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Subj: Report on the Habilitation Thesis “Eksperymentalne sygnatury kosmologicznych przemian fazowych” (Experimental signatures of cosmologic phase transitions) by Dr Marek Lewicki

Dr Lewicki has submitted a Habilitation Thesis on “Experimental signatures of cosmologic phase transitions”, which is a topic of fundamental research in a branch of Theoretical Physics concerned with Cosmology and Astroparticle Physics.
The work is of high actuality since its results are important for the interpretation of ongoing and future measurements with gravitational wave (GW) observatories.

The Thesis consists of a cycle of seven articles [H1-H7] published in leading refereed journals with high impact factor. These works of a collaboration with John Ellis, Ville Vaskonen or Jose Miguel No are explained in Section 4 of the Thesis.
The main articles are authored in alphabetic order and despite the fact that all coauthors including the candidate describe in their letters the contributions they made to the corresponding publications, it would have been desireable that the coauthors also estimate the percentage to which their contribution amounts.

The Thesis presents a rich body of frontier research work in a well structured and logic manner. It is formulated in very good English language with only a few typos*).

In the following, I shall review more in detail Dr Lewicki’s new contributions to the problem of phase transitions (PTs) in cosmology and their experimental signatures, as they are outlined in Section 4 of his habilitation Thesis and the publications [H1-H7].

In the Introduction (Subsect. 4.3), Dr Lewicki characterizes the general idea and the importance of the direction of the Thesis. While the Large Hadron Collider (LHC) did not produce signals of particles that were expected from Theories beyond the Standard Model (SM), the GW detectors LIGO and Virgo opened the window of GW astronomy. Through this window, one would “see” signals from the era of cosmic evolution <u>before</u> the decoupling of the cosmic microwave background radiation that is detected using the standard photon-based techniques. The instruments for such investigations would be the future generation of GW detectors: LISA, AION and AEDGE, where Dr Marek Lewicki is involved as one of the main authors of the whitepapers. But already the presently operating NANOGrav experiment recently

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reported the possible presence of a stochastic GW background that could be of cosmological origin, see Fig. 1 of the Thesis. The work of Dr Lewicki lays a basis for investigating the physics of cosmological PTs a few seconds after the Big Bang by the traces they left in the GW spectrum.

In Subsection 4.4, Dr Lewicki points out the basic feature of first-order PT dynamics which leads to an observable GW signal. It is the formation of bubbles, their growth and nucleation (collision). Since the expansion of spherical bubbles cannot produce gravitational waves, it is the final stage of the transition, when the bubbles collide, which can be investigated through GWs. It is this still rather poorly understood final part of the first-order PT to which the series of articles [H1-H7] is devoted.

Subsection 4.5 is devoted to the energy budget of a 1st order PT which tradtionally (as in the popular LISA cosmology group review [61] from 2015) was divided into three contributions: 1) collision of bubble walls, 2) sound waves and 3) turbulence in the plasma. The general predicton was that in a very strong transition all three would give non-negligible contributions. Due to the work of Dr Lewicki these predictions were severly modified and the revisions entered the updated LISA review of 2020 [69].
In particular, the author showed in [H4] that in order to store a significant amount of energy in the bubble walls a sufficient supercooling is necessary, which would severly dilute the plasma surrounding before the bubble nucleation starts, so that the friction with the surrounding plasma is diminished. This requires the higher order extensions of the SM featuring a polynomial potential to consist of terms which are all of the same order so that an effective action with two minima and a barrier between them results. This, however, leads to problems with the percolation of the bubbles at the end of the transition and, as shown in [H7], creates a division in two classes of models: the ones where the transition is present at the classical level with a polynomial potential and the ones where symmetry breaking is triggered by quantum corrections with a logarithmic shape of the potential. In [H6] a detailed calculation of the efficiency of GW production in polynomial models has been performed. In [H2], a novel effect was obtained which consists in a brief period of matter dominated expansion that produces a plateau in the GW spectrum at low frequencies, a smoking gun signal in the stochastic GW background!
Concerning sound waves and turbulence, the works [H7] and [H6] have triggered the second major development in the updated LISA review [69]. Dr Lewicki showed in [H7] that the sound wave source is not active over a full Hubble time as was assumed before, but develops into a non-linear regime that ends the sound wave era and makes possible the early onset of turbulence as an alternative source of GWs, of similar importance as the sound waves [H6].

In subsection 4.6, Dr Lewicki discusses the results of the computation of the GW spectrum for very strong transitions, where the plasma dynamics can be neglected.

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The corresponding works are published in [H1], [H3] and [H1]. Dr Lewicki introduced an alternative to the 3D lattice simulation that runs into severe problems with the resolution when bubbles grow by many orders of magnitude and sharpen their profiles before they collide. In the calculation method developed by Dr Lewicki one keeps track of the evolution of bubbles and GW sources individually. This removes the lattice resolution problem and allows to paint a complete picture of the transition even on cosmological scales. The progress achieved with the new simulation method in [H5] is that one could perform simplified lattice calculations of collisions of pairs of bubbles and thus to model the behaviour of the field also after the collision, while the previous modelling assumed the thin-wall approximation and that the walls would just disappear after the collision. Unfortunately, in Fig. 5 the left panel (a toy potential) is missing!
In [H3] and [H1] the candidate showed that including the field gradients as sources f GWs also after the initial collision changes the resulting spectrum dramatically. While in [H3] only a scalar field was simulated, which corresponds to global symmetry breaking, in [H1] also interactions with gauge bosons were included which allowed to describe local symmetry breaking. The characteristic features of the corresponding GW spectra are shown in Fig. 6. In contrast to usual lattice simulations constrained to use simplest possible polynomial potentials, the simulations in [H3] and [H1] were using realistic potentials. For instance, at extreme supercooling, one needs a scale invariant logarithmic potential [H6]. The importance of the choice of potentials is demonstrated in Fig. 7 for the effect of vacuum trapping which is crucial for the low-frequency part of the GW spectrum and affects the large scale structure of the sources.

Beyond the excellent scientific results that were reported in Section 4 on the main achievements of the habilitation Thesis based on the works [H1-H7], Dr Lewicki has an impressive oevre that contains also the works [O1-O33] which are put into the context of the Thesis in Section 5. Particular mentioning deserve the aspects of PT phenomenology outlined in subsection 5.1 and the effects of cosmic strings as explained in Subsection 5.2. As it was shown in the main part of the Thesis [H7], a significat amount of energy released in a PT can be transferred to turbulence in the plasma. As the candidate showed in [O9], the turbulence could be the source for a magnetic field (with a helical component) strong enough to explain current observations. Further investigation revealed that helical turbulence would produce a circularly polarised spectrum of GWs which could be detected by LISA provided the underlying PT is strong enough, as was shown in [O3].

Another important line of Dr Lewicki's research in the past few years concerns cosmic strings, which are topological defects that could have been produceed in the early universe and that would produce GWs as the cosmic string network evolves with the expansion of the universe. In [O14] and [O12], Dr Lewicki has proposed a new method that allows to probe the cosmic expansion in an era much before any currently known

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data. In [O1] he investigated the recent excess in data taken by the NANOGrav collaboration which could be a precursor for the first discovery of a stochastic GW background. This publication in Phys. Rev. Letters has been chosen as Editor's suggestion and resulted in popular news outlets!

It is important to note that Dr Lewicki has a strong collaboration with the three big GW experiments of the next generation: LISA, AION and AEDGE, for which he worked in the writing teams of the whitepapers [O6], [O5] and [O7], respectively. This is an important aspect of the habilitation as an independent scientist who is qualified to lead a scientific group.

For his publications, Dr Lewicki has earned by the time of submission of the Thesis an h-index of 20 in the INSPIRE database (meanwhile 24, without self-citations). This level is above the international standard for a professor position.

The maturity of Dr Lewicki as a researcher is documented also by his success in acquiring research grants as principal investigator. Starting with the smaller NCN Preludium and Etiuda grants which he acquired already before his PhD Thesis defense and Iuventus Plus as a young researcher, he is presently holder of two serious long-term research grants, NCN Sonata (2019-2023) and NAWA Polish Returns (2020-2024). This is an extraordinary success for a young postdoctoral researcher!

Summarizing, I conclude that the habilitation Thesis and the scientific activity of Dr Marek Lewicki fulfil all necessary criteria for promoting him to a habilitated doctor in the physical sciences. I recommend the Thesis to the Faculty for its acceptance.

David Blaschke

Wroclaw, 26.10.2022 Prof. dr hab. Dr h.c. David Blaschke

*) List of typos:
p. 2, first 10 lines of Sect. 4.3: nine missing articles “the”
p. 3, line 3: ... the observation of a collision ...
1st paragraph: form --> from, ... earlier than the standard ...
p. 4, around Eq. (3): generally --> Generally, comma after Eq. (3), depends --> depend
p. 5, last line: form --> from
p. 6, line 6 from below: “... with nearly with ...” - one “with” can be removed
p. 7, line 6 from below: witch --> which

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p. 8, 2nd line above Sect. 4.6: Turbulence --> turbulence
   1st paragraph of Sect. 4.6: there is no left hand side with the toy potential in Fig. 5
   line 6 from below: at in --> at
p. 9, 4th line: each on --> each one
p. 10, line 4 and line 6: of --> off, line 9: delete a superfluous “while”
p. 12, line 10 from below: delete a “verify”, 4 lines lower: ammend --> amend
Bibliography:
Ref. [59] identical with Ref. [105]