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Report on the thesis of Ms. Aleksandra Maria Olejak

Dear Members of the Scientific Council,

I have had the privilege of reviewing the doctoral dissertation titled "The origin of binary black hole mergers: Isolated binary evolution scenarios with and without a common envelope phase" submitted by Ms. Aleksandra Maria Olejak under the supervision of Prof. dr hab. Tomasz Bulik.

Ms. Aleksandra Maria Olejak's research dives deep into a paramount question in astrophysics: the origins of binary black (BH) hole mergers detected by gravitational wave (GW) detectors. This area of study, though intensely explored, still leaves many questions unanswered. Ms. Olejak meticulously investigates the properties of gravitational wave sources formed through the isolated binary evolution channel. Her dissertation places significant emphasis on the criteria for unstable mass transfer (commonly referred to as the common envelope) in massive stellar systems and the nuances of core-collapse supernovae physics. Throughout her doctoral work, Ms. Olejak has used a technique known as binary population synthesis to test different assumptions regarding the aforementioned astrophysical processes and infer their signatures in the observable properties of gravitational wave source populations. Namely, her research reveals how different assumptions in core-collapse supernova physics and criteria for common envelope development can influence event rates, mass distribution, system mass ratios, and spins of coalescing double compact object (DCO) populations, offering invaluable insights into the mechanisms behind these cosmic phenomena.

After Chapters 1 and 2, where Ms. Olejak introduces the field of gravitational-wave astronomy and astrophysics and the main methodologies used in her work, in Chapter 3, she uses as an example the GW190412 event, to study the formation of unequal-mass coalescing binary BHs (BBHs). The detection of the GW190412 event marked the first observation of a highly unequal mass BH-BH merger, causing significant excitement in the GW astrophysics community. Contrary to prevailing expectations, the research suggests that such mergers can arise from isolated massive binary star systems evolving in the galactic field, challenging the notion that they are primarily products of hierarchical mergers. The research presents an evolutionary track of a GW190412-like progenitor system, where the system undergoes an unstable mass transfer phase, leading to a tightened orbit. As the system evolves, the first-formed BH tidally accelerates its companion, the naked helium core. This scenario aligns with both the masses and the effective spin parameter observed for the GW190412 merger. She finds that although the majority of BH-BH formation channels typically produce mergers with similar masses, the classical isolated binary evolution channel can indeed produce mergers like GW190412. She also concludes that If more than 10% of BH–BH mergers demonstrate significant in-plane spin components, the common envelope isolated binary formation channel might be excluded as their origin.

Chapter 4 explores the two main sub channels for the formation of coalescing BBHs via the evolution of isolated binaries, namely the CE channel and the stable Roche-lobe overflow (RLOF) channel. Understanding how wide stellar binaries evolve into compact systems, especially BBHs, involves a deep dive into the CE(CE) concept. However, the exact mechanisms and nuances of this CE evolution remain somewhat mysterious, and many rapid population synthesis models may oversimplify the process. Recent studies have suggested a conservative nature for developing dynamically unstable mass transfer in massive binary systems. This new insight posits that even when a CE develops, it's challenging to bypass a stellar merger. The only scenario where a CE ejection seems probable is when the donor star is a specific type of red supergiant. Incorporating these new insights, Ms. Olejak adjusted the criteria for CE development in her population synthesis models. These adjustments primarily pertained to massive binary systems, leading to the prediction of BBHs mergers through two stable mass transfer phases. Mass transfer stability in these massive systems, although crucial, is not well-understood. It's evident that stable mass transfer might not tighten orbits as effectively as CE, which has implications for the predictions about gravitational wave sources. Ultimately, this chapter underscores the profound influence of RLOF physics assumptions on predictions made by population synthesis models. The significant differences in predictions of GW observables based on various assumptions accentuate the need for caution when interpreting results from stellar and binary evolution models in light of LIGO/Virgo findings.

In Chapter 5, Ms. Olejak explores the origin of highly spinning BHs in coalescing BBHs and explores some of the uncertainties in the physical processes discussed in the previous chapters. The BH spin measurements from the GW signal of coalescing BBHS can offer insights into the evolution of massive stars and the origins of these GW sources. Current data reveals that most BHs have low spins, but there is a segment with high spins. The population synthesis model presented in this chapter shows that under the assumption of efficient angular momentum transport and potential tidal spin-up in certain evolved binary systems can produce a spin distribution that aligns with data from the LIGO-Virgo collaboration (LVK). However, the specific pathway to high-spin BH-BH mergers varies based on the criteria for developing a CE phase. This chapter also highlights the correlation between the effective inspiraling spin (χeff) and the mass ratio (q). In scenarios with stable mass transfer, BBH mergers with nearly equal mass components tend to have low effective spins, while those originating from the CE channel tend to have unequal mass components and display a broader range of χeff values. A novel finding compared to other studies int eh literature on the same topic is a pathway that leads to the formation of highly spinning primary BHs. Furthermore, the importance of understanding the initial stellar rotation, the efficiency of angular momentum transport, and the strength of tidal interactions in close binaries are highlighted. These factors, though not well-defined, are crucial to deciphering the observed spin characteristics.

Chapter 6 underscores the significance of understanding the core-collapse supernovae (SNe) mechanisms and in deciphering astrophysical phenomena involving compact objects. This study's key element is the introduction of new formulas that encapsulate the relationship between a star's attributes before a supernova and the remnants they birth, and their influence on the population of double compact object (DCO) mergers. These formulas are versatile, allowing for a nuanced analysis of the convection growth time, which in turn offers insights into the presence or absence of a pronounced mass gap in neutron star and black hole masses. Rapid supernova models can result in a more pronounced mass gap, while models with a more prolonged convection growth can significantly reduce this gap. Ms. Olejak finds that the mass distribution of DCO mergers, specifically the masses of the primary and secondary components, is intrinsically sensitive to the supernova model in use, especially for total merger masses up to about 35 solar masses. One particular supernova model brings forth the possibility of the creation of a significant fraction of massive neutron stars, which could elucidate the origins of notable systems like GW190425. Furthermore, the chosen supernova model has a profound effect on the mass ratio distributions of BH-BH mergers, especially when considering the common envelope formation scenario. The local merger rate densities for BH-NS mergers also exhibit sensitivity to the supernova model. This chapter also delves once again into the nuances of the CE development criteria, revealing that while they majorly influence BH-BH mergers, their impact on BH-NS mergers is more subdued. NS-NS binaries, however, seem to remain unaffected by these criteria. The take-home message of this chapter is that while models that hint at a partially filled lower mass gap align well with current observational data, one should still be cautious in drawing conclusions that can be generalized.

Concluding, I would like to emphasize the outstanding quality of Ms. Olejak's thesis work, which resulted in 4 first-author publications and valuable contributions to over a dozen more. Her approach is both comprehensive and timely. She displays an adept understanding of the theoretical underpinnings of her discipline and skillfully marries this with carrying out and analyzing complex numerical simulations, demonstrating her ability to independently conduct scientific work.

Nevertheless, while reading the thesis manuscript, some questions arose that I believe can be addressed during the oral defense or with minor edits to the manuscript. I list these questions below.

1. In Chapter 3, a new prescription is introduced to treat thermal-timescale mass transfer. Knowing that thermal timescale mass transfer is one of the weak points of rapid binary population codes, I would appreciate a more in-depth explanation of what is the motivation of the new prescription, why it could be a more physically accurate treatment of the phenomenon, and how its predictions compare to detailed binary evolution calculations.
2. On page 40 of the manuscript, it is mentioned: “Binary separation […] is reduced as the donor mass is ejected from the system with the orbital angular momentum during stable RLOF”. In many other models in the literature, the standard assumption is the mass lost to carry the specific orbital angular momentum of the accreting star. Please justify the choice and explain what are the expected differences in the final orbital separation in systems of interest.
3. In the first formation scenario described in Table 1 (Page 41), there seems to be the possibility for a reverse mass transfer, initiated from the secondary star (noted as MT2(7-4)). Is my interpretation of the notation correct? If that’s the case, I would expect that after MT2 the secondary star would be a stripped helium star as well. In this case, I do not understand how we could have a MT2(14-2/4/5/7/8) after forming the first-born BH. Can you please elaborate?
4. On pages 42 and 43 there is an extensive discussion on how the mass distribution depends on the assumptions about the stability of mass transfer and the details of how one treats thermal-timescale mass transfer. One very interesting signature is the “break” in the distribution. Could you elaborate on what are the underlying physical factors that determine the position of the break, as well as the slopes on either side? Are there different sub-channels dominating at different mass ranges that cause the break? Is the slope on the power laws signatures of some specific physical process?
5. On the same topic, M480 seems similar in assessing the stability of t mass-transfer with the standard model of the COMPAS code. Yet, I see qualitatively different BH mass function compared to the study of van Son et al. (2022) that studies the same topic; specifically, a peak at ~9 solar masses that is not present in the M480 model and has been claimed to originate from the limits of mass-transfer stability. A more in-depth comparison between your study and the one by van Son et al. would be very helpful.
6. In Figure 16 (page 50), it is not clear what are the dots and the dashed lines.
7. In Chapter 5, you find that a typical formation pathway for forming BBHs where the more massive BH is highly spinning starts with a case-A mass transfer between main-sequence stars, where the more massive one loses more than 80% of its mass, and the secondary almost doubles its mass. Is this always the case? If so, how robust are the model’s predictions given the weaknesses of rapid population synthesis codes in treating case-A mass transfer?
8. On page 55 you mention, “Note, however, that we have not used the physics input here that allows for the formation o fBHs with masses over 50 solar masses.”. Given that in the LVK detections, the primary BHs that appear to be highly spinning are massive, can you please expand on this point?

Summing up, I consider the doctoral thesis of Ms. Alexandra Maria Olejak 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 a public defense.

Yours Sincerely,

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