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Report on the Doctoral Thesis of M.Sc. Suhani Gupta,
entitled
"Linear and non-linear statistics of the cosmic density field in modified gravity cosmologies"

General assessment
The thesis of Ms Suhani Gupta is devoted to the study of statistical properties of cosmic density field in modified gravity theories in comparison with standard ΛCDM cosmology. Discovery of the accelerated expansion of the Universe brought the fundamental question of what is responsible for this phenomenon: exotic unknown matter component or is this a signal that General Relativity (GR) breaks down at cosmological scales? Ongoing and forthcoming deep galaxy surveys are expected to shed some light on this mystery. Hence the research performed and presented in the thesis is particularly important and timely. Thesis was completed under the supervision of prof. Wojciech Hellwing and prof. Maciej Bilicki.

The thesis is well written in a good English. The style is transparent and easy to follow. The thesis consists of six chapters and bibliography. Its main content is preceded by abstracts in English and in Polish, acknowledgments, declaration of the originality of the thesis and the information about other papers to which the Candidate contributed, the lists of contents and figures and finally the table summarizing key notations and acronyms used in the text. Acknowledgments are among the longest I have had opportunity to read, yet touching and written in a flowery language. From the declaration one learns that the thesis is based on three papers published by the candidate together with her supervisors. In all of them Ms. Suhani Gupta was the first author. Two of the papers appeared in the *Phys.Rev.D*, which is a renowned journal, and one in the *Proc. Polish Astron. Soc.* She performed all calculations and created all figures (with two explicitly named exceptions) underlying the thesis (and the papers mentioned above). The credit is given to a colleague for translating the abstract to Polish. She also contributed to two another papers, which have not been included in the thesis.

Chapter 1 is the introductory one, setting the stage for the rest of the thesis. After recalling the fundamentals of GR and cosmology, the issues like evolution of density field and structure formation theories are reviewed. Then, two modified gravity (MG) models (Hu-Sawicki version of *f(R)* theory and DGP brane-world scenario) underlying the research presented in the thesis were introduced. Screening mechanisms and structure formation in MG theories were outlined as well as the N-body simulations used in the thesis. Of particular relevance is is the ELEPHANT suite comprising N-body simulations in MG models studied in the thesis. The chapter ends with an overview of the thesis.

Chapter 2 presents the results published in the paper *S. Gupta, W. A. Hellwing, M. Bilicki, and J. E. Garcia-Farieta, Phys. Rev. D 105, 043538 (2022)*, which is also attached *in extenso* at the end of the chapter. Research topic investigated here is the behaviour of the halo mass function (HMF) across different mas scales and redshifts in MG theories and comparison between MG and ΛCDM model. In order to facilitate the understanding of the aforementioned paper, theory of HMF in the Press-Schechter formalism is reviewed. It is extremely hard to derive the HMF in MG from the first principles, while the HMF is much better studied theoretically within the ΛCDM model. Hence, the Candidate proposes a heuristic approach to quantify the MG halo mass function by multiplying the ΛCDM HMF by certain factor Δ_{MG}, and proposes some functional expressions for it. This conjecture has been tested on simulated data and turned out promising.

Chapter 3 is based on the paper *S. Gupta, W. A. Hellwing, and M. Bilicki, Phys. Rev. D 107, 083525 (2023)*. As previously, the paper is attached at the end of the chapter. The main idea of this research was to use the results obtained in Chapter 2 together with the existing models of the halo bias parameter *b* and the halo concentration *c*, to build an analytical framework for computing non-linear matter power spectrum in MG models studied in the thesis. Power spectrum is one of the most important notions in modern cosmology. It quantifies the variance of density fluctuations for a given wave number *k* and can be studied both theoretically and observationally. On the large scales, matter power spectrum agrees very well with the linear theory predictions, and enables a direct measurement of primordial density fluctuations. On smaller scales, it carries information of the non-linear evolution of cosmic density fields and this is the regime where the (admissible) departures from GR could reveal themselves. Chapter 3 introduces the framework of the halo model (HM) and presents the details regarding functional form of the HMF, linear bias *b* and halo concentration parameter *c*. Power spectra predicted by HM in MG models and ΛCDM model were confronted with the power spectra calculated from the ELEPHANT simulations. The discrepancy exceeded the precision expected from the future surveys and the Candidate tested another approach: a phenomenological one, similar to that used in the previous chapter. Namely, by introducing the $\Upsilon_{MG}(k)$ factor such that $P_{MG}(k) = \Upsilon_{MG}(k)\ P_{LCDM}(k)$ and calibrating it within the HM framework, one obtains an improvement of precision to the level compatible with the future surveys. Hence, the idea proposed in the Chapter 3 is promising.

Chapter 4 extends the previous research by studying such important issues like Halo Bias (HB) and Halo Assembly Bias (HAB). These issues are crucial in order to properly link the observed distribution of galaxies (residing inside DM halos) with the overall matter distribution. The Candidate studied whether the HAB differs in the MG scenarios as compared to the standard ΛCDM model. Then, the intrinsic properties of the halo, i.e. concentration and spin were studied. An interesting result of this study was that HAB was not strongly impacted by MG and did not show any considerable departure from the ΛCDM HAB. These results are original and have not been published, yet.

Chapter 5 studied the impact of Modified Gravity on DM density fields and halo properties in different Cosmic Web environments. In the simulated data the Hessian of the gravitational potential was used to divide the density field into four different CW environments: knots, filaments, sheets, and voids. Regarding the density distribution, its statistical characteristics: the median, variance, skewness and kurtosis all displayed a clear environmental dependence. Moreover, they are quantitatively different between *f(R)* and DGP gravity as compared with ΛCDM. This shows the potential of higher moments of density distributions as probes to quantify the modified gravitational dynamics from the future galaxy surveys. Similarly, trends in HMF exhibit an explicit dependence on the CW environment. These results are also original and unpublished, except in the thesis.

Chapter 6 contains a comprehensive summary of the thesis, chapter by chapter and a well written section on the future prospects. In particular future opportunities to extend the study of MG effects in weak lensing statistics, cluster counts and pairwise correlations in velocities of galaxies seems well defined and promising. The need for higher resolution N-body simulations in modified gravity theories and inclusion of baryonic effects were emphasized. This section demonstrates scientific maturity of the Candidate.

My general impression is very positive – it is a solid piece of good science in the field of testing modified gravity scenarios with cosmological probes. I am also impressed by the variety of technical/numerical skills the Candidate had to acquire during completing the thesis.

I do not see any major drawbacks regarding the approach taken and the results obtained. However, I present below some really minor critical remarks, mostly regarding the presentation of general concepts.

Critical comments

Table 1 – The name of the first column "Abbreviations" is not fully appropriate. Its first half, in fact, contains the notations of respective quantities used in the text. Regarding the units, the notation is not self consistent, i.e. there is a mixture of conventions like "km/s/Mpc" and "M_0 Mpc^{-3}" this should have been unified (with the preference of using the powers of the basic units). The same comment is valid to the rest of the thesis.

My next comment is that in the case of critical density the reported item is not the unit but actually the value of the critical density. Moreover, its unit [M_0Mpc^{-3}] is never used in the thesis.

Chapter 1

1. Section 1.1. on the fundamentals of GR. In (Eq. 1.1) Einstein tensor $G_{\mu\nu}$ should not contain the cosmological constant term $\Lambda\, g_{\mu\nu}$, by definition it is solely determined by the Ricci tensor and the Ricci scalar. For decades from its conception classical GR was understood as devoid of the cosmological constant, which after the Einstein's "greatest blunder" erratically reappeared and disappeared again and again, until the discovery of accelerating expansion of the Universe. Since that time it has been taken seriously by a wider community, at least as the provisional element of the concordance cosmological model. What instead the left had side of

the Eq.(1.1) is representing is the most general rank two tensor formed from the Riemann tensor and the metric having a vanishing divergence (see e.g. Lovelock theorem).

2. In the text before Eq.(1.2) – labeling spatial coordinates with Greek indices, without proper discussion is inconsistent with the convention used previously e.g. in Eq.(1.1).

3.Regarding two equations (Eq. 1.4), calling them collectively as Friedmann's equations is not a standard nomenclature: the first one is usually called the Raychaudhuri's equation, while the second one is the Friedmann's equation. However, I'm aware that there is currently a mess in this terminology.

3. Page 6 – definition of the critical density should be given in terms of H_0 and c. It would be a rigorous one. The approximate value quoted is as reliable as the value of H_0 assumed in it (by the way the quoted expression should better contain h^2 term, which the Candidate is aware of – see Table 1).

4. The discussion of the current total density ρ_0 is not careful enough. If the index X encompasses the curvature term too (as stated) then $\rho_0 = \rho_{crit}$ by definition.

5. Small inconsistency – sometimes spatial vectors are denoted with an arrow over the symbol, sometimes they aren't.

6. Introducing the Newtonian limit, the potential is denoted as ϕ but later as Φ. In general there are several places in the thesis when the reader might be confused by the actual meaning of ϕ, Φ and φ.

7. Chapter 1.5.1 – d'Alembertian was introduced as $\nabla^\mu\nabla_\mu$ what is then ∇^2 in Eq.(1.30)? Contextually one may expect 3-d Laplacian, but it should have been stated clearly.

8. Chapter 1.7.1 – chameleon mechanism; conformal coupling $e^{\beta\phi/M_{pl}}$ should it be ϕ or φ?

9.The meaning of ΔR has not been provided – supposedly it is the thickness of the screening shell. By the way, there is an ambiguity in using R here, since typically in the thesis it was understood to denote the Ricci scalar. What is the difference between r_C and R_C ?

10. Chapter 1.7.2 – it is not understood what is the Lagrangian radius $R_L(z)$.

Chapter 2.3 – regarding the HMF in the nDGP cosmology, while discussing Fig. 2.3 the Candidate writes, that "… the redshift-dependent trend in this ratio from the top panel is eliminated in the bottom panel after this substitution [rescaling] ..." I would say it is true for N1 model, while in the case of N5 it is only alleviated. I'm curious what is the reason for that, i.e. why the rescaling works perfectly for crossover scale of the Hubble horizon and not so well for larger scales ?

What is the rationale behind the choice of parametrizations used in Eq.(2.14) and Eq.(2.15) ?

Chapter 4 While, from the theoretical point of view, it was advantageous to discuss the dependence of HAB on intrinsic halo properties like concentration or spin, I'm wondering what is the practical relevance of the latter. Spins of halos or even of early type galaxies are not likely to be measured in any of the current or future galaxy surveys.

The above comments should not be perceived as a strong criticism, but rather a notification of minor drawbacks or expression of curiosity triggered by reading the thesis.

Summary

Thesis presented by M.Sc. Suhani Gupta contained an original solution of the well defined and important research topic and has demonstrated her solid knowledge and proper understanding of modern cosmology, in particular the theory of formation and evolution of the large scale structure in the Universe within the standard and modified gravity theories. It has also proven that M.Sc. Suhani Gupta has reached a level of scientific maturity enabling her to carry on an independent research.

Concluding my review, I declare that the dissertation meets the formal and customary requirements for a PhD thesis and recommend the Candidate to the subsequent stages of the procedure, including the public defense.

The thesis belongs to the top 20% of PhD dissertations I have had opportunity to evaluate. Therefore, I also propose the dissertation to be honored with distinction because of its scientific novelty, extensive research on a timely topic of the large scale structure formation, and a very good quality of the work done.

Prof. dr hab. Marek Biesiada

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Konkluzja recenzji rozprawy doktorskiej
(Conclusion of dissertation review)

Tytuł rozprawy *(Dissertation title)*: **„Linear and non-linear statistics of the cosmic density field in modified gravity cosmologies".**

Autor rozprawy *(Author of the dissertation)*: **Suhani Gupta**

☒ Pozytywna ocena *(Positive conclusion)*:
Stwierdzam, że przedstawiona mi do recenzji rozprawa spełnia wszystkie wymagania ustawowe i zwyczajowe stawiane rozprawom doktorskim i wnoszę o dopuszczenie jej do dalszych etapów postępowania doktorskiego, uwzględniając publiczną obronę.
*(I conclude that the presented dissertation meets the formal and customary requirements for doctoral dissertations and I recommend its admission to subsequent stages of the procedure, including the public defense.)**

☐ Ocena negatywna *(negative conclusion)*
Stwierdzam, że przedstawiona mi do recenzji rozprawa nie spełnia wszystkich wymagań ustawowych i zwyczajowych stawianych rozprawom doktorskim i dlatego nie rekomenduję dopuszczenia jej do dalszych etapów postępowania doktorskiego.
*(I conclude that the presented dissertation does not meet the formal and customary requirements for doctoral dissertations and therefore I do not recommend its admission to subsequent stages of the doctoral procedure.)**

Uzasadnienie powyższej oceny znajduje się w raporcie będącym załącznikiem 1.
(The justification of the above assessment can be found in the detailed report in the attachment 1.)

08.02.2024 [signature]
Data i podpis
(Date and signature)

Załącznik 1: Recenzja rozprawy doktorskiej
(Attachment 1: Review of the dissertation)

**Zaznacz ocenę (Please tick the box with your conclusion)*