Report on the Ph.D. thesis entitled "Identification and characterization of strong gravitational lenses and low surface brightness galaxies using deep learning" by Hareesh Thuruthipilly (M. Sc.)

The doctoral dissertation presented by the candidate, M. Sc. Hareesh Thuruthipilly, deals with the application of (a specific class of) machine learning approaches to astronomical images, in order to find out the main properties and features that could help, in the very near future, to speed up, improve and extend the detection of specific astrophysical systems (strong gravitational lenses and low surface brightness galaxies).

The thesis is 147 pages long including a 15 pages of bibliography. It consists of: Chapters 1 and 2 which are introductory chapters, mostly from the literature review, but with Chapter 2 being also based on sections taken from the candidate's published works; Chapters 3, 4 and 5, are basically the author's publications; Chapter 6 provides a summary of the previous chapters and shows possible future developments.

The present work is based on 3 journal papers, of which (at the time of writing this report) 2 have been published and 1 has yet to be submitted and it is not available online as preprint. The 2 published papers have the candidate as first author. It is possible to find on arXiv and NASA ADS also two conference proceedings, a contribution to a volume of proceedings of the International Astronomical Union, and another published paper, although the latter one is not included in the present thesis and it is only cited as Grespan et al. (2024) in Section 6.2 on pag. 130. The total number of citations is 21 (including the proceedings papers), but I have no doubt that it will increase, since the topics and the methods developed here are at the core of the next future astronomy.

There are several typographical errors in the thesis that need to be corrected for publication: singular instead of plural, and vice versa; spelling errors, as in Chapter 5, pag. 109, where *"apartment magnitude"* is used instead of "apparent magnitude", or *"convolutional"* instead of "convolution"; wrong notation: there is a convention to use italic font for space-based experiments and normal font for earth-based projects, e.g. *Euclid* vs LSST; wrong naming: e.g., *large-scale structures* instead of large-scale structure, *cephid* instead of Cepheids, *Tully-Fischer* instead of Tully-Fisher.

I also notice a high degree of overlap between the introductory sections of the chapters. The collection of individual papers into a single work (thesis) could have been more homogenised.

Finally, I would like the candidate to clarify his role in the works on which this thesis is based. He appears as the first author, so I am sure he has had a relevant leading role. Initially, when reading the thesis, I thought that he had been mainly and largely involved in writing, testing and optimising the numerical codes which appear to be the main relevant core of this work. But after reading the last chapter, and seeing that he will be directly involved in astronomical observations (he plans to conduct an observing campaign and is co-investigator of two submitted proposals), and considering that many *"visual inspections"* were performed in the presented analysis, I would like to know more about this aspect as well, just to better remark and highlight his expertise and skills.

In the following, I will discuss the main criticisms and comments, divided into chapters, with the most urgent ones to be clarified by the candidate highlighted in bold.

1 Chapter 1

The chapter satisfactorily describes all the main ingredients of the current cosmological model(s), but I notice that most of the references are quite old. This might make sense while providing a historical excursus, but there are many newer and more updated references that could have been pointed out to establish the current state of the art.

A few clarification are required.

1. Pag. 3: the sentence *"This indicated that all the galaxies are moving away from each other and supported the argument that we are living in an expanding universe"* seems to implicate that a radial/distance dependence in the Hubble constant would exclude the possibility of an expanding universe. Instead, such a dependence, would point to a "differential" expansion not-consistent with the Copernican principle, but still (potentially) consistent with an accelerated expansion on large scales.

2. Pag. 5: given Eq. 1.2, it should be specified that the luminosity distance is measured in parsec. Also, strictly speaking, the distance modulus is defined as $m - M$.

3. I think that *"with the g-i color indicating the presence of an older stellar population"* should be instead "with a *larger g-i* color indicating the presence of an older stellar population".

4. Pag. 12: **the Hubble tension is between *Planck* and Riess et al. (SH0ES project), not with Brout et al. (Pantheon+), and it is at 5σ level. I would appreciate a clarification**.

5. Pag. 15: *"Strong gravitational lensing occurs as a consequence of general relativity"*. I think that the candidate has not properly communicated what he wanted to say. Gravitational lensing is also explainable and expected within Newtonian gravity, but this leads to an incorrect estimate of the deflection angle. The fact that general relativity gives the correct value does not necessarily mean that lensing is a consequence of general relativity.

6. **I think a more detailed technical description of gravitational lensing and measurable quantities is missing, together with a clear explanation of how they relate to cosmological parameters, if this is important for the purpose of the analysis.** Eqs. 1.8 and 1.11, as well as Fig. 1.9, come out of nowhere a bit, showing quantities and underlying concepts that have not been properly introduced before.

2 Chapter 2

I have a few comments about this chapter, which may sound naive because I only have a general knowledge of machine learning and neural networks, but I think that addressing them would probably also help the general reader interested in the topic.

Up to section 2.3 (included) the discussion is general but clear, and a reader can easily grasp the main concepts. But I have to admit that from Sections 2.4 and 2.5 it becomes much more difficult to follow the discussion, because many technical details are introduced without (in my opinion) sufficient explanation. For example, in relation to Eqs. 2.7-2.8, I don't understand what is meant by position, dimension, whether they are related to the structure of the network or to the input (as they are). Or what exactly and technically are the *"heads"* introduced in the discussion of self-attention in section 2.5.1, or what *"encoders"* practically do.

One thing that would have been appreciated, also to make the discussion a lot less abstract, would have been a clear, neat and more detailed (even pedantic) example of what has been done practically and technically with the data in use. It seems to me that this is limited to the caption of Figure 2.5. For example: what are these *"features"* of the input (the images of the astronomical objects) that are fed into the network? What are, in fact, the *"features learned"* and then transferred? Most of them can be guessed from the following sections, but I am still missing a single and simple example of what was practically done with what.

3 Chapter 3

This chapter is based entirely on one of the candidate's published works. I have no specific questions, just a few clarifications:

1. Pag. 37: *"Strong gravitational lensing is the phenomenon by which a distant galaxy or quasar produces multiple highly distorted images because of the gravitational field of the foreground galaxy or a nearby massive astronomical body."* It would probably have been more accurate to emphasise that the candidate was interested in a particular subclass of strong gravitational lensing events, those that produce Einstein rings. Indeed, strong lensing can also be produced by clusters, leading to a much larger (than 300) number of observable events.

2. Could the candidate say a bit more about Eq. 3.1 (or at least provide a reference)?

3. Pag. 57: *"However, for class 1, which represents the cases with an intermediate probability of being a strong lens, the 3-band Lens Detector performs poorly. This is to be expected since the 3-band Lens Detector is trained as a binary classifier."* **Can the detector(s) architectures be designed to go beyond binary classification?**

4 Chapter 4

This chapter contains material from one of the candidate's published works. As in the previous case, I have only a few questions to ask:

1. On pages 66, 97 and 102, it is said that the images have been resized. **It is not clear if this implies a loss of information and might impact the final results.**

2. Pag. 67: *"The hyperparameters for the all the LSBG DETR models were customized based on the results from Thuruthipilly et al. (2022), which extensively investigated the*

hyperparameter configurations of DETR models.”. **What exactly and practically is meant by *customisation*?** Although the methods are always applied to images, the physical problems are different between chapters 3 and 4. **Is this process somehow independent of the (physical) problem to be studied?** Section 5.3.3 introduces the concept of *transfer learning*, but it seems to be somewhat different (same physical problem, different surveys).

3. Tables 4.3 and 5.3: how is the stellar mass derived? Is the mass-to-light ratio calculated by the codes on the basis of some assumptions about the stellar populations?

4. Pag. 81: *“The slope of the number counts near 0.6 (representing Euclidean geometry) for both HSC and DES suggest that most identified LSBGs are local”*. **As someone not working on this topic, I am curious to know why this particular value implies Euclidean geometry and thus locality.**

5. Pag. 87: in what units is the R_{200}? I also see half-light radii expressed in *kpc*. Since these are physical units, what is the assumed fiducial background cosmology?

5 Chapter 5

This chapter is based on a paper which, at the time of writing, has not yet been published. It is an application of the methods developed in the previous chapter to brand new and dedicated data.

1. Pag. 96: *“In this paper, we adopt the cosmological parameters of* $(h_0, \Omega_M, \Omega_\lambda) = (0.697, 0.282, 0.718)$*”*. **Why this choice? The value of the Hubble constant is not consistent either with *Planck* or with SH0ES, and the same goes for the value of Ω_M.**

2. Pag. 100-101: in preparing images for transfer learning, it is stated that two approaches are more commonly used, i.e. rescaling to the range $[0; 1]$ vs. converting counts/seconds to surface brightness units (pixels). **Why was the second approach chosen? What are the main motivations behind this choice?** Also: **Does the lack of correct inclusion of differences in the PSF in the ML models have any consequences?**

3. Pag. 107: I don’t understand what the notation $h(0.01781) = 0.7023$ means.

6 Chapter 6

The possible uses and developments of the methods developed in this work are quite clear, and the candidate already seems to have a strong plan for the next future.

I have one curiosity, related to the “predictive” power of ML. On pag. 26, it is stated that *“One fascinating feature of the deep learning model is its capacity to generalise the data and go beyond the training data to apply learned patterns to new, unseen data”*. (N.B. I doubt that one can apply learned patterns to *unseen* data, since they are still *unseen*, not observed.) I am aware that the use of ML in this work is different, but **I would like to ask the candidate if**

ML could be used to discover *new physics*, as I often see a misuse of ML in the literature (not in this work).

The candidate states that he is *"...planning to develop ML-based segmentation models which are capable of separating the data of the SGL system into source galaxy, lens galaxy and background"*. **I wonder if he could give more details on how this will be achieved.** I suspect (but I am not an expert on the technical steps involved in analysing astronomical images of such events) that the identification of the source can come from a combination of spectroscopy and a total (i.e. stellar plus dark matter) mass modelling of the lens, which I think is probably beyond the capabilities of the ML codes developed in this thesis (but I could be wrong).

Finally, I have a question from the perspective of my personal research and interests: **For how many of these new LSB and UDG galaxies would it be possible to measure internal kinematics and dynamics? This is crucial for testing dark matter models or theories of gravity other than general relativity. Could the candidate elaborate a bit more on what can be achieved and by when?**

Conclusions

In my opinion, the dissertation meets all the necessary criteria set forth in the Polish Law on Higher Education and Science and fulfils all the necessary requirements to be submitted for the degree of Doctor of Philosophy. I therefore warmly recommend that M.Sc. Hareesh Thuruthipilly be admitted to the final defence.

Szczecin, 21.08.2024
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