Cosmological hydrodynamical simulations in various cosmological scenarios

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Abstract
We performed cosmological hydrodynamical simulations to study the growth of cosmic structures in different dark energy scenarios as well as in models with primordial non-Gaussian fluctuations. The main goal is to quantify the effects of these alternative models on the general appearance of the large scale structure of the Universe, focusing in particular on galaxy clusters and their observational properties (e.g. the X-ray and SZ properties, scaling relations and their redshift evolution, the internal structure, etc.).

Introduction

Clusters of galaxies are ideal cosmological probes. In 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 morphology are strongly dependent on the cosmological model and then permit to probe it. The increased size, range and completeness of observational data obtained using 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 per cent or better. Future instruments (like the now running PLANCK satellite and the planned e-ROSITA mission) will help to measure cosmology 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, JDEM, DarkCam, EUCLID). 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. The quality and quantity of the data in such surveys will allow also to test scenarios where the initial density perturbations are (up to some degree) non-Gaussian, which is a natural prediction of several inflationary models. However, such a precision in cosmology can be reached only through a faithful comparison with the results of detailed numerical models: an example 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, galaxy clusters turned out to be extremely complex objects, which have to be understood in much better detail if one pretentds to interpret the forthcoming observations. Therefore it is absolutely mandatory 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 toi nvestigate the ability of numerical simulations to make precise predictions.

Performed Simulations

Simulations are performed using P-Gadget3, a massively parallel Tree-PM-SPH code based on MPI. To improve work-load-balance, time consuming parts on every MPI task, it can make uses of several pthreads. Typical simulations have been performed on 256/512 CPUs in parallel, consuming ca. 70.000 CPU/h each. The largest cosmological boxes done (including hydrodynamics) produce approximately data outputs of 3.5TB each.

Dark Energy Simulations

The first set of cosmological hydrodynamical simulations investigated the effect of different dark energy models on the properties of large scale structures and galaxy clusters in general. We simulated cosmological volumes of (300 Mpc/h)^3 using 2x768^3 gas and dark matter particles, adopting cosmological parameters from the 3-year WMAP values.

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Omega           0.268
OmegaLambda     0.732
OmegaBaryon     0.044
HubbleParam     0.704
Sigma8          0.776
PrimordialIndex 0.947
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We so far performed simulations for the following dark energy models:

WMAP3 (standard cosmological constant)
RP (Peebles & Ratra 2002)
SUGRA ("Super Gravity" models)
EQ (2x, extended quintessence with 2 different parameters)

Figure 1 shows a slice through the simulation box at the final time (z=0). For each model, we performed both control runs considering only dark matter particles and full hydrodynamical runs including gas cooling and star formation. The results will be presented in several papers [1],[2], focused on different aspects. Additionally, we also produced deep light-cones of the standard cosmological run which are used to build the foreground model for the PLANCK data simulation task as well as within the PLANCK working group WG5 devoted to "Studies of diffuse and kinetic SZ signals".

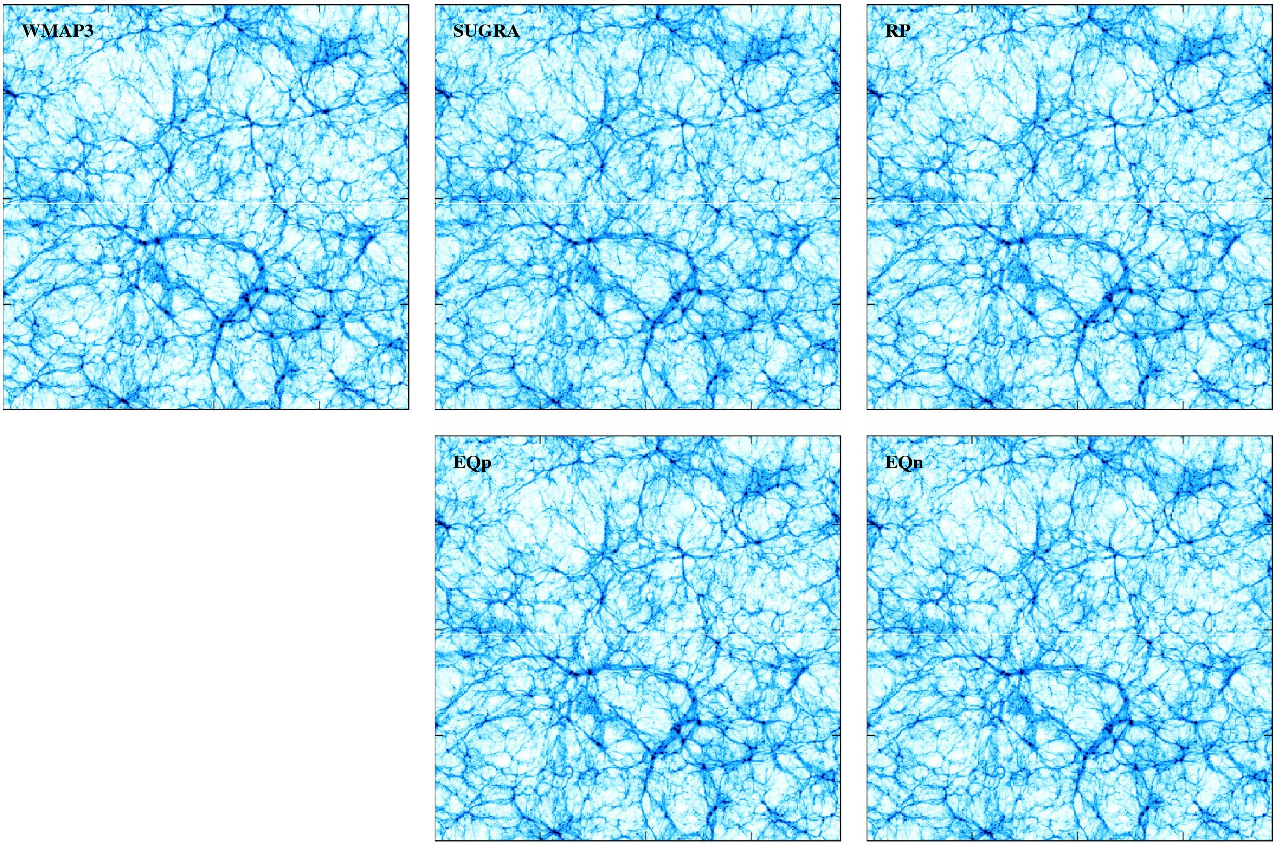

Figure 1: Maps of the final matter distribution in the different dark energy models.

Non-Gaussian Simulations

The second set of cosmological hydrodynamical simulations investigated the signatures of non-Gaussian density fluctuations with different strengths. The goal of these simulations is to estimate the effects of such non-Gausianity of the large scale structures and galaxy clusters in general, evaluating their detectability. One of the most interesting effect is on the halo bias, which for non-Gaussian perturbations has a unique scale dependent signature. To investigate this statistical test, a very large cosmological volume is needed. Therefore we considered boxes of (1200 Mpc/h)^3 using 2x960^3 gas and dark matter particles, adopting the cosmological parameters derived by the 5year-WMAP results.

Omega	0.26
OmegaLambda	0.74
HubbleParam	0.72
OmegaBaryon	0.044
PrimordialIndex	0.96
Sigma8	0.8

The deviation from Gausianity of the initial conditions is usually parametrized by a dimensionless parameter f_{NL} entering in the inital gravitational potential Φ that it is related to a Gausian random field ϕ as:

$$\Phi = \phi + f_{NL} \cdot (\phi^2 + <\phi^2>)$$

We also investigated the effect of higher order, non-Gaussian signatures parametrized by g_{NL}:

$$\Phi = \phi + g_{NL} \cdot (\phi^3 + <\phi^3>)$$

So far we investigated the following models performing dark matter only reference simulations:

$f_{NL}=0,\pm100,\pm200$
as well as
$g_{NL}=\pm10^5,\pm10^6$.

The first results of these simulations have been already published [3],[4]. Figure 2 shows the density maps at high redshift as well as at redshift zero for some of the models considered in [4]. The central column displays the density slice, while the left and right ones shows the differences in the matter distribution for the same cosmological volume but with positive and negative non-Gaussian contribution. Figure 3 (taken from [2]) shows the redshift-dependence of the non-Gaussian correction to the halo bias from the simulations (points) compared to theoretical predictions (lines). Our analysis demonstrated that the theoretical models need a correction by a factor of q=0.75 as expected considering the ellipsoidal collapse model. Full hydrodynamical simulations including gas cooling and star formation have been performed up to now on a subset of models with

$f_{NL}=0,\pm100$
and
$g_{NL}=\pm10^6$.

A paper presenting the main results of these new hydrodynamical simulations is in preparation. Taking advantage of the large simulation volume we also produced several realizations of deep light-cones for the SZ effect, based on the standard cosmological run. These light-cones are actually used by the South Pole Telescope (SPT) team to study the detection of galaxy clusters in large SZ survey campaign.

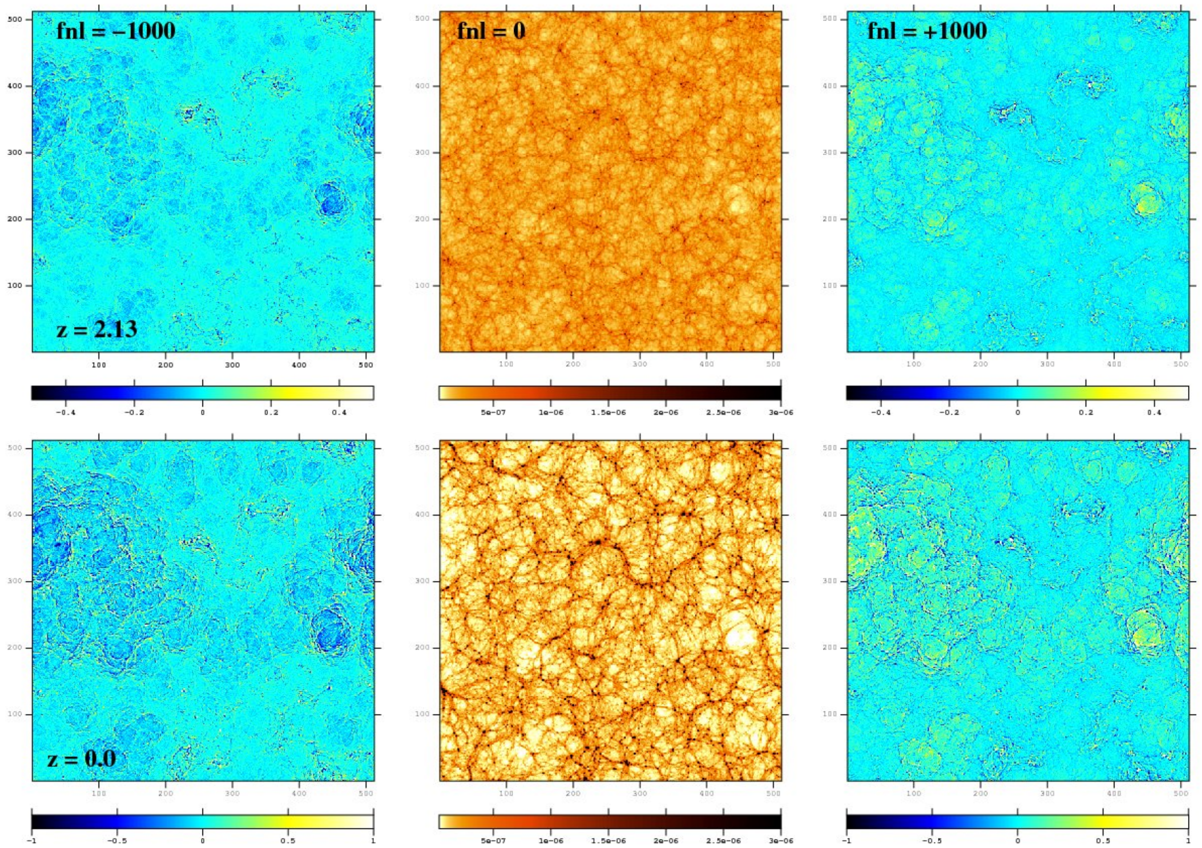

Figure 2: Maps of the high redshift and final matter distribution in models with different level of non-Gausianity as used in [4].

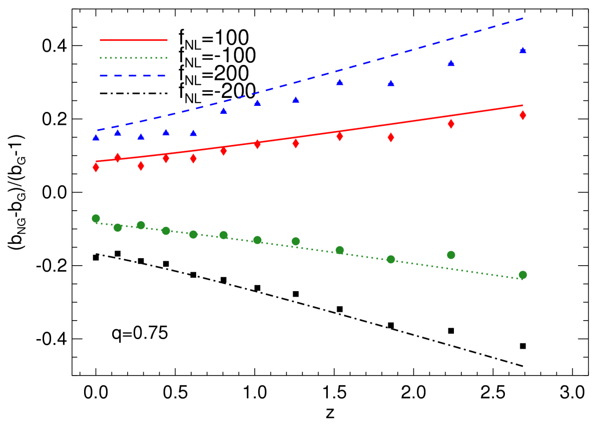

Figure 3: Non-Gaussian bias of halos as function of redshift

Outlook

The simulations performed will allow a detailed study of the properties of the large scale structures and galaxy clusters, in various alternative cosmological background models. Such models differ in the nature of dark energy and in the inflationary model leading to different amounts of primordial non-Gaussianity. Many of the starting or upcoming observational campaigns aim to measure such small differences between the predictions of different cosmological models and large cosmological simulations, as the ones performed inside this project, allow to quantify such effects from the theoretical side. Since these simulations include an hydrodynamic treatment of the gas, they can be used as reference for a much larger number of observational campaigns (specially in X-rays and at radio wavelengths for the SZ effect, where the observed signal is coming from the diffuse medium within virialized objects). The simulations performed so far are already revealing interesting details and can be used to compare the performances and the findings of different observational campaigns. Additional we plan to:

1) Finish the hydrodynamic simulations of the still missing cosmologies done as dark matter only test runs so far.
2) Complete our simulation set by the yet not investigated models for dark energy from the original proposal.
3) Complement our simulations set with some additional, non standard cosmologies.
4) Complement them with some simulations, where the standard cosmological parameters are varied within the presently allowed ranges.

This will allow us to discuss the possibility of distinguishing effects from additional physics (like dark energy and non-Gaussianity) from the uncertainties in the parameters of the standard cosmological model. We would like to remind that the treatment of hydrodynamics within these cosmological simulations reveals a key point for getting more accurate results and allows us to compare such simulation outputs to various ongoing and planned, observational campaigns (see for example the light-cones prepared for SPT and PLANCK experiment). Therefore we applied for a prolongation of our ongoing simulation campaign aiming to obtain additionally 500000 CPUh of computational time to to fill up to the originally applied (but shortened) CPU time.

References

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