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Referee 's report of the PhD thests of Mr Filip Morawski entitled „Application of machine learning methods in gravitational-wave detectors data analysis"

The PhD thesis of Mr Filip Morawski, written under the supervision of dr hab Michał Bejger and dr Elena Cuoco, describes an original work related to the analysis of the data collected by gravitational-wave (GW) detectors using machine learning. More specifically, the PhD candidate used machine learning to detect and reconstruct GW signals. He investigated various aspects of GW astronomy: both already detected types of Compact Binary Coalescence systems using a novel approach for searching for anomalies in the data and previously undetected systems such as Core-Collapse Supernova explosions and oscillating rotating isolated Neutron Stars. Mr Morawski also investigated the possibility of reconstructing Neutron Stars' physical parameters from a GW electromagnetic multi-messenger perspective using machine learning algorithms. In his thesis, Mr Morawski presented an excellent efficiency of artificial neural networks (ANNs) in hunting and reconstructing different types of GW signals.

The thesis is written in English, and it was prepared as a consistent collection of four articles published in scientific journals. It consists of six Chapters, including a complete introduction to the subject. The dissertation contains acknowledgements and two abstracts (one in Polish and one in English). At the very end of the thesis, one can find the literature (163 references in total). Mr Morawski also provided co-authors' contribution statements to fulfil the requirements for the PhD thesis written in the form of a collection of published articles.

Part I, the Introduction, describes in detail the history and state of the art of the GW astronomy and different possible challenges in data analysis. The last twenty pages of the Introduction are dedicated to introducing machine learning paradigms and algorithms, but the most extensive discussion concerns the assumptions and possible usage of artificial neural networks. This comprehensive description of a scientific problem is an in-depth introduction to the four scientific papers presented in the following parts of the thesis.

The main results, based on four published papers, form three main parts of the thesis:

Part II of the thesis presents a paper published in July 2021 in Machine Learning Science and Technology journal, titled "Anomaly detection in gravitational waves data using convolutional autoencoders" (hereafter **Paper I**) . This paper was written by Mr Morawski, both supervisors (Michał Bejger and Elena Cuoco), and Luigia Petre. Mr Morawski presented all needed statements of contributions signed by the co-authors. According to the statements, Mr Morawski performed 65% of the work for this paper. According to the Dimensions – the research information dataset, this publication has been cited once.

Part III consists of two Chapters:
Chapter 3 is based on the paper published in the Machine Learning Science and Technology Journal in May 2020, "Core-Collapse supernova gravitational-wave search and deep learning classification", written by Alberto Iess, Elena Cuoco, Filip Morawski and Jade Powell (hereafter **Paper II**). Mr Morawski wasn't the first author of the publication, but from the statements provided with the thesis, he contributed 40% to the total effort of this paper. According to the Dimensions, this publication has been cited 14 times.

Chapter 4 is based on the paper published in the Machine Learning Science and Technology Journal in June 2020, "Convolutional neural network classifier for the output of the time-domain *F*-statistic all-sky search for continuous gravitational waves", written by Filip Morawski, Michał Bejger and Paweł Ciecieląg (hereafter **Paper III**). According to provided statements, Mr Morawski contribution was 75% of the total effort for this paper. According to the Dimensions, this publication has been cited ten times.

Part IV was based on the "Neural network reconstruction of the dense matter equation of state derived from the parameters of neutron stars" by Filip Morawski and Michał Bejger, published in the Astronomy and Astrophysics journal in 2020 (hereafter Paper IV). According to the statement provided by Michał Bejger, Mr Morawski contributed 90% to this paper. According to the ADS - astrophysics data system – this publication was cited nine times.

The final summary and future perspectives are presented in a very short (one page) **Part V** of the dissertation.

Description of work and main results:

The **Introduction** is the only extensive part of the dissertation which was written on the purpose of the thesis. It contains a very detailed presentation on the topic of GWs and machine learning techniques. This part demonstrates that Mr Morawski can very clearly and in a didactic way present complicated interdisciplinary knowledge that he used to finalise his PhD thesis.

The second chapter,and at the same time the first paper from the collection of four articles, presents how GW detections can benefit in the future from autoencoder-based anomaly detection. In that work, GWs are defined as anomalies in the data and originate only from binary Black Hole system mergers. Using ANNs algorithms Authors of the paper were capable of detecting those anomalies after training on either simulated or real data. The method's efficiency was checked on all three confirmed gravitational waves used as a test case demonstrating the ability to detect gravitational waves that weren't used during the training process.

The second paper, presented in **the third chapter**, describes a search and classification procedure for GWs from previously undetected Core-Collapse Supernova explosions. For this purpose, a convolutional neural network (CNN) combined with an event trigger generator was used. To test the accuracies of the CNN classification, the five hydrodynamical simulations of neutrino-driven core-collapse with different zero age main sequences were used (both time series and spectrograms) to simulate Gaussian noise for Virgo O3 run and the future Einstein Telescope. Published results show that spectrograms are significantly better representations than time series as they are directly related to emission features expected from a Core-Collapse Supernova signal. Moreover, spectrograms should be able to distinguish between a Core-Collapse Supernova and some other kind of GW burst and from noise. This work also showed that the robustness of Core-Collapse Supernova search using CNN improves significantly with the future Einstein Telescope.

The fourth chapter (paper III) describes work that naturally follows paper II: in this work, Mr Morawski was searching for GW signal in oscillating rotating isolated Neutron Stars. Again he used CNN algorithms to classify GW signal candidates related to the continuous signal emission by deformed rotating Neutron Star. The novel approach presented in this paper is adopting signal candidates as the deep learning input instead of raw data. Moreover, using the time-domain F-statistic rather than individual candidates increases the significance of possible astrophysical signal detection. Additionally, in this work, Mr Morawski showed that the CNN method is able to distinguish GW signals from the detectors' artefacts and noise. This method achieved more than 90% accuracy to classify the GW signal using one-dimensional and 85% for two-dimensional CNN implementation. This method is highly accurate for sources characterised by low, continuous GW emitted by isolated Neutron Stars.

Paper number IV, presented in **chapter five,** shows the possibility to reconstruct the neutron star equation of state (EOS) based on the electromagnetic information (masses, radii) and/or the GW signal (component masses, tidal deformability during the system's inspiral). Together with his supervisor, Michał Bejger, Mr Morawski conclude that the ANN algorithm can be successfully applied in the precise reconstruction of the dense matter equation. For this purpose, the electromagnetic (masses and radii) or GW (masses and tidal deformability) measurements can be used. The detailed analysis of the Neutron Star mass function showed that the realistic distribution of this parameter based on presently known observations is insufficient for a detailed reconstruction of the EOS. To overcome this problem, many observations of massive stars are required. Also, the future telescopes and detectors (i.e. Einstein Telescope for gravitational observations) characterising much smaller measurement uncertainties can decrease reconstruction errors. They also show that ANN can be successfully used to reconstruct radius based on the gravitational observables – this ability can be particularly useful for gravitational astronomy.

The Chapter six, the last chapter of the thesis, and also the shortest one, consist of a summary and outlook. I was a bit disappointed at this part, as I was expecting an extensive summary of all four papers.

To conclude, the reviewed doctoral dissertation is a comprehensive study whose undoubted achievements are the successful implementation of machine and deep learning techniques to look for GW signals in very noisy data and how to use the reconstructed signals for scientific analysis. What is also stressed by Mr Morawski is the bright future for artificial neural networks (ANN) in the GW astronomy, even though the black-box nature of this method.

The thesis is written in very good English. I would also have to stress that Mr Morawski published three refereed first-author papers and one proceeding from the XXXIX Polish Astronomical Society Meeting. He is also a co-author of many publications of the LIGO Scientific Collaboration. I would like to say that all four articles presented in this dissertation are already cited in different scientific journals. All publications have a very comprehensive and complete Introduction. It is evident that Mr Morawski has a thorough knowledge of machine learning techniques and the possible disturbance of the GW signals.

Referee's comments

1. In my impression the description of papers used as separate chapters is too short. I would expect a kind of storytelling to show how different papers are connected and how they build a homogenous whole, especially as the dissertation has a form of a collection of articles. In total, 1.5 pages can hardly create a necessary justification why Mr Morawski chose this form of a dissertation. From my perspective, the detailed physical understanding of the process is more important than tests of ANNs performed on different samples. From used articles, it is evident that all tests were done to improve the GW signal analysis, but from the last two pages of the Introduction, one can have an impression that it is more about machine learning and less about the physics of astrophysical objects.
2. In my opinion, one paragraph (or appendix) is missing in Paper I which would describe the specific choice of physical parameters used for the electromagnetic simulation of the signal emitted by a binary black hole system. The Author used both masses and IMFs compatible with the first GW150914 but not GW170608 or GW170814. I think the additional analysis should prove this choice. I am also missing a paragraph to compare obtained results with additional simulations compatible with both GW (or only with the second or third). It was also not written what the 'relatively strong' signal of the GW detection means (Section 4.3) and why only those three events were chosen for the test.
3. I found information about the accuracy and efficiency of the ANN method in all presented papers but not about contamination. In Paper II an excellent total accuracy is shown (for example, Figs. 7 and 8), similar to Paper III. In my opinion, contamination, defined as the ratio of misclassified signals and the total number of signals classified by ANN as GW signals, is also an important factor determining the method's

usefulness. To summarise this comment, I am missing a dedicated discussion on the purity of the final classification.

4. There is no description of the alpha parameter for ADAM optimiser. In paper I alpha parameter is equal to 0.0005, while in the second and the fourth ones alpha=0.001. Why are those numbers so different between articles? What does it mean for the final results?
5. I was surprised reading Papers I and II that the model validation in the deep learning pipeline was done using only 10% of the dataset. Wasn't it too small to create a final conclusion? Paper III uses 20% of the dataset to validate the results, which sounds more reasonable to me. More surprisingly there is no validation sample in Paper IV. Why is so?

Minor comments:

1. I would sugget to use a different style of references (name and the year of the publication) instead of numbers – it makes reading more demanding.
2. In my opinion, the dissertation mises a table with all abbreviations used in the text and the attached articles. The thesis consists of acronyms related to gravitational-wave astronomy, statistics and machine learning techniques. The number of used abbreviations is large, and the thesis would benefit from such a Table a lot.
3. In the Introduction and Paper I, some figures are presented in an untidy way: lack of scale or axis description (i.e. Fig. 1.4 from the thesis – lack of scale on the y-axis, Fig. 3 from Paper I – no X nor Y axis' description, different scales in Figs. 7, 8, 9, 11, 12, 13 and 16 in Paper I which makes a difficult comparison between different samples and realisations). I am very surprised because it is the latest paper of the PhD candidate, and the other articles are much better edited.
4. Paper II – I couldn't find the description in the text for Fig. 4.
5. In the paper III, in the summary, it is written „This project is one of the few that research the application of DL as a supplementary component to MF". What the MF stands for in this sentence?

The comments presented above do not diminish the value of the work of Mr Morawski. In my opinion submitted dissertation provides new valuable input to the area of gravitational wave astronomy. The thesis written by Mr Morawski constitutes an original solution to a scientific problem of detecting and reconstructing gravitational waves signals. Presented introduction, as well as published articles, undoubtedly shows that Mr Morawski has good and solid knowledge in the area of machine learning application and the data analysis of gravitational wave detectors data analysis. Three first author papers and one second author paper also shows the PhD candidate's ability to independently conduct scientific work.

Summing up, I consider the doctoral thesis of Mr Filip Morawski to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to public defense.

dr hab. Katarzyna Małek