Universiteit Leiden
The Netherlands

Lorentz Institute & Leiden Observatory

Subject: Thesis review for Feven Markos Hunde

To whom it may concern,

This is my review of the thesis "T*he Role of the Cosmic Web in the Structural and Dynamical Evolution of Dark Matter Subhaloes*" by Feven Markos Hunde for the degree of Doctor of Philosophy in Physics awarded by the Center for Theoretical Physics of the Polish Academy of Sciences.

The thesis consists of an introduction, three main scientific chapters, and a conclusion bringing together the results obtained in the main chapters. The first chapter has been accepted for publication and the second one is under review. The third chapter is in an advanced state and is at the level required for submission (and acceptance) to a scientific journal. As such, the thesis consists of important body of scholarly work and is at the required level for the degree of Doctor of Philosophy in Physics. Overall, the work is very solid, well placed in the context of the existing literature and of direct relevance to modern cosmological surveys.

I comment below on the various chapters, mainly the three scientific chapters, and highlight their strengths and their contributions to the body of literature in the field.

Chapter 1 & 2 – *Introduction + Methodology*

This is a well-constructed and thorough introduction for a thesis of this kind. It builds a clear, logical story line so a reader unfamiliar with the field can follow the full chain of reasoning that motivates the thesis's central questions. The physics is presented with appropriate rigour, and the writing is careful to flag nuance where it matters, such as noting that the missing-satellites and too-big-to-fail problems are now considered largely alleviated once baryonic physics and selection effects are properly accounted for, and that the small-scale challenges section doesn't overstate ΛCDM's problems. I would particularly commend Ms. Hunde on this part as the debate in the literature has been strong.
The explicit three research questions at the end, and the chapter-by-chapter roadmap connecting each question to specific later chapters, is a strength.
Overall, these are solid, well-organized, and appropriately scoped introduction & methodology sections, with a good selection of references, that successfully sets up the thesis's central contribution: quantifying how cosmic web environment shapes subhalo populations and propagates into DM annihilation signal predictions. The discussion of the tools in Chapter 2 is well designed and is sufficiently critical of the weaknesses. All the relevant technical aspects are discussed.

Chapter 3 – *Caught in the cosmic web: Environmental effects on subhalo abundance and internal density profiles*

This chapter focuses on the fact that many dark matter annihilation models are expected to produce Standard Model particles and this is thus a potential indirect detection signal. The substructure within haloes significantly

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amplifies this signal, an effect called "subhalo boost factor." Until now, semi-analytic models (often informed by simulations) treated this boost as a universal function of halo mass, neglecting systematic variations induced by the large-scale environment. In this chapter, Ms. Hunde addresses that gap by explicitly incorporating how the cosmic web shapes the properties of subhalo populations. The process is built on earlier frameworks that were environment-independent.

Using environment-dependent ratios for host-halo concentrations, the subhalo mass function, and internal-structure proxies of subhalos based on the Vmax-Rmax relation, Ms. Hunde compute environment-conditioned boost predictions for haloes residing in filaments, walls, and voids. The main result is an expression of the boost factor at fixed host-halo mass relative to the cosmic-mean prediction. Clear environmental modulation is identified: filament haloes show a mass-dependent transition from roughly 15% suppression at low masses to about 12% enhancement for massive hosts, wall haloes sit at an intermediate level, while void haloes remain suppressed by roughly 30% across the explored mass range. These are deterministic model predictions (a key strength) and the chapter also provides an environment-aware prescription for subhalo boosts along with modular tools.

This chapter fills a genuine gap in the modelling done by the community. It moves beyond the common assumption that the boost is universal. An other key aspect is the use of multiple structural properties jointly. Finally, the prescription written as a ratio relative to the mean field results will allow other researchers to directly include the correction presented here in their work.

Chapter 4 – *Caught in the Cosmic Web: Environmental Impacts on the Halo Substructure Boosts to Dark Matter Annihilation Signals*

In this chapter, Ms. Hunde uses the COLOR n-body simulation and its CACTUS cataloging of environments to study how the host halo’s environment affects the internal structure of the sub-haloes. This would in-turn affect some of the results of Chapter 3. Ms. Hunde used three different mass bins to cleverly isolate the halo mass effect from the environment effect.

The results show that the subhalo mass function is strongly affected by environment: filament hosts typically contain 5–20% more subhaloes than average, while void hosts are “subhalo-poor”, with roughly 25% fewer. Additionally, the most massive subhaloes are the most sensitive to the environment classification. Subhaloes in filaments and walls are found to be more concentrated than those in voids. This could lead to biasing effects, including in the case of the famous “too-big-too-fail” problem in near-field cosmology.

This chapter combines two important strengths: A large sample and a state-of-the-art environment classifier. This leads to a very competitive (and unique) dataset from which the clear signal was extracted. The use of the equally weighted sample is also innovative in this field. I would commend Ms. Hunde for the strong statistical work performed here, which allowed for the clear identification of the trends and removal of confounding factors. Similarly, using multiple independent, but related, diagnostics allowed to build strong confidence in the results.

Chapter 5 – *Caught in the Cosmic Web: Environmental Effects on the Evolution of Subhalo Properties*

This chapter extends the earlier cosmic-web analyses by asking whether the environmental differences seen in z=0 subhalo populations are inherited from the infalling population or built up through post-accretion tidal evolution. Using merger trees built from the COLOR simulation and subhalo catalogues, Ms. Hunde tracks each subhalo's peak mass and peak circular velocity and compare these against z=0 values across environments and three host mass bins. The chapter finds that subhaloes lose a substantial fraction of their bound mass after accretion, while

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their peak circular velocity is far better preserved, since Vmax traces the more tidally-resilient inner potential rather than the easily-stripped outer envelope. Notably, environmental differences are already present at peak mass/velocity, showing they aren't purely a post-infall effect, as is often assumed, but they also evolve and even reverse over time.

Ms. Hunde later focuses on the mass accretion history of host haloes and the redshift evolution of the subhalo mass function and Vmax–Rmax relation along the main progenitor branch. Host halo growth histories themselves show only weak environmental dependence, but the subhalo abundance in different environments evolves in a non-trivial way across mass environment and redshift. Ms. Hunde thus demonstrates that the present-day environmental signal is not fixed at a single epoch but is gradually assembled through a mix of environmentally-biased accretion histories and differential, mass-dependent tidal stripping efficiency.

This chapter, though unpublished, presents some key results. The results clearly distinguish the pre-infall and post-accretion effects. That is something that is missing from the general litterature and is thus an important contribution. I encourage Ms. Hunde to submit this work to a journal.
The careful work tracking objects through merger trees and performing an analysis at multiple epochs is also strong and represents the state-of-the-art in the current published papers.

Chapter 5 – *Conclusion*

The conclusion is a good summary of all the scientific chapters above and places the results in the right context. The key contributions are highlighted. The future work section highlights the key area for improvements in the future: the extension to simulations with baryon physics inclusion. I would, indeed, encourage Ms. Hunde to pursue such an endeavour in the future. The link to forthcoming observations is also briefly discussed, which places the thesis in the context of upcoming surveys which will need the results of this thesis.

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.

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Konkluzja recenzji rozprawy doktorskiej
(Conclusion of dissertation review)

„The Role of the Cosmic Web in the Structural and Dynamical Evolution of Dark Matter Subhaloes"

Tytuł rozprawy *(Dissertation title)*: ………………………………………………………………………………………………………..

Feven Markos Hunde

Autor rozprawy *(Author of the dissertation)*: ………………………………………………………………………………………………

☒ 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.)

Dr. M. Schaller - 02/08/2026
M Schaller
…………………………..
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)