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DUSTGRAIN Follow Up report

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Abstract. The DUSTGRAIN project is an extended programme of cosmological simulations to test the observational degeneracies between Modified Gravity theories and massive neutrinos. It consists of an exploratory suite of small-scale simulations, called the DUSTGRAIN-*pathfinder*, and a few larger simulations to investigate the most degenerate parameter combinations. The DUSTGRAIN Follow Up project was designed to extend the *pathfinder* suite of the project to include variations of the standard cosmological parameters Ω_M and σ_8 and investigate their impact on the degeneracy and to help calibrating emulators of modified gravity and massive neutrinos cosmologies.

1. Introduction

The DUSTGRAIN Follow Up project was designed with the aim to provide a follow-up of the recent DUSTGRAIN (Dark Universe Simulations to Test GRAvity In the presence of Neutrinos) simulations that have been performed thanks to a PRACE allocation at the Tier-0 supercomputing machines Marconi (Cineca) and MareNostrum4 (BSC). The DUSTGRAIN simulations are large cosmological simulations of structure formation featuring the combined effects of a Modified theory of Gravity (in the form of f(R) gravity) and of massive neutrinos. In fact, it is well known that these two phenomena have very degenerate imprints on several observables characterising the large-scale structures of the Universe, and that their combination may result in a partial or total cancellation of their respective signatures.

The DUSTGRAIN simulations have been carried out using a combination of the `MG-Gadget` code (Puchwein, Baldi & Springel 2013) with a particle-based solver for massive neutrinos (Viel, Haehnelt & Springel 2010) that allows to follow the evolution of the structure formation processes in the presence of massive neutrinos down to the fully non- linear regime also in the context of an f(R) gravity theory. These codes nonetheless introduce significant overheads in the numerical requirements of the simulations, so that the main DUSTGRAIN runs - with their large box size (2 Gpc/h) and their relatively high resolution (2×2048^3 particles for a mass resolution of about 6×10^{10} $M_\odot/h$) - could be run only for a limited number of parameters combinations due to their very large computational cost. More specifically, only three models (one standard LCDM and two f(R) gravity models, for two different values of the total neutrino mass) could be run with the full CPU budget obtained through the PRACE allocation, about 18 Mio CPU hours. Therefore, the dependence of the degeneracy on the standard cosmological pa-

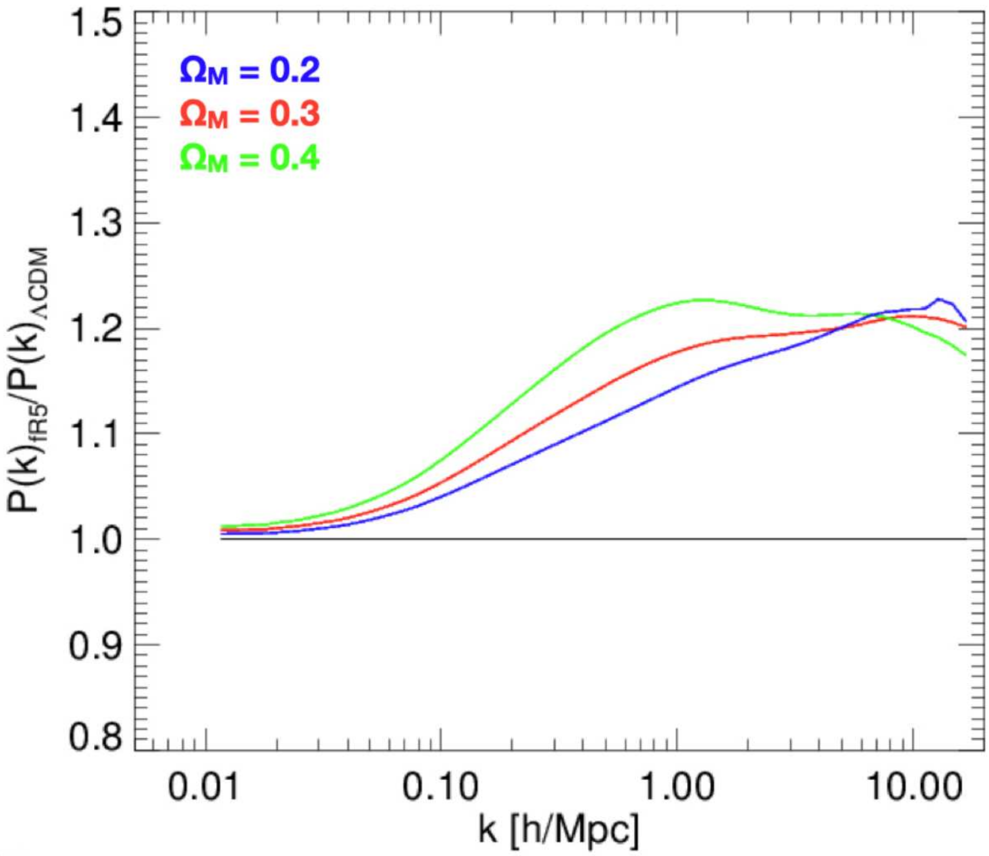

Fig. 1. The relative deviation ("boost factor") of the nonlinear matter power spectrum of a $f(R)$ gravity model from the respective General Relativity counterpart for three different values of the $Omega_M$ parameter, as extracted from the DUSTGRAIN Follow Up simulations

rameters could not be tested as all these three simulations have been performed assuming the same underlying cosmology. The follow-up planned with the DUSTGRAIN Follow Up project was specifically aimed to fill this gap by running a suite of 10 simulations with much smaller box size and resolution, but varying the standard cosmological parameters so to get a first rough estimate of the dependence of the degeneracy on the latter and tune a possible second cosmological setup for a future extension of the full-scale DUSTGRAIN simulations.

As described in the proposal, the full range of 10 simulations would have required an allocation of about 1 Mio CPU hours, which was not granted in full in the first approval of the project, with an initial computational budget of 500 k CPU hours. Therefore, it was not possible to complete the set of 10 simulations that was necessary to sample the cosmological parameter space in order to provide the planned follow-up with this first allocation. The assigned budget has been sufficient, however, to run 6 of the 10 planned simulations, corresponding to varying the value of the Ω_M parameter, while the variation of the other relevant parameter (i.e. σ_8) could not be performed so far. The 6 completed simulations correspond to two different values of Ω_M

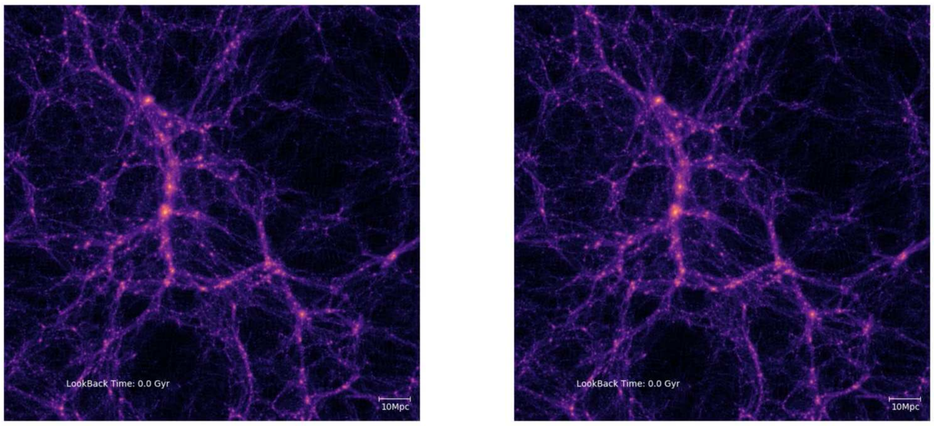

Fig. 2. Visual comparison of the large-scale dark matter density field in General Relativity (left) and in one of the simulated $f(R)$ gravity models, as extracted from the DUSTGRAIN Follow Up simulations at $z = 0$.

equally distant from the value adopted in the fiducial cosmology of the DUSTGRAIN runs (namely $\Omega_M = 0.2; 0.4$) for both standard gravity and f(R) gravity, and in the latter case also for two different values of the neutrino mass (namely $m_\nu = 0.1$ and 0.15).

These first six simulations allowed to test how the combination of the nonlinear effects of Modified Gravity and of massive neutrinos depend on the underlying cosmological parameters, while a fully meaningful sampling of the (Ω_M,σ_8) parameter space will need to wait for the completion of the remaining 4 simulations. However, as a first result of this preliminary analysis, we have been able to estimate the dependence of the f(R) gravity effects on the matter density Ω_M and to conclude that the deviation of the matter power spectrum of f(R) gravity cosmologies from their General Relativity counterparts (which is known as the "boost factor") only weakly depends on this cosmological parameter (see figure 1 below) so that its effect can be accurately captured by simulating a single fiducial cosmological setup.

2. Relation with other supercomputing projects

As discussed above, this project represents the follow-up of a series of simulations carried out in the context of a multi-year PRACE allocation at Marconi and MareNostrum4. Therefore, this project is based on the outcomes of the larger simulations (as far as the definition of the maximum degeneracy between $f(R)$ gravity parameters and neutrino mass is concerned) and will similarly serve as a guideline to define the setup of future larger simulations to explore in full detail the dependence of the degeneracy on the cosmological parameters. Some of the results obtained in this project have been used to tune the parameters setup of a subsequent ISCRA-B project (called SIMCODE2). The main advantage of the allocation obtained with the present call stands in the quick response to the project submission, which allowed to start running the simulations with a very timely schedule and to produce the first results on a relatively short timescale. Unfortunately, however, the initial partial allocation of resources (a half of the requested budget for the completion of the project) did not allow to immediately pursue the original goals of the project in full, so that a new allocation was necessary in order to complete the simulations. At the time of writing this report, the remaining 4 simulations have just been completed on the Marconi-KNL partition using the ISCRA-B resources of the SIMCODE2 project mentioned above.

Due to this delay, no publication has yet been completed for this project. However, the 6 simulations performed in the DUSTGRAIN

Follow Up project have already been employed for an extended effort to calibrate an emulator for Modified Gravity models carried out within the Euclid collaboration. In particular, the simulations have contributed to a paper (Winther, MB, et al. 2019) showing the accuracy of a calibrated $f(R)$ gravity emulator for Euclid-like specifications. When the remaining simulations will be analysed, a series of analysis papers will be produced.

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