\qquad b_k = \sqrt{P(k)}\frac{Gauss(0,1)}{k^2} \tag{7}$$

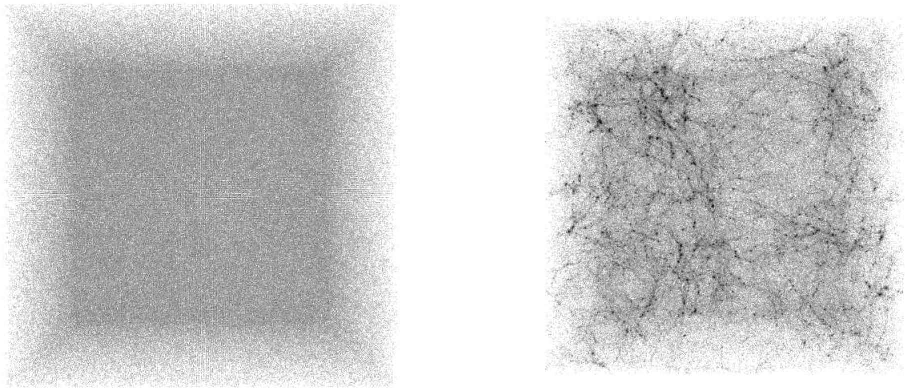

Figure 1: To the left, an image of a realisation of initial conditions for 10^6 dark matter particles in a cosmological simulation in a cube of side $100h$Mpc at z=26.95. To the right the evolution of the same volume evolved up to z=0.

With this information, to build initial conditions using the Zeldovich approximation would follow the next series of steps:

1. Fix the size of the box L and the number of particles in simulation N.
2. Once we have fixed L and N, we can build a uniform grid in coordinated space, such that in each grid node we will locate a particle with coordinates $q_{i,j,k} = \Delta q(i, j, k)$, where $i = j = k = 0, \pm 1, \pm 2, ...$ and $\Delta q = L/N^{1/3}$
3. Soon, we build the reciprocal network, using $\Delta k = 2\pi/L$, such that $k_{i,j,k} = \Delta k(i, j, k)$
4. Next, using an approximation for the power spectrum we can compute a_k and b_k, and with this and using the reciprocal network we can compute $S(q)$ for each q using Fourier techniques.
5. Finally using $S_k(q)$ and q_i we can compute x and p.

Following this procedure we can approximate the conditions of matter distribution for a given cosmic time, like shown in figure 1

Simulations.

Once there are appropriate initial conditions, the equations of motion of the system can be integrated to follow its evolution. In this case, the problem is to solve the gravitational N-body problem involved, in a way that computing forces between particles becomes an efficient work. It has been shown that Particle Mesh methods (thereafter PM, which are methods where the force field is interpolated along a regular grid containing the density field) are appropriate to follow the evolution of this kind of problems because his simplicity and efficiency (Gross 1997, Springel 2005). Nevertheless, sometimes these methods are

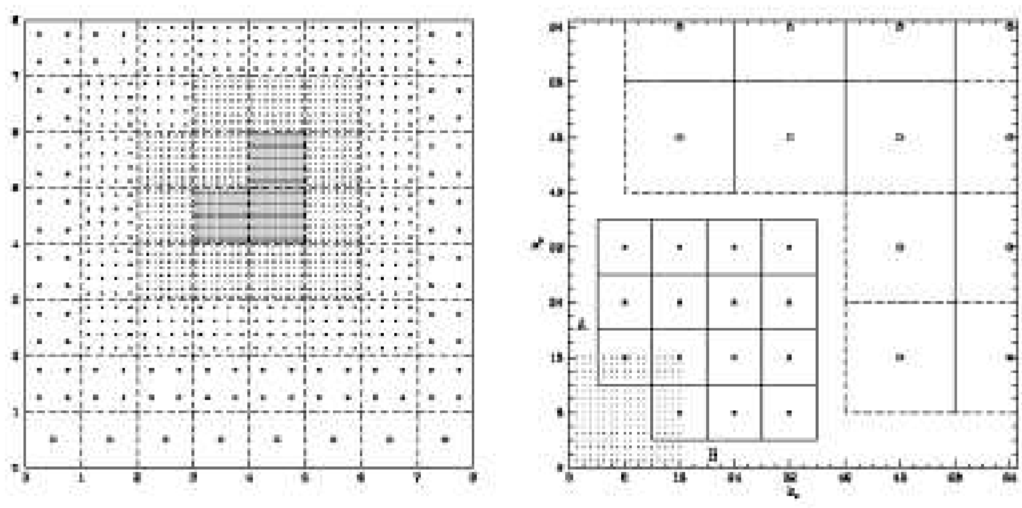

Figure 2: In this figure is shown schematically the behaviour of the method used to approximate the force field on particles in simulation. Regions with high density of grids are regions near a given particles in that forces are computed with high resolution, increasing the size of cells decrease the resolution in computing force field

refined by a rescaling procedure that allows to evaluate fine local forces using Particle-Particle techniques or Tree methods, this kind of refinements allow us to compute the force on a particle in two different steps

$$F_{total} = F_{near} + F_{far} \tag{8}$$

where F_{far} is a deep force field exerted by the overall density field and is computed by the PM algorithm, while F_{near} is a local force exerted by the nearest particles and commonly is computed with Particle-Particle or Tree methods, with which we can increase the local resolution in regions of high density and low symmetry. Figure 2 shows schematically the operation of this procedure.

Simulations analysis
Once we have a record of positions, velocities and other dynamical properties for all the particles in the simulation (recently, simulations incorporate dark matter and baryons together (Hernquist& Springel 2005)) one can begin the analysis of the characteristics of structures formed in simulations. There are two steps to do it:

Dark matter halos.
One identifies the bound structures in simulations (commonly referred as halos) and once they are identified his dynamical properties are computed: Virial mass, radius, inertia tensor, virial temperature, angular momentum, rotation parameters, etc. This must be

done many times in simulations (really it depends on the available number of snapshots), and with this a merger history tree can be built (Hatton et.al. 2003, Cole et.al. 2000, Croton et.al. 2006, Bett et.al. 2006). The merger tree history is a structure used to track the evolution of each halo, allowing us to determine where the halo is, what is the origin of his constituent particles, precedent parent halos, etc.

In the simplest situation, bound structures can be identified through the friend of friend method (Davis et.al. 1985). This consist on searching, for each particle, other particles inside a sphere of radius b (the linking length) and for those particles find the neighbor ones, and so on. Under this procedure groups of particles are identified when they are bound with a density contrast

$$\delta_{thrers} \sim \frac{3}{2\pi b^3} \tag{9}$$

setting $b = 0.2$ (in terms of the mean inter-particle distance) one obtains a density contrast of nearly 200 times the critical density.

Once structures are identified one verifies if they are bound and stable, and compute then its virial mass M_{200} (assumed as the mass for the group of particles), virial radius R_{200}, associated circular velocity V_{200}^2 (Hatton 2003, Cole 2000 et al.)

$$V_{200}^2 = G\frac{M_{200}}{R_{200}} \tag{10}$$

and the halo spin parameter λ defined by

$$\lambda = \frac{J|E|^{1/2}}{GM^{5/2}} \tag{11}$$

and other structural and useful halo properties.

Baryon cooling and galaxy formation.
A complete simulation process must study the joint evolution of baryonic and dark matter including non-gravitational baryonic procesess. Baryon simulations incorporate problems associated with magnetic fields, heating via shock waves, star formation affected by supernova and gravitational feedback, and by radiative processes that affect the cooling of the intergalactic medium (Scannapieco et.al. 2005, Robertson et.al. 2006). Incorporating directly this kind of process in cosmological simulations will involve a higher resolution which is more expensive in terms of use of computer resources (we will need more and more memory space). Furthermore, the incorporation of the baryonic physics will increase the requirement of computing effort by the difficulty of this kind of physical process.

To overcome this inconvenient the method commonly used is to implement semi-analytic recipes to study the properties of galaxies that must be formed in simulations in connection with the properties of dark matter halos detected in cosmological simulations that take into account only dark matter evolution. In this semi-analytical approach, well known properties of galaxies (dynamical and observational properties) are related to computable properties of the halos previously identified in the simulation. The semi-analytic procedures have been broadly implemented, and although they are far, at least in the present, to give an exact description of the physics associated with the evolution of baryons, are one of the most powerfull techniques and match very well with observational results.

In the spirit of showing in more detail how semi-analytic recipes are implemented in analyzing simulations, we will show the simplest way in that one can model some physical properties of baryons in previously identified halos. Once halos have been identified, then one defines the fraction of baryonic matter associated to this halo (Hatton et.al. 2003, Crain et.al. 2006), the simplest way to do it, is to say that the content of baryonic matter in the halo is

$$M_{hot} = M_{200}\frac{\Omega_b}{\Omega_m} \tag{12}$$

with this simple recipe we can compute the available gas in the halo to form stars, nevertheless this gas is hot, and this will begin its cooling once it is on the halo. The cooling time scale is commonly computed as the ratio between the specific thermal energy content of the gas and the cooling rate per unit volume

$$t_c(r) = \frac{3}{2}\frac{\mu m_p k T(r)}{\rho_{hot}(r)\Lambda(T)} \tag{13}$$

where μm_p is the molecular mass of the gas, ρ_{hot} is the gas density and $\Lambda(T)$ is the cooling function that depends on the chemical composition of the medium and its temperature. If we suppose that the gas distribution is more or less isothermal (a well known fact from observations for clusters) we can compute the gas temperature as

$$T = \frac{\mu m_p}{2k}V_c^2 \tag{14}$$

and in the same order of ideas, from the observational properties of clusters, that gas distribution seems to follow an isothermal density profile

$$\rho_{hot}(r) = \rho_0\left(1+\frac{r^2}{r_c^2}\right)^{3\beta/2} \tag{15}$$

with $\beta = 2/3$ such that with this information the cooling time could be computed. With this cooling time, the gas fraction cooled in a time fraction Δt could be computed as

$$M_{cool} = \int_0^{r_{max}} \rho_{hot}(r)d^3r \tag{16}$$

where r_{max} is the minimum between the cooling radius, the free fall radius and the virial radius.

Once the cold gas has been determined this is allowed to form stars. The star formation rate can be modelled in a simplified form like

$$\Psi_* = \frac{M_{cold}}{\beta t_{dyn}} \tag{17}$$

where Ψ_* is the star formaion rate, β^{-1} is the star formation efficiency and t_{dyn} is the dynamical time scale of the galaxy, that can be computed as the time that take a particle in the half mass radius to move up to the opposite side of the galaxy using the circular velocity (for disks), or the radial velocity dispersion for spheroids.

Following this kind of procedures that relate galaxy properties with dark matter halo and observational properties, the basic characterstics of all galaxies identified in simulations can be reproduced, including chemical and spectro-photometric properties and evolution.

Although in recent years, cosmological simulations incorporating gas dynamics and some baryonic processes (cooling, star formation, supernova and black hole feedback, etc.) has been incorporated, his description is even approximated, and semi-analytic procedures play a very important role in studying the statistical properties of galaxies in cosmological simulations.

3 Antecedents

At the present and in the past year, the activities in the FACOM group concerning the problem of hierarchical galaxy formation has been intense. In the past year, the student attended the XIII Escola Avanzada de Astrofísica, in Foz do Iguazu, Brasil, school dedicated to the study of observations and simulations of large scale structures, and where he acquired a noticeable quantity of information about novel simulation techniques and observational results, and also developing interesting contacts with workers in the problem.

Also in the past year, with the economical support of the Institute for Computational Cosmology of the Durham University (contact developed in the Brazilian school) the author attended the International School of Galactic and Cosmological N-body Simulations, at Puebla, Mexico. An interesting school in that we had the opportunity to *put hands on* the problem and work directly on procedures of simulation and analysis of LSS.

In the last semester, the activities of the master program allowed us to attend a course on the problem of galaxy formation in cosmological contexts, with this opportunity we acquired an appreciable knowledge about formal theories of galaxy formation, as well as experience in the numerical treatment of the problem. Finally in January of the present year, we have been working with another important contact in the Lyon Observatory in the conclusion of some methodological facts and in the adequate orientation of our final work.

Finally, we should comment that the development of the software we want to use to analyze the simulations is under work. At the moment we have a plan about the design of the software (the flow chart and required features). There are implementations of routines which allow us to identify the halos in simulations, and to compute its properties, and we are beginning to study the best way to implement the baryon cooling and star formation. In the same sense, we have results of our first cosmological (with up to 252^3 particles in a cube of side 100Mpc) simulations to test the code.

Whit this, we show the development of the work in the last year, showing that our background allows us to face the compromises of the project.

4 Scientific Impact

In astrophysics and cosmology there are a series of problems still to be solved, between them, the problems associated with formation of galaxies and their early evolution are among the most important and exciting topics of present research.

In cosmological scales, all properties of galaxies and stars we observe today are the result of millions and millions of years of evolution of the universe, but the initial condition in that the universe born are the final responsible for this characteristics. To study the evolution of galaxies and his properties can give results that guide us to understand the fundamental mechanism driving the early evolution of the universe, that in deep sense, can carry us to understand the fundamental mechanism driving the universe like a whole.

Understanding galaxy evolution we can measure mass ratios (the mass-energy content) in the universe, and know about the fundamental components and interactions that drive his evolution.

Another important problem of interest in astrophysics is the problem associated with massive star formation. In astrophysics, the description of birth and evolution of a single star, is a procedure that more or less can be followed theoretically and observationally, such that we can describe with some confidence the born and evolution of individual stars. Nevertheless when one want to describe the formation and evolution of stars in a collective way, there are a series of problems that must be taken into account to describe the process, giving rise to a big problem, the problem of star formation in galaxies. The star formation process affect notably the chemical and spectro-photometric evolution of galaxies (which is finally we can measure from observations), becoming the study of this process a first line problem in astrophysics. To approximate the star formation process in a way as proposed in this work can give results of remarkable importance in understanding galactic star formation.

5 Expected Results

Whit the development of our research we hope to obtain the following results:

- A code to analyse cosmological N-body simulations.
- A MSc. thesis.
- Submit almost an article in a national or international journal or the participation (with an oral presentation or a poster) in an international event.

6 Summary

The main procedures we will follow in order to fulfill the objectives of the work are the following:

- Run N-body simulations with different resolution to allow the development of the analysis software
- To use cosmological N-body simulations using new results of WMAP for the cosmological parameters to study the star formation process in galaxies at high redshift.
- Build a software that allows the analysis of cosmological N-body simulations through semi-analytic recipes.
- Study the influence of the parameters on the results of modeling the process of star formation.

7 Cronogram of Activities

The next table shows the cronogram of activities

Activities	Febr.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Halo detection and properties	X	X									
Halo Merger Trees		X									
Bibliographic revision	X	X	X	X	X						
Establishment of semi-analytic recipes			X								
Implementation of semi-analytic recipes			X	X							
Seminars					X	X					
Code tests and debugging	X	X	X	X	X	X					
Release of the β version of the code						X					
Realisation of N-body simulations			X	X	X	X	X	X			
First results: Galaxy statistics							X				
Parametric study (star formation)							X	X	X		
Text Reports						X	X				
Article							X	X	X	X	X
Manuscript					X	X	X	X	X	X	X

Table 1: Cronogram of Activities

References

[1] Baugh C.M.; Lacey C.G.; Frenk C.S.; Granato G.L.; Silva L.; Bressan A.; Benson A.J.; Cole S., 2006, astro-ph/0603679

[2] Bett P.; Eke V.; Frenk C.S.; Jenkins A.; Helly J.; Navarro J., 2006, astrp-ph/0608607

[3] Bower R.G.; Benson A.J.; Malbon R.; Helly J.C.; Frenk C.S.; Baugh C.M.; Cole S.; Lacey C.G., 2006, MNRAS, 370, 645.

[4] Cole S., Aragón-Salamanca A., Frenk C.S., Navarro J.F., Zepf E.S., 1994, MNRAS, 271, 781.

[5] Cole S.; Lacey C.G.; Baugh C.M.; Frenk C.S., 2000, MNRAS, 319, 168.

[6] Crain R.A., Eke V.R., Frenk C.S., Jenkins A., McCarthy I.G., Navarro J.F., Pearce F.R., 2006, astro-ph/0610602.

[7] Croton D., Springel V., White S.D.M., De Lucia G., Frenk C.S., Gao L., Jenkins A., Kauffmann G. Navarro J.F., Yoshida N., 2006, MNRAS, 366, 499.

[8] Davis M.; Efstathiou G.; Frenk C.S.; White S.D.M., 1985, ApJ, 292, 371.

[9] Gross A.K., 1997, PhD Thesis.

[10] Hatton S., Devriendt J.E., Ninin S., Bouchet F., Guilderdoni B., Vilbert D., 2003, MNRAS, 343, 75.

[11] Hernquist L., Springel V., 2003, MNRAS, 341, 1253.

[12] Kang X.; Jing Y.P.; Mo H.J.; Borner G., 2005, ApJ, 631,21.

[13] Klypin A., 2000, astro-ph/0005502.

[14] Longair M.S., Galaxy Formation, 1998, Astronomy and Astrophysics Library.

[15] Masjedi M.; Hogg D.W.; Cool R.J.; Eisenstein D.J.; Blanton M.R.; Zehavi I.; Berlind A.A.; Bell E.F.; Schneider D.P.; Warren M.S.; Brinkmann J., 2006, ApJ, 644, 54.

[16] Padmanabhan T., Theoretical Astrophysics Vol 3., 2002, Cambridge University Press.

[17] Robertson B.; Bullock J.S.; Cox T.J.; Di Matteo T.; Hernquist L.; Springel V.; Yoshida N., 2006, ApJ, 645, 986.

[18] Scannapieco C.; Tissera P.B.; White S.D.M.; Springel V. MNRAS, 2006, 371, 1125.

[19] Schneider R., Salvaterra R., Ferrara A., Ciardi B., 2006, MNRAS, 369, 825.

[20] Sirko E., 2005, ApJ, 634, 728.

[21] Somerville R.S., Kolatt T.S., 1999, MNRAS, 305, 1.

[22] Spergel D.N.; Bean R.; Dore O.; Nolta M.R.; Bennett C.L.; Hinshaw G.; Jarosik N.; Komatsu E.; Page L.; Peiris H.V.; Verde L.; Barnes C.; Halpern M.; Hill R.S.; Kogut A.; Limon M.; Meyer S.S.; Odegard N.; Tucker G.S.; Weiland J.L.; Wollack E.; Wright E.L., astrp-ph/0603449

[23] Springel V., 2005, MNRAS, 364, 1105.

[24] Springel V., White S.D.M., Tormen G., Kauffmann G., 2001, MNRAS, 328, 726.

[25] Springel V., Hernquist L., 2003, MNRAS, 339, 312.

[26] Springel V., White S.D.M.; Jenkins A.; Frenk C.S.; Yoshida N.; Gao L.; Navarro J.; Thacker R.; Croton D.; Helly J.; Peacock J.A.; Cole S.; Thomas P.; Couchman H.; Evrard A.; Colberg J.; Pearce F., 2005, Nature, 435, 629.

[27] Springel V.; Frenk C.S.; White S.D.M., 2006, Nature, 440, 1137.

[28] White M., Hernquist L., Springel V., 2001, 550, L132.

[29] Yoshida N., Springel V., White S.D.M., Tormen G., 2000, 544, L87.