Dark Energy Tomography with the Euclid survey

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Context

While the Universe is expanding with increasing velocity, the question of what is causing cosmic acceleration remains unsolved. A cosmological constant seems to fit current data, but its value is not understood theoretically and rather raises more open questions. Is it really a constant or is it rather associated to a dynamical dark energy? Was dark energy 'frozen' in recent times resembling a constant? Does dark energy change in time and space, like the matter and the radiation we have already observed? Is there any chance to observe this evolution with future surveys?

ESA *Euclid* satellite[1], to be launched in 2022, will observe how galaxies formed to study the nature of dark energy and dark matter. *Euclid* will collect 170 million gigabytes of data, observe the shapes of 1.5 billion galaxies in different redshift epochs, thus providing the largest data set available to test dark energy. While the *Euclid* likelihood is under development (within a taskforce led by the supervisor) under the assumption of a cosmological constant, Euclid data provide the opportunity to test cosmologies beyond the standard model. This PhD proposal is meant to contribute to this effort by implementing the possibility to test dark energy at different redshifts, or what I refer to here as 'dark energy tomography', and integrate it in the Consortium validated likelihood. This project will therefore contribute directly to develop the results of a space mission on which CEA has invested, with a concrete, useful addition to the standard pipeline. CEA will have the opportunity to be actively involved in the scientific exploitation of the mission. This project will be an interesting opportunity for the PhD candidate to work at the interface between theory and data.

The PhD Thesis

Rather than focusing on a specific model, which would be too risky to address in a PhD project, the thesis aims at investigating, in more general terms, how much dark energy density we can have in different redshift bins. To do so, we will use different dark energy amplitudes per redshift bin; this will allow to use Euclid cosmological probes to test how much dark energy we can have in each bin. While the outcome will be simple to deliver conceptually

[1] https://www.euclid-ec.org/

(and therefore feasible to integrate in the official pipeline), it will involve a series of necessary, and instructive steps that are the objectives of this PhD Thesis. This analysis may also provide input to interpret the tension observed in the measurement of the expansion parameter H0, between the data from the Planck satellite data and late time cosmological probes such as Supernovae. While we often see tensions in cosmology, this difference has now reached at least 4.4 sigma. One intriguing possibility is that dark energy may be related to this tension: *early dark energy* scenarios and *coupled dark energy* cosmologies have in particular raised some interest in this direction [see letter of interest in SnowMass 2021, [1] and [4]]. In both cases, dark energy is non-negligible in the past.

Objectives

Boltzmann code development: the *Euclid* likelihood needs a Boltzmann code to calculate theoretical predictions for the matter power spectrum; these are then compared to data within the Likelihood. The first objective will then be to modify the background equations in the Boltzmann code, so that the expansion depends on different amplitudes A_i per each redshift bin z_i. Within such a parameterization, the growth of structure (and therefore perturbations) will behave differently, reflecting the different amplitudes A_i. If time allows, the PhD could realize a second binning directly on those functions that are used to describe perturbations. There is currently no publicly available code that allows to do that. [Paper I: A Boltzmann code for dark energy tomography; the code will be made publicly available].

Integration within the *Euclid* Likelihood: the *Euclid* Likelihood is currently developed within the *inter-science* taskforce (led by the PhD supervisor of this project). A new *Euclid Cosmology Software* is under development: it will read the input from a Boltzmann code, and will infer cosmological parameters. The likelihood is written in python, developed on gitlab, and adapted to work within Cobaya Monte Carlo simulation package, which is publicly available and includes samplers and routines for the analysis. The second objective of the PhD student will then be to integrate the Boltzmann code developed above within Cobaya. This will allow on one side to be ready to use it with *Euclid* data, when available, but also to test it, in the meantime, with current datasets. These include Planck data, supernovae data, growth of structure information contained in eBOSS and DESI (whose results will be available during the thesis). The *Euclid* Likelihood will also be available to run using simulations, and thus forecasting how well *Euclid* can constrain dark energy tomography. The student will be able to reliably include systematic effects, as implemented within the taskforce, and test the impact of different systematic modeling on the final parameters. [Paper II: Cosmological parameter inference for Dark Energy Tomography].

Principal Component Analysis: in order to reach the final constraints, the student will need to decorrelate redshift bins, using techniques such as principal component analysis, or Zero-phase Component Analysis [2].

Machine Learning: within a follow-up project, the student will be able to use machine learning based interpolation methods developed within CosmoStat, to reconstruct Dark Energy at different redshift bins, with a first test done on *Euclid* simulations. While these can be used to reconstruct the non-linear matter power spectrum, we plan to also use them to reconstruct dark energy density itself, as a function of z.

The PhD Candidate

The candidate would have a master in physics (cosmology and/or astrophysics), and would have preferably attended a class in general relativity. The candidate would have experience with python programming language, in order to use and develop *Euclid* likelihood software. Furthermore, the candidate would show interest in working at the interface between data, software development and theory. The PhD student will be able to concretely collaborate to a large collaboration, extending the likelihood software and joining the inter-science taskforce team led by the supervisor. At the same time, the student will be able to develop tools that can be used with other datasets, and will be able to release its Boltzmann code and implementation in Cobaya publicly, independently of the *Euclid* Likelihood publication. The student will have the possibility to learn about different steps which are required to arrive from data to cosmological parameter inference: from the modification of the equations in a Boltzmann code, to the Likelihood development, to the comparison between data, simulations and theory. Through the taskforce, the candidate will also 1) learn new statistical tools, used to develop covariance matrices; 2) learn about current theoretical cosmologies. Furthermore, Python software development, Principal Component Analysis, as well as alternative machine learning methods such as dictionary learning, are statistical tools that are useful in many applications, within and outside cosmology, providing a training in skills which are transferable to other sectors. At the same time, the student will be encouraged to publish independently of collaborations, in order to guarantee visibility that can reinforce chances for the future career of the candidate.

The scientific environment

The thesis will take place within CosmoStat, within the Astrophysics Department (DAp) under the supervision of Valeria Pettorino. CEA and the CosmoStat group are key contributor to the Euclid mission. The PhD supervisor (*Euclid* Builder status since 2020 and in Euclid since 2007) is expert on theoretical dark energy models, led the Planck Dark Energy analysis, and is now leading the inter-science taskforce responsible for the *Euclid* Likelihood development. Valeria Pettorino has supervised 3 PhD students so far. She is a member of the science policy work group of the Marie Curie Alumni Association and of the EuroPython Society: the first provides a network for career development within academia, with seminars specifically meant for early-career researchers that the PhD student may want to join; the second, EuroPython, encourages networking among users of python programming language applications, within and outside academia. The PhD student will then also have the opportunity to present results to the python community, which can be useful for enlarging career path perspectives in the industrial domain. The supervisor is also mentor for the Supernova Foundation, a mentoring programme for women in physics that provides guidance on career development.

The student will be able to take part to monthly group training sessions organised within CosmoStat on a variety of topics (from cosmology, to astrophysics to software development to communication, available on the YouTube Channel of the group). Mock interviews for postdoc applications and a school on cosmology are also organised every year by the PhD supervisor.

References

[1] Cosmology Intertwined II: The Hubble Constant Tension https://arxiv.org/abs/2008.11284 Di Valentino, Pettorino et al 2020.

[2] Linear and non-linear Modified Gravity forecasts with future surveys https://arxiv.org/abs/1703.01271 Casas, Kunz, Martinelli, Pettorino 2017

[3] Casas, Baena, Pettorino, etal, in preparation.

[4] Update on Coupled Dark Energy and the H0 tension, https://arxiv.org/abs/2004.00610 Gomez-Valent, Pettorino, Amendola 2020.