This dissertation is very unique in the sense that it aims to predict astronomical observables of a possible Quantum Chromo-Dynamical (QCD) phase transition in compact stars. In this context, there are several preceding studies, which, however, have been carried out in an approximate way with respect to the treatments of neutrino-radiation hydrodynamics and the QCD physics. Going far beyond such previous studies, the results of this dissertation are based on full-Boltzmann, neutrino radiation-hydrodynamics simulations in full general relativity (GR) of massive stellar core-collapse, only by which the aim of this dissertation, namely, to predict the observational signals of the QCD phase transition, can be achieved. In fact, this thesis contains a significant amount of important results to achieve the scientific goal. By this, I can judge that this dissertation can be accepted as a successful PhD thesis and Ms. Largani is rightly bestowed a PhD degree from the Faculty of Physics and Astronomy, University of Wroclaw.

In what follows, I summarize briefly novel aspects of this dissertation with some suggestions and comments, which I am happy if the defendant (Ms. Lagarni) could think them useful for possible revision.

In Section 1, this dissertation starts with a concise summary of core-collapse supernova (CCSN) theory. Particularly, it is impressive that the candidate mechanisms of CCSN is accurately explained, whereas the "acoustic" mechanism seems to be outdated at present. Even the Princeton group does not mention it in their most recent publications. I may suggest that the acoustic mechanism can be removed here or included only in the footnote.

Section 2 describes the foundation of neutrino-radiation hydrodynamics simulation and the numerical schemes. It summarizes important formulation of the AGILE-BOLTZTRAN code, which is the workhorse of this dissertation. In addition to the GR hydrodynamics (hydro) schemes, this Section also describes the detailed treatment of microphysics including the collisional terms in the Boltzmann equation and how to solve it in a consistent manner with the GR hydro. In this sense, this Section is informatively rich, so much so that I can judge that this Section provides a useful, sort-of guide book for broad researchers in this field. Among major updates added to the code, the inclusion of convection via the mixing length theory (MLT, page 72-75) is unique. From Figure 2.7, one can see the comparison between the results with and without the MLT, showing only minor differences between them. If it is possible, I would recommend that the comparison more up to the late phase could be investigated, by which the importance of MLT can be understood.

Section 3 summarizes Equation of State (EOS) employed in this dissertation also with the treatment of the QCD phase transition in detail. As clearly written in this dissertation, the physics of the (first/second-order or cross-over) phase transition(s) has not been understood unambiguously yet. However, it is true that the best available and rich variety of the EOSs are indeed considered in this dissertation, which is scientifically significant. Regardless the differences of the EOSs, it is interesting to note that the so-called universal relation is obtained. As a small note, at page 95, see “Table 3.1” should be “Table 3.2”, and the meaning of indices of RDF such as from 1.1 to 1.7 could be better explained (what does “1.1” mean physically? For example, does this relate with the strength of the phase transition?).

Section 4 describes one of the main results, CCSN simulations covering a wide range of progenitors 25 – 40 solar-mass using the representative EOSs with the phase transition carefully chosen from the outcomes of Section 3, namely via recent observation of gravitational-waves (GWs) and the neutron stars (NSs). Among the findings, it is particularly novel that this dissertation points out the two channels (namely, prompt vs. delayed collapse of a proto-neutron star (PNS) into a black-hole (BH)), which provides important and unique probe into the physics of BH formation via the neutrino signals. Moreover, the dependence of the time interval between the first (neutronization) and second bursts (Figure 4.8) with respect to the stiffness of the RDF EOSs, newly found in this dissertation, is also of high scientific significance. On the other hand, the physical origin of the linear relations (Equations 4.10 – 4.12) is not very clear to me, which could be provided if possible. In Figure 4.9 (panel (e)), the relation between the explosion energy and the latent heat is plotted, which is mentioned to have no clear correlation. But, why is it so? (naively one may speculate that bigger latent-heat release could help explosion). Any comments/speculations could be added.

Section 5 focuses on NSs in accreting systems as the possible appearance of QCD phase transition. For representative models, it is important that this dissertation points out an observable signal for the current generation of water-Cherenkov detectors for a galactic event. On the other hand, the expected event numbers of the signals for the detectors seem to be yet estimated. If the defendant could have time, I would recommend to give an estimate for this. If the defendant could get a number regarding the occurrence probability of the accreting NSs in our Galactic center, this could be also informative.

Section 6 describes the GW emission properties estimated by means of the linear perturbation analysis via the so-called asteroseismology. The obtained results such as the time evolutions of the fundamental (f), buoyancy-drive (g) modes in the GW spectrograms are consistent with previous studies. I would add that the confirmation of this is scientifically significant because the impact of the EOSs with the phase transition is investigated in a systematic way (namely both in the CCSN and the accreting system contexts), for the first time, in this dissertation.

Section 7 provides summary and conclusions of this dissertation. Here the essential findings of this dissertation (Sections 3-6) are concisely provided, which I judge as persuasive and (again) impressive. Several limitations of the numerical schemes and exciting possibilities of extending the contents of this thesis for future researches is also described, which is judge as reasonable. As a final comment, I would like to ask the defendant what an emerging theme (a landscape view) could be obtained from this dissertation, namely what we can learn about the phase transition physics if we could succeed to detect both the electromagnetic-wave, neutrino, and GW signals for example from a Galactic event? This is one of the aims of the multi-messenger astrophysics, right? I understand that the correlation analysis between the neutrino and GW signals is beyond the scope of this dissertation, but if you could give us some scenarios to this end, I think it invaluable. For example, one may could speculate that a 40 (or 50?) solar-mass progenitor star with the phase-transition (again, this is a hypothetical case) lead to hyper-energetic explosion (a large amount of nickel production?, light curve signature?), leading to the second neutrino burst, which would also cast a ramp-up f and g modes in the GW spectrogram. This dream scenario could not be the case for a 25 (or 11.2?) solar-mass case. Any comments towards such multi-messenger perspectives could be given in this thesis, which further brightens the value of this dissertation, I believe.

Having written the comments above, I can reassure myself that this dissertation, consisting of the published results that the defendant has made so far with huge efforts and admirable enthusiasms, reaches well above a level of PhD thesis. I recommend Ms. Largani to be awarded a PhD degree from University of Wroclaw.

June 12th 2025,

K. Kotake