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To Whom It May Concern:

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Report on the PhD thesis by ENRICO LAUDATO entitled "A DHOST MODEL TO UNIFY THEM ALL "

The purpose of the candidate's thesis is to investigate the viability of gravity theories beyond General Relativity, in particular the so called Degenerate Higher-Order Scalar Tensor (DHOST) theories with a broken screening mechanism, by testing them with observational data from galaxy clusters and galaxies.

The thesis has an extensive and complete bibliography, and its research methods are well established, scientifically sound, clearly defined and properly used.

The structure of the thesis consists of 6 chapters: Chapter 1 is a concise but systematic introduction of present days cosmology and in particular to the evidence for dark matter and dark energy; Chapter 2 gives a thorough summary of the DHOST theories; Chapter 3 provides a detailed resume of galaxies and galaxy cluster properties that are relevant for the thesis work; Chapter 4 focus on testing DHOST theories at galaxy clusters scales; Chapter 5 aims at using ultra-dwarf galaxies´ properties to assess the viability of DHOST theories; Chapter 6 is a summary of the previous chapters results. The thesis concludes with a very complete Bibliography.

The core of the original and most important work of this thesis are in chapters 4 and 5. Therefore, I will only give a short summary of those bellow:

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In chapter 4, the candidate studies a modified theory of gravity belonging to the family of degenerate high-order scalar-tensor theories (DHOST) which have embedded the Vainshtein screening mechanism that render them viable at Solar System scales. However, these models are characterized by a partial breaking of the Vainshtein screening mechanism at clusters scales. The candidate studied this model in two different scenarios: the first, as a dark energy explanation, and the second as an alternative to both dark matter and dark energy. Such scenarios have been tested by analysing a sample of 16 high-mass galaxy clusters targeted by the cluster lensing and supernova survey with Hubble program using two complementary probes, namely X-ray and strong- and weak-gravitational lensing observations. The candidate has modelled the mass of the clusters by adopting a multicomponent approach including hot gas and galactic stellar contributions. For most of the clusters in the sample, results show some evidence in favour of the DHOST model as a description of dark energy over General Relativity. This model also appears to alleviate the discrepancy present in General Relativity between X-ray hydrostatic and lensing mass estimates. For the second scenario, where gravity acts as both dark energy and dark mater due to the partial breaking of the Vainshtein screening mechanism at cluster scales, the model is statistically disfavoured compared to General Relativity.

Chapter 5 focus testing DHOST theories with properties of Ultra Diffuse Galaxies (UDGs). These are a family of gravitational systems with quite varied properties, counting both objects highly deficient in dark matter and others which are dark matter-dominated. These systems are therefore very interesting to test Extended Theories of Gravity, as they show very different properties, including galaxies with a very low Dark Matter content, such as NGC 1052-DF2 and NGC 1052-DF4, and others that are Dark Matter dominated, such as Dragonfly 44. The idea is to analyse the kinematics of a sub-sample observed with the Dragonfly Telescope Array.

The candidate starts the chapter by considering a DHOST model to study the internal kinematics of NGC1052-DF2. The candidate then investigates two theoretical scenarios: one in which the model only describes dark energy; and one in which it additionally entirely substitutes dark matter. An important result that is found by the candidate is that the best model to explain the data is General Relativity with stellar contribution only. Despite that, the alternative model is not ruled out.

Afterwards, the candidate considers two systems, NGC1052-DF4 and Dragonfly 44, which are respectively dark matter deficient and dark matter dominated. For NGC1052-DF4, within General Relativity, the candidate shows that the galaxy dynamics can be described by a stellar component only. Within the framework of the DHOST, the candidate shows that the model is consistent with data and is statistically equivalent to General Relativity with cold dark. On the contrary, the analysis of the Dragonfly 44 concludes that it requires dark matter both in General Relativity and in the DHOST theory. When the latter is considered, only as a cosmological dark energy fluid, it is statistically equivalent to General Relativity. But when the candidate tried to use it to substitute dark matter the constraints on the theoretical parameters are in sharp contrast with those derived from more stringent probes from the stellar scales.

In the following, I will comment on some parts of the thesis that could be improved and some clarifications to the reader would be useful:

- The thesis would benefit from a language "polishing". It is in general well written, but it would benefit if the candidate would use a grammar corrector like "Paraphrasing" or "DeepL Write" to check for typos and small grammar errors for example.

- Chapter 1: Since this is a review/introductory chapter, I would expect to see a section summarising the challenges faced by ΛCDM on small scales. Is the candidate aware of the Core-Cusp problem, Too Big to Fail and Missing Satellites? Does he expect the DHOST model help solving or alleviate those problems?

- Chapter 2: Since this is a review/introductory chapter, I would expect to see a section that gives a more detailed overview (with the "pros" and "cons") on other theories of modified gravity, besides DHOST, that can be an alternative to dark matter. Could the candidate elaborate on how the DHOST as an alternative to dark energy and dark matter compares to other models like TeVeS, Gallileons or Moffat MOdified Gravity (MOG)?

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- Chapter 3: I would have liked to see a discussion about the main sources of observational and modelling errors and uncertainties related to the observables studied in this chapter and that will affect the model testing in the following chapters of the thesis. Could the candidate elaborate on them, and point out what would be the main source of uncertainty?

- Chapter 4: This chapter is published in *Mon.Not.Roy.Astron.Soc.* and it is clear and well written. Therefore, I have no comments. However, this is a collaborative publication, and since the candidate uses the term "we" in the thesis so I would like the candidate to describe what was his own contribution to the article and what were the collaborators' contribution.

- Chapter 5: This chapter is published in *Eur.Phys.J.C.* and it is clear and well written. Therefore, I have no comments. However, this is a collaborative publication, and since the candidate uses the term "we" in the thesis so I would like the candidate to describe what was his own contribution to the article and what were the collaborators' contribution.

- Chapter 6: While this chapter gives a detailed description, analysis and interpretation of the results of the thesis, it lacks a critical assessment of the possible shortcomings in the methodology and approach chosen, both from the theoretical modelling as well as the observational data analysis. It would like to have seen a section on what could have been improved in the methodology and what are the weak points in the approximations implemented. Also, in my opinion, this chapter misses a section on the possible future avenues and new directions to follow up this thesis research. Could the candidate elaborate on these 3 points?

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In summary, the thesis is quite impressive by its combination of technical power and physical insight. Moreover, it covers an impressive range of material. The manuscript shows that the candidate has both good mathematical skills and good physical insight. Moreover, the work presented shows that the candidate can independently conduct scientific projects and is not afraid to address new issues and to undertake long and complex computations, that he pushes to the end in a fully rigorous manner. The value of this work is of the best quality, regarding both its originality and the power of the results obtained. It is therefore of no surprise that several articles were published from its content.

In conclusion, the thesis meets *all the necessary criteria set in the Polish Act - Law on Higher Education and Science* - ***art. 187 ust. 1-2 act (Dz. U. Z 2023 r. Poz. 742 ze zm.).***

Yours Sincerely,

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