Title: Large-Scale Structure Simulations to address fundamental questions in Cosmology

One Post-Doctoral Fellowship funded under the **PRIN - 2017YJYZAH** project

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Duration: 2 years

## Scientific Rationale

Over the past two decades, Cosmology witnessed an experimental revolution that led to firmly establish and accurately test a "Standard Cosmological Model": the Lambda Cold Dark Matter ($\Lambda$CDM) scenario. Using a small number of free parameters, today known with percent accuracy, $\Lambda$CDM is able to consistently and precisely explain a vast number of observations, from Cosmic Microwave Background (CMB) to Large Scale Structure (LSS) data.

However, despite all its impressive successes, the $\Lambda$CDM model remains an extremely good effective description of unknown physical components and processes. Some of the biggest open questions in $\Lambda$CDM are represented by Dark Matter – the dominant, yet unknown, matter component in our Universe – and by Dark Energy or Modified Gravity – the mysterious field, or alternatively the yet unknown modification to General Relativity on cosmological scales, which drives the accelerated expansion of the Universe today. To this, one must add fundamental questions related to the nature and energy-scale of the scalar field – the inflaton – that drove inflation, that is, a very early, accelerated expansion phase, at the end of which primordial density fluctuations were generated. These initial perturbations are crucial, as they are the primordial seeds for the formation of CMB anisotropies and of all structure in the Universe, via gravitational instability.

In order to solve these conundrums, a massive experimental effort is planned for the next decade, and beyond. New large sensitivity improvements in CMB observations will come both from a campaign of ground-based experiments ("stage IV") and from the LiteBIRD space mission, both aiming for the first detection of the so-called CMB polarization B-mode (a potential "smoking-gun" probe of inflation). Crucially, a similar sensitivity leap is also about to take place in the study of the Large Scale Structure of the Universe. The main actors in this field will be the forthcoming – optical and infrared – Euclid galaxy clustering and lensing survey and, later on, the SKA radio survey.

Besides the improvement in the quality of observational data, the solution of these cosmological puzzles will require also an exquisite accuracy in the theoretical prediction of observable quantities for a number of competing cosmologies extending beyond the standard $\Lambda$CDM scenario by encompassing a wide range of yet untested hypotheses for new physics as an explanation for the observed phenomenology of the universe. In order to obtain such accuracy over a wide range of scales and epochs, the use of large and complex numerical simulations represents an essential tool.

In particular, this project will focus on the development of optimised numerical techniques for the production of mock observables matching the specifications of future wide-field surveys in a variety of cosmological scenarios covering several possible new hypotheses for the physics beyond standard Dark Matter, Dark Energy, and Inflation.

## The Research Project

The present Post-Doctoral appointment is part of a joint research project with the *University of Padova* and the *Padova Division of INFN* coordinated by Prof. Michele Liguori and funded through the PRIN 2017 national funding scheme. The main objectives of the joint project are:

**1) Testing Inflation: Primordial non-Gaussianity and spectral features**

Inflation predicts some small level of non-Gaussianity in the initial density field, called primordial non-Gaussianity. The strength of such primordial non-Gaussianity signal is described by an amplitude parameter, called $f_{NL}$. The simplest, "standard single-field slow-roll" Inflation models predict a bispectrum amplitude $f_{NL} \approx 0.01$, which is a very small value, way beyond current and forthcoming experimental sensitivity. For this reason, a detection of primordial non-Gaussianity would be groundbreaking and rule out all the simplest inflationary scenarios. Future LSS data contain, in principle, enough information to achieve a key, order-of-magnitude improvement in primordial non-Gaussianity constraints, but will include also many non-primordial sources of non-Gaussianity, in particular from non-linear gravitational evolution of cosmic structures at intermediate and small scales, and from non-linear galaxy bias, which represent an undesired noise in the quest for the primordial signal. Such noise is however much larger than the target signal, which demands for an unprecedentedly accurate modeling of late-time non-linearities to allow the separation between primordial and late-time non-Gaussian components. One of the goals of the project is to tackle this hard challenge by developing dedicated numerical mock observations with different strengths and shapes of primordial non-Gaussianity.

**2) Testing Dark Energy and Modified Gravity scenarios**
Many theoretical ideas have been put forward so far to explain present cosmic acceleration, generally pertaining to the two broad classes of Dark Energy models and Modified Gravity theories. Such extended landscape of models has found a unified description within the Horndeski Lagrangian formulation. Interestingly, the recent observation of the gravitational wave event GW170817 has actually ruled out in one shot a large portion of the Horndeski landscape. This provides an even stronger motivation to test in detail the few remaining competing models – such as f(R) or k-essence models, for example – in order to either finally detect them or conclusively rule them out. To this purpose, the DE/MG phenomenology may actually show its most distinctive features in the highly non-linear regime of structure formation (for the study of which N-body simulations are essentially mandatory). It is thus essential to maximize the range of scales and redshifts over which these observables are investigated – including non-linear scales – and ideally to combine and cross-correlate different probes to break possible degeneracies of these models with standard cosmological parameters. One of the main goals of the project is then to test and validate such approach – before applying it on actual data – using mock observations, which have to be produced and validated using optimised numerical tools in order to keep under control the required computational costs.

**3) Testing Dark Matter models**
While the general Cold Dark Matter paradigm is very successful at explaining a large range of cosmological observations, it does show some problems in reproducing observed galactic phenomenology (e.g. abundance of substructures, central densities, satellites velocity distributions, etc.). Furthermore, all the attempts for a direct or indirect detection of WIMP-like CDM particles have so far failed their target. A possible way to explain these issues, alternative to invoking baryonic physics, is that of introducing more complex physical mechanisms in the dark sector at small galactic scales, leading e.g. to non-WIMP DM particle candidates, such as Warm and Self-Interacting DM, or Axion DM scenarios. Like for MG/DE models, these modified DM scenarios can carry distinctive signatures in specific cross-correlation signals as e.g., the galaxy-galaxy strong lensing cross section and the LSS weak lensing signal, and in the bispectrum generated at these highly non-linear scales. The aim of the project is thus to employ a completely analogous strategy to that described in the previous section: building large (high-resolution, small volume) mock datasets, and employ sophisticated post-processing pipelines to verify the combining power of different probes and observables to detect and discriminate among different DM models.

## Research Plan

The successful candidate will join the Bologna University node of the project which is in charge of the development of all the required mock observations through dedicated large-scale and high-resolution cosmological simulations. To this end, the post-doctoral researcher will work on the **implementation, optimization, and exploitation of specific extensions of the standard N-body code GADGET3**, in order to achieve the main objectives of the project described above. In particular, a significant effort will be necessary to optimise the codes in terms of accuracy and computational requirements, and to design I/O modules allowing to produce the largest possible range of simulated observables to enable **a multi-probe approach for the investigation of extended cosmological models**.

More specifically, the research activity will cover the following aspects:

- Develop and calibrate numerical tools for analysing large cosmological simulations in terms of **large-scale clustering** (dark matter, halos, and galaxy power spectra, 2- and 3-point correlation functions, cosmic voids, Lyman-$\alpha$ and 21-cm intensity mapping, galaxy clusters counts) or **gravitational lensing** (CMB lensing, large-scale weak lensing shear maps, strong lensing peak counts, ISW and Rees-Sciama effect, galaxy clusters structural properties);
- Whenever needed, modify standard algorithms in order to include in the simulations a variety of non-standard cosmological scenarios, including **Dark Energy and Modified Gravity** theories, **non-standard Dark Matter particle candidates**, and **non-standard initial conditions**;
- Combine the various post-processing tools developed for the different observables into a single numerical pipeline allowing for their cross correlations, in collaboration with the other research nodes of the project (Padova University and Padova INFN Division), in particular for cross correlation with mock CMB observations featuring the expected data quality of the next generation of CMB experiments.