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Re: Evaluation of the doctoral thesis submitted by Mgr. Michal Vraštil

Dear Colleagues,

This is a report to evaluate the doctoral thesis "Study of dark energy and modified gravity and their influence on the cosmological parameters of the universe", submitted by Mgr. Michal Vraštil. It was a pleasure to read the thesis and I would like to start the report with a brief summary of my findings. Understanding the cause for the accelerated expansion of the universe is one of the most challenging endeavors in fundamental physics today. Many large-scale cosmological surveys are being carried out or are under construction to help us to shed light on this puzzle. The thesis by Mgr. Vraštil makes an important contribution to this field. In this work several different approximations are investigated that enable fast simulations of structure formation in the Universe for modified gravity theories. The accuracy of these approximations is evaluated by measuring a range of statistics, including power spectra, correlation functions and mass functions, all important to understand the signatures of different modified gravity models on structure formation. These investigations are important to aid the interpretation of upcoming measurements from large-scale cosmological surveys carried out from the ground and from space. In particular, if we indeed find hints for deviations from the current Standard Model of Cosmology, these methods will be extremely valuable and will allow us to explore new physics. The work is innovative and creative and enables a thorough investigation of modified gravity in the context of upcoming surveys. In the following, I provide some more details that support these overall findings.

The thesis starts with a comprehensive overview of cosmological structure formation and a description of the different cosmological probes employed to explore the cause for the accelerated expansion of the universe. The section shows a good understanding of important measurements that are targeted to uncover possible deviations from General Relativity on large scales. In particular, baryonic acoustic oscillations provide a probe that is central to the investigations in this thesis and are carefully investigated later on. The section also contains a brief overview of ongoing and upcoming surveys, providing more of the context for the importance of the work carried out in the thesis. While some of the content in this section was already presented in the Master's Thesis delivered by Vraštil, the discussion is important to set the context for the new work presented later in the thesis. The second section turns towards dark energy and modified gravity. The section starts with an insightful discussion of the cosmological constant problem. This discussion again shows a very good understanding of the problem targeted for the new simulation approach and provides important background information about the models to be later investigated. The section also provides a summary of a study that had been carried out as part of the author's Master's Thesis on chameleon gravity effects in spherical systems. This investigation is helpful to guide the later new study described in Section 5 with regard to the length scales of interest. Section 3 summarizes currently employed methods for simulations to investigate the formation of structure in the Universe. The author briefly describes the Core Cosmology Library, CCL, which is developed within the LSST Dark Energy Science Collaboration (DESC). The CCL provides predictions for basic cosmological observables. Vraštil has made contributions to the CCL development and some of the tools provided by the library are employed as part of the thesis for comparison purposes.

The next two sections, in particular Section 5, describe the new and innovative work carried out as part of the thesis. In order to understand the signatures of modified gravity models on large-scale structure probes, numerical simulations are essential. As detailed in the thesis, such simulations are very expensive (up to an order of magnitude more expensive than simulations of the Standard Model of Cosmology which already require large computational resources). Given the large model space described in Section 2, approximate methods that enable an exploratory approach are crucial in order to make progress in understanding signatures of modified gravity models on cosmological probes. In this thesis, these approximate methods are implemented, compared and evaluated and therefore add an important new contribution to the field. While the methods themselves have been suggested in the past by other authors, the comprehensive implementation and comparison in the context of modern cosmological surveys and modified gravity theories is new and innovative. Section 4 starts with an overview of the different approximate methods and contrasts their advantages and disadvantages. The discussion focuses in particular on the length scales of validity and at what point in the evolution of the universe they break down. This discussion is extremely important in order to understand if the approximations are valid for the probes of interest discussed further on. Section 5 then describes the implementation of the methods first for the Standard Model of Cosmology and next for the modified gravity models of interest in the thesis. As stated above, these approximations have not been studied before in the context of modified gravity models and the implementation therefore is a major new contribution to the field. The section also provides the details of the large simulation suite that has been carried out as part of the thesis to study several important aspects of the approximations. Again, a simulation suite as described here, has not been carried out before and enables to obtain new and interesting insights to the field of modified gravity studies.

In order to understand the usefulness of the approximations, it is important to connect them to a set of cosmological measurements. The thesis provides first visual impressions of the differences and then continues to discuss quantitative results. Measurements for the matter power spectrum, the correlation function and the halo mass function are described. These measurements map onto the different cosmological probes (weak lensing, large-scale structure and clusters, as described in Section 1.3) and are commonly used to determine the effects on cosmology for models beyond the Standard Model of Cosmology. The section describing the modified gravity theory results (Section 5.2) starts with an important discussion on resolution effects. The section then not only explores the validity of the different approximations but also explores the parameter space relevant to the specific chameleon model under investigation. The results are carefully interpreted and possible further applications of the different approximations are discussed (e.g. the improvement of the speed of full N-body simulations at early times). The discussion also provides some insights in how the approximations can be used for the purpose of reconstruction techniques, an important area for analyzing the measurements from baryon acoustic oscillation experiments. A major conclusion in this section is that the approximate methods are most useful for exploring the baryon acoustic oscillation peak. This conclusion makes sense in that this probe focuses on large scales that should be captured reasonably well with the schemes employed.

The newly developed tools and approaches in this thesis can now be extended to the larger model space discussed in Section 2 as well. It will be extremely important for the cosmology community to have approaches readily available that will enable the fast explorations of different models and scenarios beyond the Standard Model of Cosmology. The upcoming surveys promise to deliver measurements at exquisite accuracy and means to predict signatures of new physics will be critical.

This thesis delivers an important milestone by enabling the rapid investigation of modified gravity theories and clearly is a new contribution to the field. The measurements relevant to the different cosmological probes are insightful and provide together with the simulation suite an important capability for the field. I would like to reiterate that it was a great pleasure to read this thesis.

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