Review of thesis “Linear and Non-linear Statistics of the Cosmic Density Field in Modified Gravity Cosmologies” by Suhani Gupta

Brief Summary

This thesis presents a study of how dark matter halo statistics are affected by departures from General Relativity. After a comprehensive introduction to the field, the first line of investigation is the halo mass function (HMF) in two particularly modified gravity (MG) models, namely f[R] gravity and nDGP gravity. Fitting formulae deriving the boost of the HMF relative to its LCDM equivalent are derived, and the universality of the HMF is probed. Next, these parameterisations for the HMF boost are used, together with other phenomenological relations, to construct a modified version of the halo model (HM) for nonlinear structure. The accuracy of the modified HM for the same two gravity models as above is assessed.

The fourth chapter of the thesis moves on to study the topic of halo assembly bias (HAB), that is, how halo properties such as spin and concentration vary in concert with the density of their local environment. Finally, the fifth chapter introduces the T-WEB classification scheme for cosmic structure based on eigenvalues of the tidal tensor. Various statistics of the density field (variance, skewness, kurtosis) and the HMF are assessed in different cosmic web environments (filaments, knots, voids etc), and again the different behaviour from LCDM is highlighted. The thesis concludes with indications of present work in progress and some future directions.

General Comments

In general I find the thesis to be well-written and scientifically detailed. The set of topics presented here hangs together well as a coherent body of work, with the later chapters sometimes drawing upon results of the earlier studies. The figures herein are generally useful and clear; the language is excellent throughout, and the incidence of typos is impressively low.

I appreciated that at the start of each chapter, as well as for the overall thesis itself, a detailed motivation is given describing why this particular study is needed by the field. Much of the technical work undertaken here is ‘up-close’; by this I mean that the text delves deep into the specific of how halo property X behaves in environment Y in gravity model Z, etc. There are a lot of permutations to be carefully interated through. There is less attempt to answer broad-brush questions. However, through this thesis the candidate is convincing that fine-detail studies are indeed what is needed to make progress in such a complex field. The relationship between changes to gravity and galaxy observables is infamously difficult to unpick.

One aspect which was slightly unclear to me was the relation of the latter chapters to published work. I see that chapters 2 and 3 are based upon published works. Chapters 4 and 5 seemed to contain a reasonable body of work that has not yet been published. I was left wondering if there were some technical difficulties I could not perceive that had prevented this. Or is publication on the cards after this thesis has been defended? Similarly, in section 6.5 indications were given for ongoing work, I was left unclear whether this was to be the work of the candidate directly, or of their home research group more broadly. If my understanding is correct, much of the research performed here was done using the

ELEPHANT simulations; it was not clear to me if the candidate was involved in running parts of these, or worked entirely using their outputs. This could be clarified at a thesis defense.

On the theme of simulations, one component which I felt was missing from the introductory material was a discussion of the literature of modified gravity simulations. The ELEPHANT simulation suite was adequately described in section 1.9, but there are many other implementations and techniques within the community. Some target specific code requirements, e.g. COLA implementations such as MG-PICOLA and Hi-COLA that have been developed for speed and flexibility, respectively, at a cost of accuracy on small scales. Others such as g-evolution and k-evolution incorporate relativistic effects. Other methods such as the ReACT framework aim to be a surrogate for simulations altogether, once sufficiently calibrated. I felt that the thesis would benefit from setting its work in the broader context of these other efforts. In particular, would the candidate expect that they would find similar trends for dark matter halos in other simulation suites as found in ELEPHANT? Or are particular reasons the ELEPHANT simulations are optimally suited to their work?

In a similar vein, I felt that the disucssion of modified gravity models in section 1.5 could have made a greater effort to look beyond the models studied in this work. f[R] and nDGP gravity have proved invaluable testbed theories, as presentative examples of two major screening mechanisms (chameleon and Vainshtein). However, both theories are strongly constrained (one might say virtually ruled out) as viable alternatives to LCDM. As such, their worth is as well-studied signposts of the broader theory landscape, not as 'good' models in their own right. I think it therefore befits the thesis to contain some pointers on other theories which might share screening mechanisms and phenomenology, or warnings which results may not transfer easily to other theories.

The nature of this work is that it often involves functional forms to describe boost factors of biases, e.g. section 3.2 contains multiple examples of this. Sometimes these are phenomenological fitting functions designed to capture some bump or trend in a ratio. But at other times (e.g. eq.3.14? Maybe eq.3.13?) it's unclear whether some of these might have an understandable physics basis. I'd appreciate it if the text clarified when such expressions are entirely phenonmenological, or where possible, tried to explain to form of these fitting functions.

Despite the requests above for an extended discussion in places, overall I find the thesis to be sound, representing a body of detailed work in an important and challenging area by the candidate. I am satisfied that the candidate has shown both theoretical understanding of their field, and the ability to develop their own independent research. *Therefore, I conclude that the presented dissertation meets the formal requirements for a Ph.D. thesis and recommend admission of the Candidate to the subsequent stages of the procedure, including the public defense.*

Below follow some more specific comments on each chapter.

<u>Chapter 2</u>

P35 The statements immediately below eq2.3 are quite hard to untangle physcially. Why does F(0), ie. the zero mass variance/small R limit give the fraction of mass in collapsed objects?
P36 Eqs.2.5 and 2.6 – it's not immediately obvious how these follow from the above. Is it possible to explain them a little more without reproducing all of PS74?
P37, eq.2.11. It's stated that this is the modified version of the above expression for ellipsoidal collapse, but it's not really explained physically.
P38 sec 2.2, halo multiplicity function F(\sigma). Is this the same F as F(M) or F(\nu) that appear above? I infer it's just the halo count expressed in term of lots of different variables?
In 2.3/related article, the existence of a universal halo mass function: the text indicates it's approximately obeyed by eye, but is too uncertain to be reliably used. Is this a dead end then? Is there some way to quantify its reliability?
P40 Why to the f(R) and DGP models produce different trends? Can this be explained in terms of their physics/screening? The text says it's an interplay of effects, but doesn't really elaborate.
I guess 2.14 and 2.5 are fitting functions. Do we expect these forms to be general for all gravity theories with a certain kind of screening?

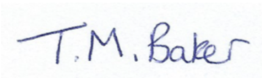
<u>Chapter 3</u>
Fig.3.1 – refers to a shaded region, this was very hard to make out on my pdf.
P64 – mentions analytical approaches to modelling the PS, but only gives references. A slightly more extended discussion would be useful here. What are the basic components/methods of these approaches? The candidate should show that they know.
P65 Eq.3.6 – "as the matter is not biased w.r.t. itself" + eq3.6 – please clarify, it's not immediately obvious where (say) the extra factor of M comes from.
P66 Eq3.8, the 1- and 2-halo terms. Should it be obvious why the sequence stops there? Can there be a 3-halo term?
P72, the text indicates that this approach could be opened up to much more general situations, other models of gravity and beyond. Could the candidate discuss what the challenges might be? How would one verify such models, if detailed simulations are not already available?

<u>Chapter 4</u>
Physics intro here is especially good, also in 4.2.1.
Fig 4.1, please remind me why the z=1 curve goes to higher log\nu than any of the others?
Eq.4.8, why does E appear here? It would seem at risk of a degeneracy with J, mixing ordered and randomly components? Would be useful to the reader to comment on this directly.

<u>Chapter 5</u>
Unclear if this chapter is linked to published work?
P115, second paragraph "we expect that the statistics…for each CW environment". How would this work in practice? Would there be a version of familiar statistics (power spectrum etc) conditioned upon environment? I understood the general principle, but couldn't quite get a clear picture of how this would be put into practice.
Bottom of p116 – setting of \lambda_threshold seems a bit arbitrary, what are the consequences of changing this?

End of p125 – this study has show the CW environment has clear measurable relevance in simulations, but what about in observables? Is it possible the ~5% changes seen here between MG and GR will be subsumed by larger observational systematics?
Fig.5.8 Comment on the noisiness of the data here.
Discussion around fig.5.9 – does this change any of the conclusions of chapter 2? I wonder if the preservation of the universal halo scaling relation looks like more of an `accident' now, as it clearly has to be averaged over CW environments to hold.
Fig5.13 – large errors on these curves, I think this is worthy of some commentary/explanation in the text.

Signature:



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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**

[X] 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.)

T.M. Baker 12/02/2024
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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)*