Cosmological hydrodynamical simulations in various dark energy scenarios

Klaus Dolag[1]

[1] MPI for Astrophysics, P.O. Box 1317, D-85741 Garching, Germany,

ABSTRACT

We propose to perform a set of cosmological hydrodynamical high-resolution simulations to study the growth of cosmic structures in various dark energy scenarios. We want to quantify the effects of different modelings of dark energy on the appearance of the large scale structure and galaxy clusters, paying attention to their observational properties (e.g. the X-ray scaling relations and their redshift evolution, the internal structure of clusters, etc.).

Main collaborators

- Prof. Baccigalupi (SISSA, Trieste)
- Prof. Moscardini (Università di Bologna)
- Prof. Bartelmann (ITA, Heidelberg)

Additional collaborators

- Dr. Perotta (SISSA, Trieste)
- Dr. Meneghetti (INAF, Bologna)
- Dr. Pettorino (ITA, Heidelberg)

Introduction

Clusters of galaxies are ideal cosmological probes. To first approximation, they can be considered as closed systems, thus their content reflects the overall cosmic composition. In particular their number counts, as well as their internal structure, their redshift evolution and their appearance permit to probe cosmology. The increased size, range and completeness of observational data based on the latest generation of astronomical instruments recently opened the so-called period of precision cosmology, meaning that the basic parameters describing our universe can be in principle determined with a precision of ten percent or better. Future instruments (like the forthcoming PLANCK satellite and the planned e-ROSITA satellite) will help to measure them to even higher precision. Additionally, huge observational efforts will be spent to investigate the nature of dark energy, thanks to a large number of future experiments (like the CFH Legacy survey, DES, SNAP, DarkCam, DUNE, SPACE). Having its origin in the fundamental nature of gravity or in the super-symmetric extension of the standard model, the aim of such projects is not only to measure the amount of dark energy present today, but also its redshift evolution, which is needed to trace back its fundamental origin. However, such a precision in cosmology can be reached only through the comparison with the results of detailed numerical modelling: a case in point is the number density of galaxy clusters, which represents one of the best tools to discriminate between various cosmological scenarios. Therefore cosmological simulations play a key role in our understanding of the universe. However, clusters as their pinpoints turned out to be extremely complex objects, which have to be understood in detail in order to interpret the forthcoming observations. Therefore it is absolutely necessary to improve cosmological simulations to obtain precise and comprehensive predictions, specially in the field of large scale structure formation. Thanks to the richness and variety of available observational data, galaxy clusters represent an ideal test to investigate the ability of numerical simulations to make precise predictions.

The quest for dark energy

One of the most recent and heavily discussed topics in astrophysics is the observational evidence that today the Universe is dominated by a dark energy component. This also triggered studies aimed at replacing the 'ad hoc'-introduced cosmological constant by a better motivated concept stemming from modern particle physics, like the super-symmetric extension of the standard model. In this framework the cosmological constant can be replaced by the energy density originating from an extra field, and the equation of state of this field can become a function of time. Using the simplification of no coupling between dark energy and matter, this model can be investigated by modifying the background cosmology, e.g. by changing the Friedman equations. It is well known that these models can have measurable effects on the process of structure formation: for this reason there are several new experiments underway (like DUNE, DarkCam, SNAP, SPACE) which are specially designed to take advantage of this property to shed light on the nature of dark energy.

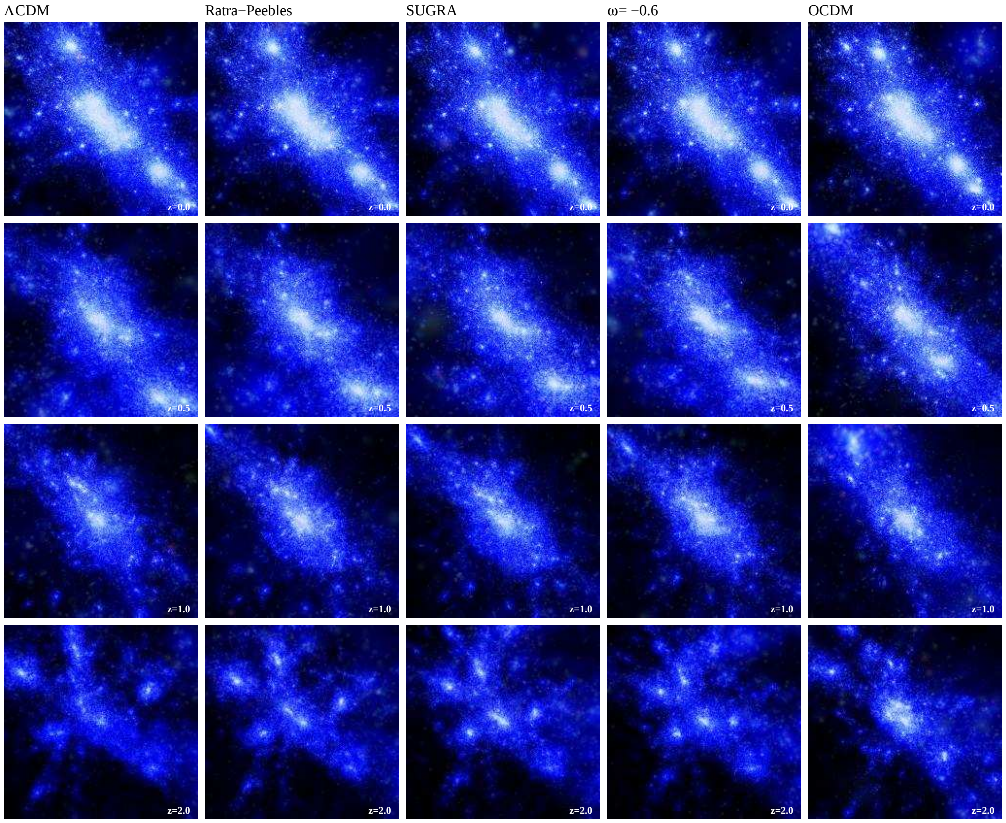

Fig. 1.— One single cluster is shown at different redshifts ($z = 0$, $z = 0.5$, $z = 1$ and $z = 2$ from top to bottom) in different cosmologies (labelled on the top of each column). The panels illustrate that in different cosmological models the clusters, being originated from the same initial conditions, appear morphologically similar, but subtle differences are visible when analyzed in detail.

Previous Work

So far, we have used the massively parallel Tree+SPH GADGET code, which includes a fully adaptive and local time-stepping[1] (Springel et al. 2001, Springel 2005) to simulate galaxy clusters evolving in various dark energy models. Within the co-moving coordinate scheme of GADGET, the only place where the dark energy has to be taken care of is in the calculation of the Hubble function, or some combination of the Hubble function with the scale factor a. This is used when a conversion to physical quantities is needed, like converting the internal time variable $\log a$ to physical time t, or in the equation of motion in a cosmological context. Thus, for running cosmological simulations including dark-energy, one can rewrite the usual Hubble function

$$H(a) = H_0 \left[\frac{\Omega_0}{a^3} + \frac{1 - \Omega_0 - \Omega_\Lambda}{a^2} + \Omega_\Lambda \right]^{1/2} , \qquad (1)$$

holding for a flat cosmology with cosmological constant as

$$\begin{aligned} H(a) &= H_0 \left[\frac{\Omega_0}{a^3} + \frac{1 - \Omega_0 - \Omega_Q}{a^2} \right. \\ &+ \left. \Omega_Q \exp\left(-3 \int_a^1 \frac{1 + w(a')}{a'} \mathrm{d}a' \right) \right] . \qquad (2) \end{aligned}$$

[1] http://www.MPA-Garching.MPG.DE/gadget/

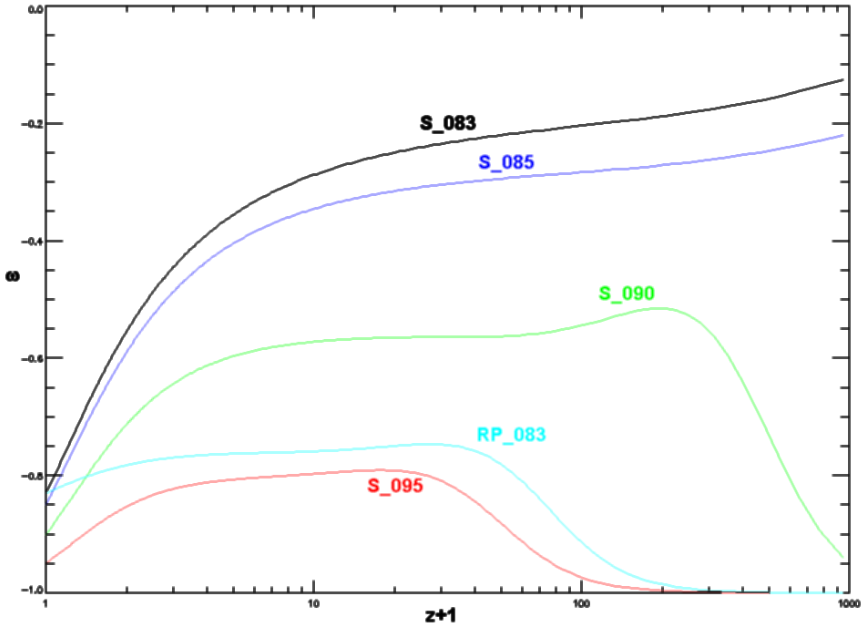

Fig. 2.— Equation of state for the different RP and SUGRA quintessence models studied in this work.

Inside the new integration scheme of P-GADGET, this is also done within the calculation of the drift and kick factors. By applying these techniques to pure dark matter simulations, we investigated the appearence of galaxy clusters (see figure 1) in various dark energy models assuming a different evolution for the equation of state parameter $w(a)$ (see figure 2). So far, we have studied and compared results obtained for the following cosmological models: an open Cold Dark Matter (OCDM) and four flat dark-energy cosmogonies: a model with cosmological constant (ΛCDM), a dark-energy model with constant equation of state (DECDM), and two quintessence models, one with inverse power-law Ratra-Peebles potential (RP, see Peebles & Ratra 2002, and references therein) and one with SUGRA potential (SUGRA, see Brax & Martin 2000, and references therein).

New simulations to be performed

In previous work (Dolag et al. 2004) we investigated the effects of these different dark energy models on the internal structure of galaxy clusters. These predictions can be used in the comparison with the internal structure of galaxy clusters derived from most recent X-ray and lensing observations (see e.g. Pratt & Arnaud 2005, Buote et al. 2006, Comerford et al. 2006), demonstrating the enormous potential of (and the high interest of the scientific community in) cosmological simulations for a robust interpretation of observational data. Within this proposal we now want to extend the previous work in various respects, in order to allow a better and more detailed comparison with observations.

First of all, we want to extend the simulations including the baryonic component with its associated physics. This will allow us to better compare the simulation results with various observables, most of them coming from X-ray data of galaxy clusters. The available version of GADGET2 includes an entropy-conserving formulation of SPH (Springel & Hernquist 2002)

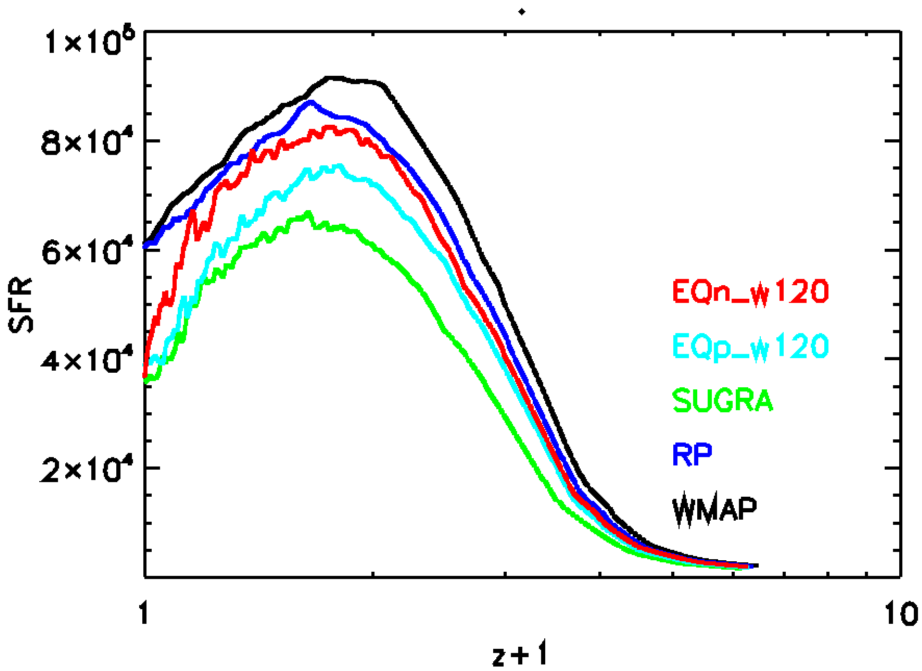

Fig. 3.— Comparison of the starformation rate found in the test simulations: the results demonstrate the differences in the non linear evolution between the various dark energy models.

and follows in a self-consistent way different processes relevant for cluster formation: radiative cooling, heating by an UV background, and a treatment of star formation and energy feedback from galactic winds powered by supernova explosions. An example of the different starformation rate expected in various dark-energy cosmologies is shown in figure 3, obtained from our test simulations.

Second, we want to study the effect of minimally coupled dark energy and extended quintessence models on the large scale structure formation. These two kinds of models either couple dark energy and dark matter (CQ) within the usual General Relativity framework (Einstein frame), or explore the possibility that dark energy might derive from a non-minimal interaction (EQ) to gravity via an explicit coupling to the Ricci scalar (Jordan frame). In particular we are investigating the resulting effects of varying the dark matter mass, varying the gravitational constant and having different (gravitational) interactions of dark matter / dark matter and dark matter / baryons in a self-consistent way. The possibility of considering more general behaviors of the expansion rate and possible variation of the gravitational constant is already implemented into the GADGET code, and has been successfully tested in a series of small validation runs. Figure 4 presents a comparison of the predicted theoretical linear growth rate of the large scale structure (lines) with the measured linear growth derived in the simulations (diamonds) for various models which we want to investigated in more detail. The small deviations reflect the (too) small volume and the poor resolution used for these sets of validation runs.

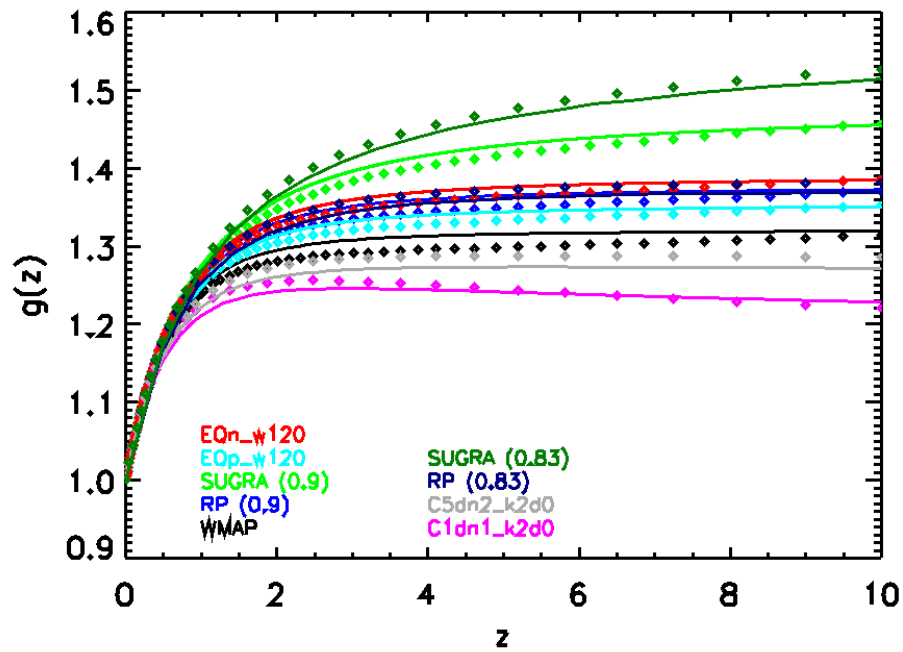

Fig. 4.— Comparison of the predicted theoretical linear growth rate (lines) with the measured linear growth in the simulations (diamonds) for various models which we want to investigate in more detail. Taken from the code validation simulations.

Primary goals

Thanks to the expertise of the researchers involved in the project, we will be able to create mock lensing and X-ray observations to be compared to real data. We will mainly focus on 3 aspects.

The relation between concentration and mass

In the standard cold dark matter (CDM) paradigm, the radial profiles of dark matter halos are very nearly self-similar from galaxy up to cluster scales, and are fairly well approximated by the NFW profile (Navarro et al. 1997). This quasi-self-similarity is a key prediction of CDM models and illustrates the importance of comparing dark matter profiles on all mass scales. The concentration parameter of dark matter halos c (i.e. the ratio between the virial radius and the scale length of the NFW profile) varies slowly with virial mass M (Bullock et al. 2001, Dolag et al. 2004) and is expected to be larger for galaxy mass haloes compared to cluster halos. Low mass haloes are more concentrated, because they collapsed earlier than haloes of larger mass. A significant scatter at fixed virial mass is expected and thought to be related to the distribution of halo formation epoch (Wechsler et al. 2002). The precise relation between concentration and mass is expected to vary significantly as a function of the cosmological parameters, including the power spectrum normalization σ_8 and the dark energy equation of state parameter (Dolag et al. 2004, Kuhlen et al. 2005) making an observational test of this relation a very powerful tool for cosmology. Recent attempts of an observational test have been made in X-rays (Buote et al. 2007) and lensing (Comerford & Nataryan 2007) revealing a promising agreement of the observed c-M relation with the predicted one, with interesting independent constraints on σ_8 (Buote et al. 2007). These studies have also highlighted the future work needed to use the c-M relation for precision cosmology: on the observational side increase in the samples size, and a deeper understanding of the systematics involved in the mass profile reconstruction using different methods; On the theoretical side the refinement of the predictions of halo concentrations produced in different cosmological models. This will be addressed by analysing the outputs of our large-scale, state of the art hydro-dynamical simulations, which allow to assess the scatter, to reproduce the sample selection effect as close as possible and to investigate the role of the dissipative collapse of baryons in shaping the resulting dark matter density profiles (i.e. the issue of adiabatic contraction).

Calibration of galaxy clusters as tools for cosmological studies

The large statistical sample of clusters we will obtain from the cosmological boxes, together with the detailed study of the complexity of astrophysical processes controlling the baryonic phase will allow us to afford the problem of the systematic effects which affect the use of clusters as cosmological tools. Temperature and X-ray luminosity are used as proxies of the cluster virial mass thanks to the existence of robust scaling relations between them. We will use our simulations to calibrate these relations and to find the optimal proxies for mass, discussing any possible intrinsic and observational bias. Moreover, having state-of-the-art hydro simulation allows us to work directly on the observables (Temperature and X-ray luminosity) to be compared to observations. This will largely avoid complications in the definition of virial mass and radius present in some of the complex dark energy models. As demonstrated in figure 4, the different growth of structures in the different dark energy models is expected to leave its imprint on the evolution of the cluster scaling relations, and therefore opens more possibilities to discriminate between them.

Non-linear growth

On large scales, the growth of structures can well be described by the linear evolution (as shown in figure 4); however at smaller scales (still above the size of galaxy clusters), non-linear effects are getting important. Here usually empirical descriptions (calibrated using N-body simulations) are adopted to get a proper description in analytic treatments. Building up our simulation library for various dark energy models will allow the addaption (e.g. calibrateion) of these descriptions also for these dark energy models.

On much smaller scales, by applying a well-tested code which allows to identify overdensities of gravitationally linked particles, we will analyze the outputs in terms of substructures. We plan to investigate their radial distribution in mass, as a function of the cosmological model and redshift. The goal is to build a model which can be easily inserted into the analytic models aiming at faithfully describing the lensing effects of substructures in galaxy clusters. Moreover we will investigate the dynamics of the matter assembly inside clusters, evaluating the typical surviving times of substructures. A by-product of this analysis will be a check of the validity of the extended Press-Schechter formalism in non standard cosmologies (quintessence, modified gravity).

Methods and requests

Implementation on HRLB2. GADGET has already been ported to and extensively used on the HRLB2 system. It uses the MPI protocols for communication between different tasks. Although it has been used already with several thousands of cores on the HRLB2 system, our typical production runs will need only 256 or 512 cores, each consuming approximately 512 GB of RAM. One full simulation will involve of the order of 15 (automatic) re-submissions to the queuing system, using a 12h running time of each submission. Our test calculations show less than 10% imbalance losses when using the foreseen number of cores.

Data storage requirements and data analysis. One snapshot of the simulation will take about 45GB of disk memory. We plan to produce 46 outputs for each run. The number of outputs is constrained by keeping the physical time interval between them short enough to allow a proper estimate of the strong lensing signal. Including the post processing results, we expect the data volume for each run to be of the order of 2.5-3.0 TB. These data have to be available for the full post-processing procedure, which needs simultaneous access to all the data (e.g. merger tree construction, light cone construction). In order to allow a continuous procedure, it should be possible to keep several simulations online, before archiving them to tape.

CPU request and justification Code validation simulations have already been performed and post-processed. The expected CPU needed for each simulation is estimated to be **50.000** CPU hours for the main run and approximately **30.000** CPU hours for the corresponding post-processing. The plan is to investigate appr. 13 different cosmological scenarios, sampling nearly the complete range of dark energy models under debate. There should be room for repeating one or two simulations with different assumption for the normalization of the power spectrum. Therefore the total request amounts to **1.000.000** CPU hours.

Dark energy models to be investigated:

- **WMAP** (model with the standard cosmological constant)
- **RP** (Peebles & Ratra 2002)
- **SUGRA** ("Super Gravity" models)
- **EQ** (2x, extended quintessence with 2 different parameters)
- **CQ** (2x, coupled quintessence with 2 different parameters)
- **EDE** (2x, early dark energy with 2 different parameters)
- **OscDE** (2x, oscillating dark energy with 2 different parameters)