1 Name

Marek Lewicki

2 Education

- 2012: Master of Physics at the University of Warsaw
  Low energy implications of high energy boundary conditions in SSM
  Advisor: prof. Zygmunt Lalak †
- 2016: PhD at the University of Warsaw
  Aspects of electroweak symmetry breaking in light of new data from the LHC
  Advisor: prof. Zygmunt Lalak†

3 Academic career

2016-2017	University of Adelaide Postdoctoral researcher
2017-2020	King's College London Postdoctoral researcher
2020-present	University of Warsaw Assistant professor

4 Indication of achievement resulting from art. 16 sec. 2 of the Act of 14 March 2003 on academic degrees and academic title, and degrees and title in the field of art.

4.1 Title of the scientific achievement (series of articles):

Experimental signatures of first-order cosmological phase transitions

4.2 Series of articles:

[H1] Marek Lewicki and Ville Vaskonen. Gravitational waves from colliding vacuum bubbles

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in gauge theories. *Eur. Phys. J. C*, 81(5):437, 2021. arXiv:2012.07826, doi:10.1140/epjc/s10052-021-09232-3
Impact Factor (IF): 4.59, citations: 14

[H2] John Ellis, Marek Lewicki, and Ville Vaskonen. Updated predictions for gravitational waves produced in a strongly supercooled phase transition. *JCAP*, 11:020, 2020. arXiv:2007.15586, doi:10.1088/1475-7516/2020/11/020
Impact Factor (IF): 5.21, citations: 26

[H3] Marek Lewicki and Ville Vaskonen. Gravitational wave spectra from strongly supercooled phase transitions. *Eur. Phys. J. C*, 80(11):1003, 2020. arXiv:2007.04967, doi:10.1140/epjc/s10052-020-08589-1
Impact Factor (IF): 4.59, citations: 26

[H4] John Ellis, Marek Lewicki, and José Miguel No. Gravitational waves from first-order cosmological phase transitions: lifetime of the sound wave source. *JCAP*, 07:050, 2020. arXiv:2003.07360, doi:10.1088/1475-7516/2020/07/050
Impact Factor (IF): 5.81, citations: 53

[H5] Marek Lewicki and Ville Vaskonen. On bubble collisions in strongly supercooled phase transitions. *Phys. Dark Univ.*, 30:100672, 2020. arXiv:1912.00997, doi:10.1016/j.dark.2020.100672
Impact Factor (IF): 4.24, citations: 19

[H6] John Ellis, Marek Lewicki, José Miguel No, and Ville Vaskonen. Gravitational wave energy budget in strongly supercooled phase transitions. *JCAP*, 06:024, 2019. arXiv:1903.09642, doi:10.1088/1475-7516/2019/06/024
Impact Factor (IF): 5.21, citations: 116

[H7] John Ellis, Marek Lewicki, and José Miguel No. On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal. *JCAP*, 04:003, 2019. arXiv:1809.08242, doi:10.1088/1475-7516/2019/04/003
Impact Factor (IF): 5.21, citations: 140

4.3 Introduction

The Standard Model of particle physics forms the base for current understanding of elementary particle interactions. However, despite its overwhelming phenomenological success culminating with discovery of the Higgs boson [40, 41], there is no doubt that new physics beyond SM is needed to explain crucial observed phenomena such as existence of dark matter or generation of baryon asymmetry. LHC has already reached its planned maximal energy and with every bit of new data analysed it becomes less and less likely that LHC will simply provide us with a clear direction through a direct discovery of particles from beyond the SM. In this situation it is natural to turn to the source of the observations we had hoped to explain through accelerator experiments, that is, to the connection between particle physics and cosmology.

At the same time we are witnessing dawn of a new era in astrophysics and cosmology thanks to the LIGO and VIRGO experiments. Beginning, of course, with the first detection of

Gravitational Waves (GWs) from collision of two black holes [42], a discovery already crowned with a Nobel Prize in physics. This success was followed by many more similar events [43, 44, 45, 46, 47] as well as an observation of collision of two neutron stars [48]. Currently most of our knowledge about the early universe is based on data coming from analysis of the cosmic microwave background produced when photons begun propagating freely after recombination which occurred when the universe was a few hundred thousand years old. However, GWs are coupled very weakly and essentially propagate freely after their production which allows us to observe phenomena form times much earlier the standard photon based techniques. Thus, even though all the observed GW events are astrophysical in nature and occurred very recently in cosmological scales they clearly confirm we have a new unprecedented observational window into the early universe.

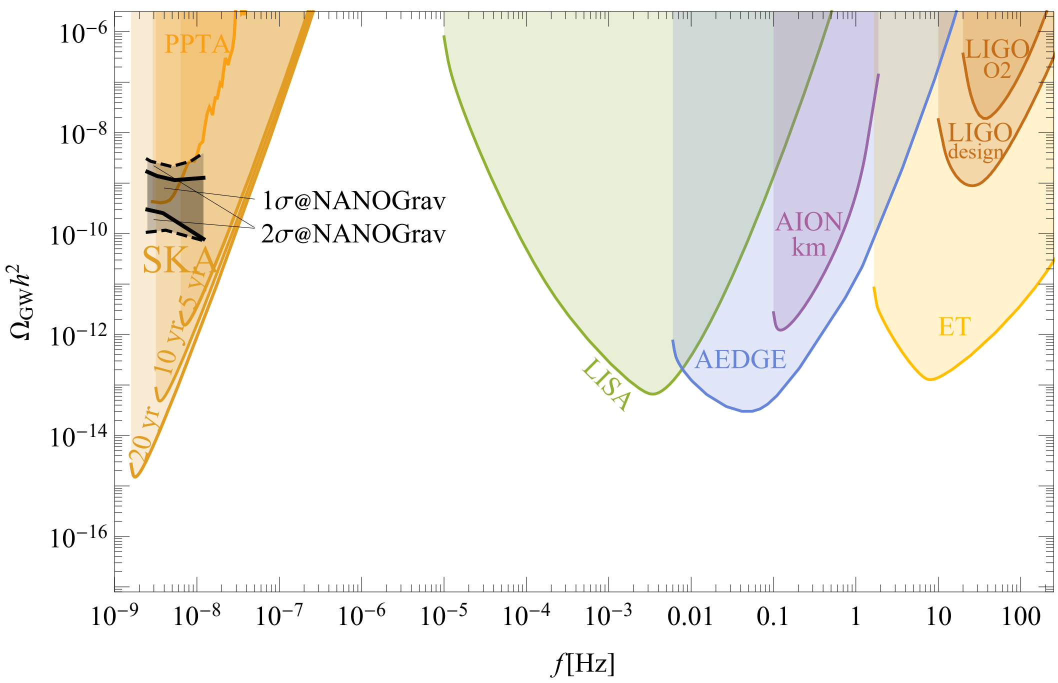
In the coming years many more GW experiments are planned to come online greatly improving our current reach in terms of sensitivity and frequency coverage. Most notably of course LISA [49] which has already been approved for funding by the European Space Agency and is scheduled to launch in 2034. Other upcoming projects well on their way are the Einstein Telescope (ET) [50] and the Square Kilometer Array (SKA) [51]. Two other noteworthy experiments planning to use atom interferometry techniques to probe GWs are AION [10] and AEDGE [52]. I was heavily involved with both these proposals as one of the main authors of the whitepapers.

We show the sensitivities of planned future detectors together with the currently operating LIGO [53, 54, 55, 56] as well as pulsar timing arrays PPTA [57] and EPTA [58] in Fig. 1 using the abundance of GWs which is most commonly used measure in cosmology. We also show the gray region where another pulsar timing experiment, the NANOGRav collaboration recently reported indications for a possible presence of a stochastic GW background [59]. With such optimistic prospects for new data it becomes a key task for the theoretical physics community to properly model sources of GWs and ascertain what information on the Early Universe we can learn through them. The overarching aim of the presented series of articles was to open a new possibility for catching a glimpse of events taking place within seconds after the Big Bang by broadening our understanding of the physics of cosmological Phase Transitions (PT).

4.4 Phase Transition Dynamics

Typically in models featuring a phase transition a scalar field is stabilised in a local minimum of the potential by thermal correction. As the Universe expands and cools thermal corrections diminish and the global minimum develops. Eventually the barrier between the minima becomes small enough that the field can tunnel through it. The transition then proceeds as the field penetrates the barrier in small areas creating bubbles containing the global vacuum. These bubbles then grow and collide until the entire Universe has transitioned the global minimum.

Fig. 2 shows the logarithmic energy density in a collision of two bubbles. The non-zero energy density outside the bubbles is simply the energy of the local minimum which is converted into a more and more energetic wall as the bubbles grow. During nucleation and growth of bubbles their spherical symmetry prohibits any GW production and the spectrum is only produced in the final moments of the transition as the bubbles collide [60]. The nucleation process is fairly well understood and has been described in a plethora of particle physics models to find the nucleation rate which in turn gives the transition temperature and average bubble size upon collision. At the same time the final part of the transition process and GW production is much more poorly understood, this is precisely the issue at the heart of the described series of articles.



Rysunek 1: *Coloured regions correspond to experimental sensitivities discussed Sec 4.3 while the gray region is an overlay of power-law signals that could fit the recent data from the NANOGRav collaboration [59].*

The first basic parameter describing the phase transition is the so-called strength

$$\alpha = \frac{\Delta V}{\rho_R} \tag{1}$$

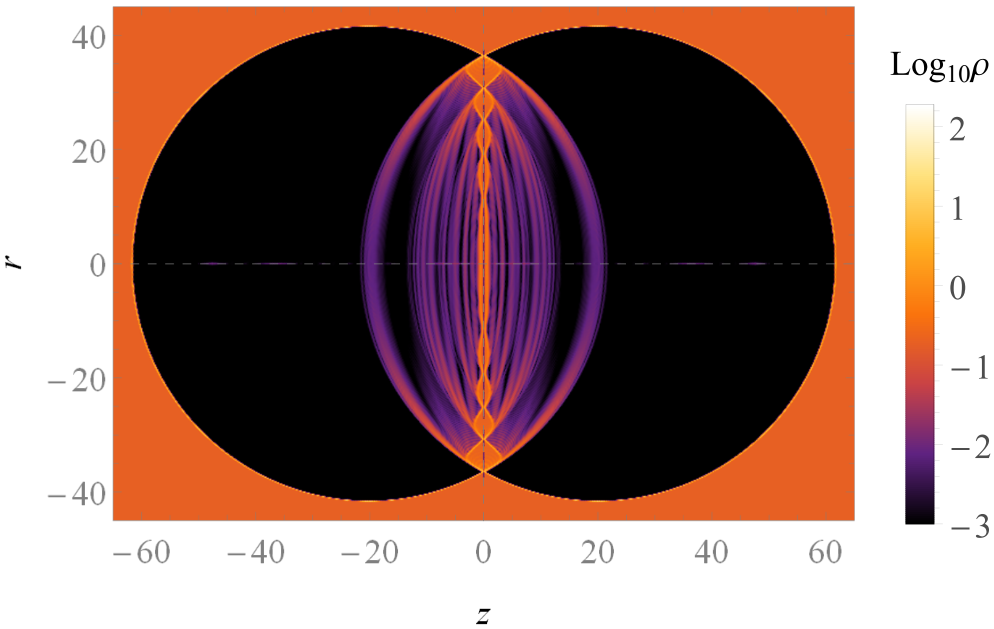
that is, the ratio of the energy density of the vacuum given by the differences between the minima of the potential to the energy density of the plasma filling the universe before the transition. Another key parameter describing the transformation is the timescale β related to the width of the false vacuum decay by

$$\Gamma \propto e^{\beta t} \tag{2}$$

and is usually expressed in relation to the Hubble parameter at transition time as β/H. The total density of gravitational waves increases with the energy density of the vacuum involved in the transformation. On the other hand, it decreases with the speed of transformation because it corresponds to a smaller support of the source in time. generally for all sources we have

$$\Omega_{GW} \propto \left(\kappa_n \frac{\alpha}{\alpha+1}\right)^2 \left(\frac{\beta}{H}\right)^{-a_n} . \tag{3}$$

where the specific values of the efficiency κ_n and the power a_n depends on which production mechanism is dominant in a given transition. This brings us to the key problem of the energy budget of the transition we will discuss in the next section.



Rysunek 2: *Cut through a collision of two bubbles showing logarithmic energy density.*

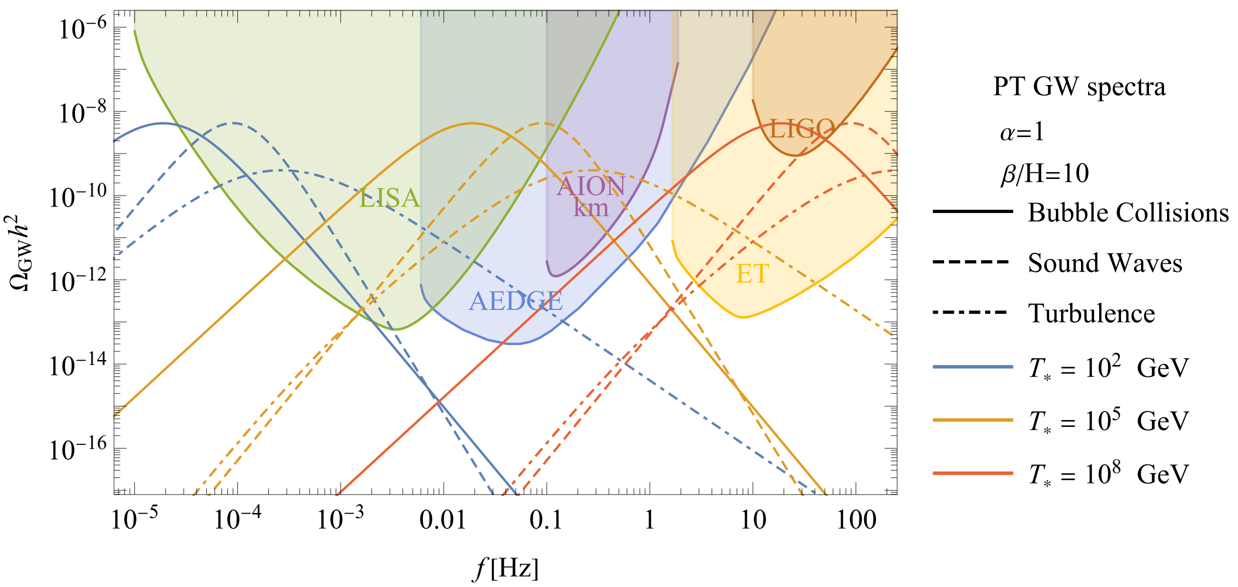
4.5 Energy Budget of a First Order Phase Transition

While it is clear PTs can produce a strong potentially observable stochastic gravitational wave background and such signals would provide very interesting prospects for observations the field is evolving rapidly and the details are at best uncertain at this point. To exemplify this let us discuss the very popular LISA cosmology working group review from 2015 [61] which summarised the state of the art six years ago. It pointed to three main sources of GWs

1. Collisions of Bubble Walls [62, 63]
2. Sound Waves [64, 65]
3. Turbulence in the Plasma [66, 67]

The first of these contributions can be large if a significant fraction of the energy gained from converting the vacuum as the bubble grows would be used to accelerate and sharpen the field profile. If the friction of the surrounding plasma stops the acceleration of the wall the energy will be transferred to a plasma shell the bubble creates with a snowplough like effect and the latter two sources dominate. The balance between the two remains uncertain as turbulence can be a long lasting source yet its onset is not yet well understood [68, 66]. In the review the fraction of energy stored in the sound waves later used to source turbulence was estimated with a simple fudge factor found as a lower bound in a simulation that did not last long enough for turbulence to develop [64]. The general prediction was, however, that in a very strong transition all three would play a role with non-negligible abundances. All of these predictions were modified severely since then prompting an update to the review [69].

Derivation of these factors is also crucial for possible differentiation between models. Spectra produced by each of these sources are different and would allow us to identify the corresponding source only based on the GW signal narrowing possible set of underlying models. We show examples of spectra form all the sources in Fig. 3.



Rysunek 3: *Examples of GW spectra from sources active in PTs with* $\alpha = 1$ *and* $\beta/H = 10$ *occurring at temperatures* $T_* = 10^2$ *GeV,* 10^5 *GeV and* 10^8 *GeV.*

4.5.1 Collisions of Bubble Walls

New calculations of the bubble wall velocity [70, 71] showed that friction with which the surrounding plasma acts on the walls has been severely underestimated. The problem came from the fact that older calculations at leading order in perturbation theory [72] found only constant contributions to the friction proportional to the change in particle masses upon crossing the bubble wall. While the newer calculations showed that higher order contributions grow with the wall velocity.

As a result the only way to store a significant amount of energy in the bubble wall is to reduce the friction by severely diluting the surrounding plasma before the bubbles nucleate. However this significant supercooling is not easy to realise in all types of models. In typical extensions of the SM featuring a polynomial potential all terms featured in the potential have to be of the same order to have two minima with a barrier between them. If the barrier is generated purely by thermal effects it will disappear quickly and no significant level of supercooling is possible. We verified this insight in H4 using simplified semi analytical calculation of the tunnelling rate which allowed us to extensively scan the entire parameter space of this simple model.

Thus the only polynomial potentials that could support supercooling feature a barrier between the minima also at temperature equal zero. This, however, leads to problems with percolation of the bubbles and successful completion of the transition H7. As the temperature drops the expansion of the Universe is driven by the vacuum energy leading to an inflationary phase with exponential growth of the scale factor. In this environment a bubble expanding with nearly with the speed of light will still reach a finite size in comoving coordinates. The physical volume of the parts of the Universe still in the unstable vacuum are expanding exponentially and so the rate of nucleation has to grow for the bubbles to convert the entire Universe. Unfortunately, the barrier between the minima is not generated by thermal effects such that as the temperature drops, the nucleation rate reaches a finite constant value. As a result in H7 we concluded only a very small amount of supercooling is achievable in models with polynomial potentials.

This creates a simple division between two classes of models. First in which the transition is already present at the classical level and the potential is a polynomial. Second with models where the symmetry breaking is triggered by quantum corrections and the shape of the potential is dictated by logarithmic corrections.

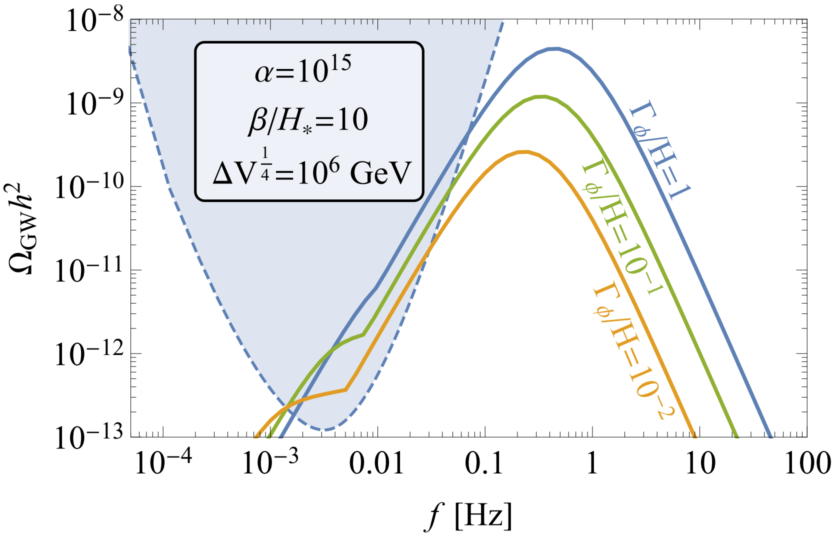
In models exhibiting classical scale invariance the barrier eventually disappears and the transition can be completed successfully even when the plasma is severely diluted [73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84]. Still very significant supercooling is simple to realise as the terms in the potential governing the size of the barrier and depth of the global minimum have very different functional dependence and such separation of scales is not a problem. In H6 we performed detailed calculation of the efficiency of GW production in such models. We explained how to compute the total energy going into acceleration of the bubble walls starting from the nucleated bubbles. This allowed us to show that classically scale invariant models naturally produce a signal mostly through collisions of very energetic bubbles in large parts of their parameter space.

Soon after, it was shown that not only higher orders in perturbation theory had a significant impact on the friction produced by the plasma but resummation of soft gauge boson emission [71] resulted in an even stronger dependence on the velocity. In H2 we updated our calculation of the energy budget to take that effect into account. We also performed a scan of the parameter space of a simple classically scale invariant $U(1)_{B-L}$ extension of the standard model showing that despite this new effect a significant part of the parameter space of the model still predicted a signal produced predominantly through collisions of very energetic bubbles. In that paper we also discussed a novel effect associated with the fact that a very slow decay of the field after the transition can lead to a short period of matter like expansion as the energy density is dominated by the field oscillating around the global minimum of the potential. In fact this mechanism produces a smoking gun signal in the stochastic GW background. This is because at super horizon sales our transition is always effectively a white noise source as it is uncorrelated in different horizons. This leads to a characteristic f^3 slope of the spectrum at low frequencies corresponding to such large scales provided said scales enter the horizon in radiation dominated expansion. Our brief period of matter domination instead produces an f^1 plateau at low frequencies providing a very distinct experimental signature. We show an example of spectra with this feature in Fig. 4.

4.5.2 Sound Waves and Turbulence in the Plasma

We showed in H7 that the sound wave source is not active for a full Hubble time as previously assumed [65]. Instead the flow quickly becomes non-linear ending the sound wave period and making possible early onset of turbulence. Concerning the impact on the GW signal this means the sound wave contribution is suppressed compared to previous prediction typically by more than an order of magnitude. At the same time the turbulence contribution should be boosted accordingly witch we discussed in H6. This was the second of the two major developments that prompted the update of the LISA review [69].

Older estimates assumed that the sound wave period defined by linear flow of the plasma would continue until Hubble friction eliminates this source. This linear flow essentially constitutes of plasma shells propagating with no interaction between them after the vacuum bubbles have collided. This would render production of turbulence impossible and the old efficiency factor was



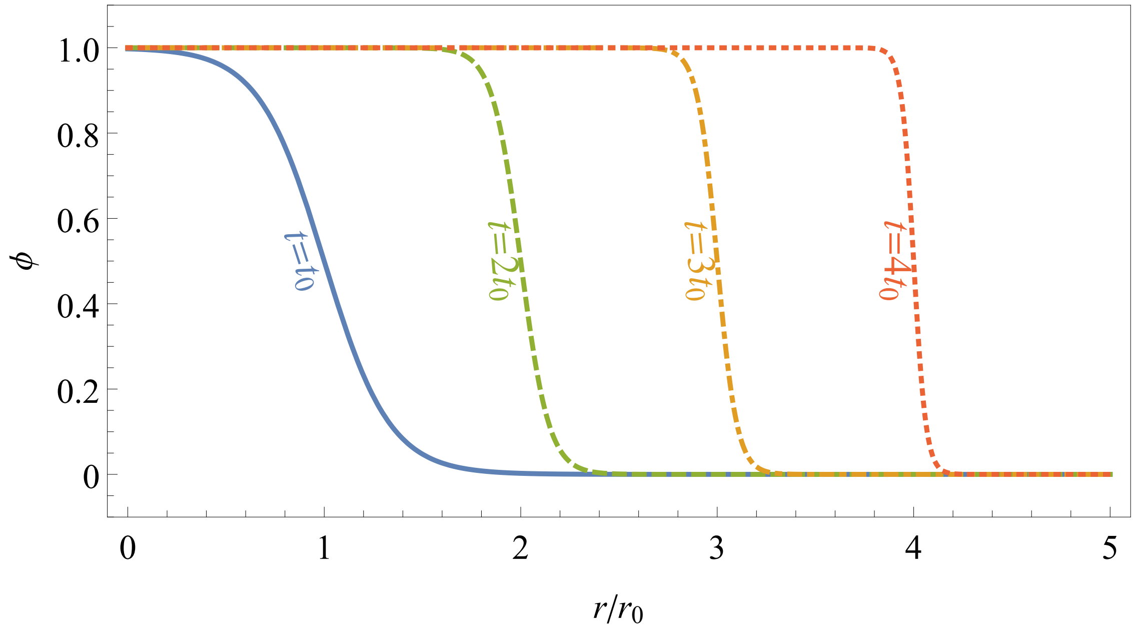
Rysunek 4: *GW spectra from a strongly supercooled phase transition with* $\alpha = 10^{15}$, $\beta/H = 10$ *and the energy scale set by the energy of the unstable vacuum* $\Delta V^{\frac{1}{4}} = 10^6$ *GeV. The decay of the field undergoing the transition is set by* Γ_ϕ *and we show examples with the field rather quickly* $\Gamma_\phi/H = 1$ *up to decay taking much longer than a Hubble time with* $\Gamma_\phi/H = 10^{-2}$.

simply a tiny fraction of energy corresponding to numerical error of lattice simulations [64, 61] that could have initially been converted into vorticity. Early onset of non-linearities allows the turbulence to develop while most of the energy is still stored in kinetic energy of the fluid and its contribution to the total energy budget can be as large as that of the sound wave source [65]. Our estimates in H7 based on that insight showed that as a result Turbulence can be a source of GWs as important as the Sound Waves.

4.6 Computation of GW spectrum in very strong transitions

In papers H5, H3 and H1 we focused on description of very strong PTs where plasma dynamics can be neglected. The most obvious way to compute the GW spectrum from a phase transition would proceed through a lattice simulation. In recent years there has been a significant progress on this front [85, 86], however, this approach faces one fundamental problem. After nucleation the bubbles encapsulating the global vacuum areas grow at the same time accumulating the energy gained from vacuum conversion in sharpening field profile corresponding to the bubble wall. We illustrate this effect in Fig. 5 showing on the left hand side a toy potential and on the right hand side a global vacuum bubble growing in the local vacuum background. The bubble is a spherically symmetric field profile and function of the usual radial coordinate r shown at in several moments of time as it grows. As the bubble grows larger so does the lattice needed to describe it. Even worse the lattice also needs to grow more dense at later times to properly resolve the steepening bubble wall. In realistic models the bubbles always grow by many orders of magnitude before they collide making direct lattice simulations of physically relevant situations an impossible task.

The alternative we followed uses modelling of GW sources that will allow us to paint a



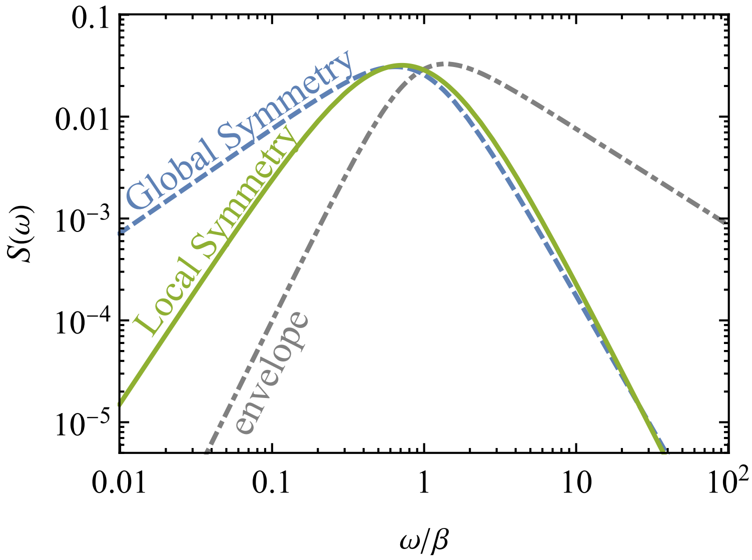
Rysunek 5: *Evolution with time of a field profile corresponding to a growing bubble as a function of the usual radial coordinate r scaled with the initial radius r_0*

complete picture of the transition even on cosmological scales. The practical calculation here would proceed in a similar way to lattice calculations with random nucleation of bubbles, however, instead of resolving the field one keeps track of the evolution of bubbles and GW sources modelling each on individually. This rids us of the lattice resolution problem and allows to reproduce even extremely sharp features provided only we can model and understand their behaviour.

The simplified modelling previously used in the literature relies on thin-wall approximation describing the wall as zero-width sheet with a large surface energy density. In a 3D simulation instead of resolving the field one just models the bubble wall as a sphere growing according to a simple analytical prescription. This simplification makes the calculation much less time consuming and the hope was it allows one to describe very strong transition with sharp field profiles. However, the drawback is of course that the result depends crucially on assumptions one makes concerning the processes responsible for GW production in a phase transition [87, 88]. The most widely used approximation assumes that the walls simply disappear after collision [62, 63]. In H5 we performed simplified lattice simulations of collisions of pairs of bubbles using additional cylindrical symmetry of the problem. These simulations are much less demanding than full 3D ones allowing conditions closer to physically relevant cases. Crucially, the simulations allowed us to model the behaviour of the field also after the collision.

In H3 and H1 we showed that including propagation of field gradients that source GWs also after the initial collision changes the resulting spectrum dramatically. The main difference between H3 and H1 was the model used in the lattice simulations. In H3 the simulations involved only evolution of the scalar field which would correspond to breaking of a global symmetry while in H1 we also included interactions with gauge bosons allowing us to describe breaking of a gauge symmetry. This resulted in energy stored in the gradient of the field propagating after bubble collision scaling as $E \propto r^{-2}$ and $E \propto r^{-3}$ respectively.

Fig. 6 shows the comparison of the spectral shapes we obtained with the older envelope

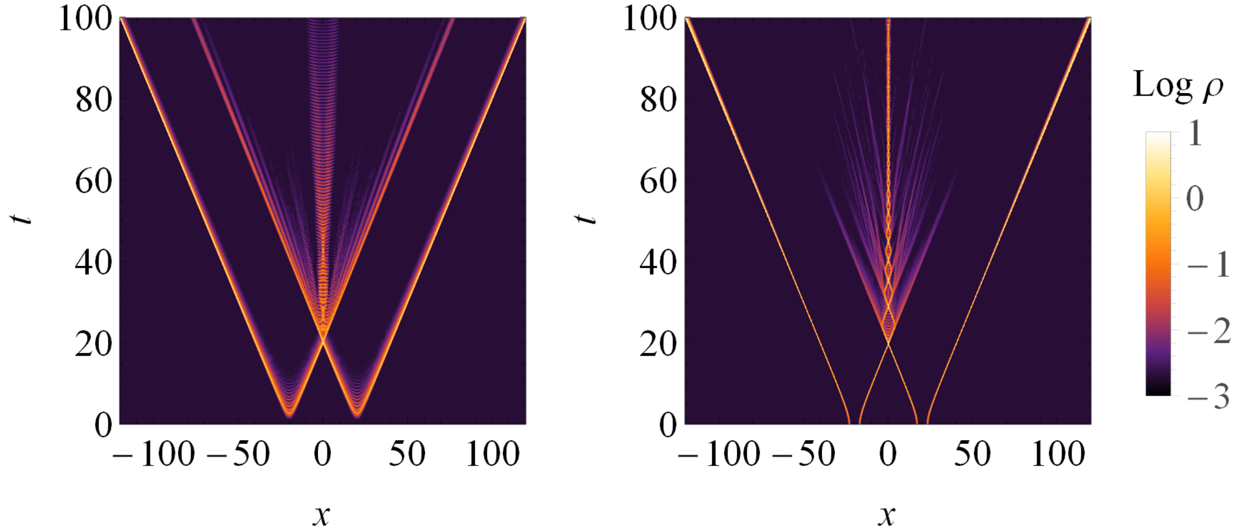


Rysunek 6: *Spectra produced by very strong phase transitions in case of a global $U(1)$ symmetry breaking a gauged $U(1)$ symmetry breaking and a simple envelope approximation in which the walls simply dissapear upon collision.*

approximation. Firstly, inclusion of gradients propagating after the collision made the source more smooth at small scales due to removing sharp features which appeared for examples where the two bubbles joined after the already collided part of the wall was removed. This made the resulting spectrum fall of much more steeply at high frequencies. As a result the slope of the spectrum changes from f^{-1} in the envelope approximation to f^{-3}. Secondly the improved spectra fall of more slowly at low frequencies as the propagating gradients keep expanding after the collision and provide additional energy sourcing GWs at very large scales. As expected the resulting slope depends on how quickly the energy of the propagating field gradients dissipates. In case of a global symmetry breaking we find the low frequency slope to be f^1 while while for a local symmetry breaking faster energy dissipation leads to more steep slope $f^{2.2}$. This difference would allow us to uncover some information of the underlying particle physics model only from the GW spectral shape. It is also important to note that both the spectra we found are markedly different from the older envelope approximation.

Another key feature of H3 and H1 is the use of realistic potentials. Typically in lattice studies one is constrained to use simplest possible polynomial potentials due to evaluation time [85, 86]. However in models capable of producing a signal predominantly through bubble collisions one needs extreme supercooling which requires a classically scale invariant logarithmic potential H6.

We will show the importance of the choice of the potential on one crucial effect that has a significant impact on the results called *vacuum trapping*. That is the phenomenon of the field being thrown back into the initial vacuum by the force of collision of bubble walls [89]. This is a typical occurrence in polynomial potentials and was indeed featured in most recent simulations which focused on polynomial toy models [85, 86]. However, in potentials of interest the barrier is tiny and no vacuum trapping can take place. We illustrate the impact of this in Fig. 7 which shows the evolution of the energy density on the axis connecting the centres of two colliding bubbles in two representative examples. The outer bright lines in both plots



Rysunek 7: *Left panel: Evolution of energy density on the axis joining the centres of two colliding bubbles in a potential featuring symmetry breaking by logarithmic quantum corrections. Right panel: Similar energy density evolution in a model with polynomial potential where vacuum trapping occurs and a significant amount of energy is concentrated in the collision point after the collision.*

correspond to outer walls of the two bubbles that never collide and instead simply propagate and become more energetic as the time passes. We are mostly interested in the two inner lines which are walls colliding at $x = 0$ at time $t \approx 20$. The right panel shows the case of a polynomial potential where vacuum trapping occurs and as a result we see a significant amount of energy remaining at the point of collision. On the left hand side we show the case of symmetry breaking by quantum logarithmic corrections. Here the barrier is negligible and as expected no trapping occurs which as we see leads to most of the energy propagating onward in form of field gradients after the collision.

This result is crucial for the calculation of the GW spectrum performed in H3 and H1. To that end we used a 3D simulation approximating the bubbles and gradients propagating after collision simply as spheres keeping track only on the time of the collision to scale the energy with time appropriately. If trapping took place it would instead be more appropriate to assume the energy of the collided walls is trapped in one place after the collision which would have a crucial impact on the low frequency part of the spectrum as the resulting large scale structure of the sources would be very different.

4.7 conclusion

The described series of papers focused on dynamics of first-order phase transitions. Starting with improvements of the energy budget of the transition predicting which mechanisms will provide the dominant source of GWs in a given model. Our results changed the previous estimates by orders of magnitude impacting all subsequent results in the literature. In case of extremely strong phase transitions we provided the first reliable estimate of the contribution from bubble wall collisions thus clearly identifying the models which could produce such a signal. This was followed by new and improved derivation of the spectrum produced by bubble wall collisions again improving our ability to identify this source together with the new possibility to identify additional features of the underlying model purely based on the GW spectrum.

This line of research will have important consequences for our ability to extract information on the early universe from GW signals. This will become crucial in the coming decade as LISA is launched in 2034 and the Einstein Telescope just placed on the European Strategy Forum on Research Infrastructures Roadmap allowing operation in a similar time frame. The future importance of this entire effort is perhaps best summarised by the recent recommendation of the European Space Agency senior committee for the future generation of experiments to be realised in its Voyage 2050 programme. Under which one of the three large scale missions to be realised in the 2050s is to be dedicated to new probes of the early Universe possibly through a new GW experiment.

5 Presentation of significant scientific or artistic activity carried out at more than one university, scientific or cultural institution, especially at foreign institutions

Most of the work described in the main achievement was carried out during my postdoctoral stay at King's College London. Publications O1-O17 from the list of other works not included in the main achievements listed in Sec. 5.4 and described in more detail below were also produced during my postdoctoral stay at King's College London and the University of Adelaide. All of these works were also conducted in international collaborations with exception of O10, O13 and O15 completed together with colleagues from Warsaw. Finally papers O18-O33 from the list Sec. 5.4 were completed during my PhD.

5.1 Phase Transition Phenomenology

In recent years phenomenological studies of models predicting a first order PT became a very popular topic in the literature, see [61, 69] for a review. My research into the topic begun in a similar manner with O17 which described in great detail phenomenology of arguably the simplest extension of the SM through addition of one extra neutral scalar. Our aim was to verify verify whether the model could support a strong PT and provide a Dark Matter (DM) candidate at the same time. The result was negative as the phase transition requires a significant modification of the potential and a strong coupling between the new scalar and the Higgs boson which in turn diminishes the abundance of the scalar DM. We also verified even a period of non-standard expansion affecting the DM freeze-out could not ammend this problem. In O11 we checked that a simple extension of the model by additional fermions coupled to the new scalar and plying the role of DM was enough to fix the issue. We performed global scans of the parameter space and verified that large part of the parameter space facilitated a first order PT while providing a viable DM candidate.

As described in sec. 4 our results in H7 showed that a significant amount of energy released in a PT can be transferred into Turbulence in the plasma. Aside from enabling turbulence to produce a characteristic GW spectrum with amplitude of the same order as sound waves the development of strong turbulence would have other interesting phenomenological implications.

Firstly, it could source a primordial magnetic field [90] explaining the very weak fields observed in intergalactic voids [91, 92, 93, 94, 95]. We explored this possibility in O9 showing that magnetic fields from a first order phase transition could indeed produce a field strong enough to explain the current observations. The parameter space fulfilling these bounds is appreciably large provided that the magnetic field had a significant helical component. Helicity is conserved in later evolution of the plasma and leads to a much slower decay of the magnetic field energy with time [96].

Secondly, helical turbulence would produce a circularly polarised spectrum of GWs [97, 98] giving a smoking gun signal of this production mechanism. Detection of polarisation of GWs in a planar experiment such as LISA is difficult since one cannot distinguish a polarised wave coming from a given direction with opposite polarisation wave arriving from the opposite direction [99]. For a stochastic background arriving from all sides simultaneously this means we need to use anisotropy of the signal associated with motion of the satellites for detection. This is, however, a higher order effect which renders the sensitivity to polarisation orders of magnitude smaller than that of detection of the background in the first place. In O3 we investigated the issue and again showed LISA could detect polarisation of such a background originating in a PT provided only the underlying transition is strong enough and the fraction of helical turbulence is significant.

5.2 Cosmic Strings

One important line of research I pursued in the last few years involves cosmic strings. These are topological defects that would also have been produced in the early universe if a symmetry with a $U(1)$ subgroup was broken (See O6 for a comprehensive review). The key aspect I focused on were the GW signals that would have been produced throughout the history of the universe as the cosmic string network evolves with its expansion.

In O14 and O12 we proposed a novel method for probing the expansion history using its imprints on the GW spectrum produced by cosmic strings. These topological defects are a long lasting source that generically produces a broad and flat spectrum in which all features are results of cosmological expansion. We showed that this effect could be used to probe the expansion to times much before any currently known data. This idea was later used in a variety of specific models in order to check the area of their parameter space in range of future GW experiments [100, 101]

Ref. O4 is the last paper in this series and takes this idea to its limit. Here we show that even a cosmic string network diluted by inflation could regrow its density up until today and produce a novel smoking gun signal from this scenario where the stochastic background is suppressed but the network can be discovered through recently produced strong GW bursts. This signal is also present in more standard models of strings that are not diluted, however, contrary to our case here the bursts would always be a much weaker probe than the stochastic background and would certainly not be visible if the background was beyond our reach.

Recently in ref. O1 we investigated the last year's excess in data taken by the NANOGrav collaboration [105] which could be a precursor for the first discovery of a stochastic GW background. We showed that cosmic strings provide a very good fit to the data and pointed out future experiments are sure to verify this possibility. This paper achieved particular renown being chosen as Physical Review Letters editor's suggestion and sparking interest of more popular news outlets. This interpretation was also explored in [102, 103, 104]. Ref [103] in particular found that cosmic strings produce the best fit to the data set from amongst the considered sources, while [104] explored the impact of uncertainties in the string theoretical modelling on the resulting fit.

5.3 Involvement in experiments

I have also been actively involved in engaging the experimental community working on probing GWs. Since 2018 I have been an active member of the LISA cosmology working group. I participated in the LISA cosmology working group review of cosmic string physics ref. O6 where I was responsible for describing the impact of expansion of the Universe on strings. Since then my involvement with LISA keeps growing and currently I am coordinating two chapters of the upcoming LISA cosmology working group white paper dealing with phase transitions and cosmic strings.

I have also been involved in the AION and AEDGE projects which are aimed at realising novel GW experiments using atom interferometry to probe the mid frequency band between the sensitivities of LISA and the Einstein Telescope.

I had an important role in writing the whitepaper for AION O5 acting as a coordinator of the GW section which is a key part of the science case for the proposal. AION is the terrestrial implementation of atom interferometer based GW observatory. Thanks to this effort it has already obtained funding for its initial phase and a prototype is being assembled in Oxford.

I took up a similar role while writing the AEDGE whitepaper O7. This is the satellite implementation of this technology which we proposed to the European Space Agency as a large scale mission in the Voyage 2050 framework. Probing the early Universe through GW signals was a key part in our proposal and as we already mentioned the recent results of this competition in the form of recommendations from the senior committee which advises dedicating one of the three large scale missions to be realised in the 2050s to new probes of the early Universe. A new GW experiment operating in the mid band frequency is mentioned as one of the possible outcomes. AEDGE itself was noted for the lack of technological readiness due to ongoing development of the necessary cold atom technology, however, the collaboration is now in contact with the ESA's Director of Science in order to workout a roadmap towards acceptable level of technological readiness.

5.4 List of publications not included in the achievement described in sec 4

[O1] John Ellis and Marek Lewicki. Cosmic String Interpretation of NANOGrav Pulsar Timing Data. *Phys. Rev. Lett.*, 126(4):041304, 2021. arXiv:2009.06555, doi:10.1103/PhysRevLett.126.041304

[O2] Rouzbeh Allahverdi et al. The First Three Seconds: a Review of Possible Expansion Histories of the Early Universe. 6 2020. arXiv:2006.16182, doi:10.21105/astro.2006.16182

[O3] John Ellis, Malcolm Fairbairn, Marek Lewicki, Ville Vaskonen, and Alastair Wickens. Detecting circular polarisation in the stochastic gravitational-wave background from a first-order cosmological phase transition. *JCAP*, 10:032, 2020. arXiv:2005.05278, doi:10.1088/1475-7516/2020/10/032

[O4] Yanou Cui, Marek Lewicki, and David E. Morrissey. Gravitational Wave Bursts as Harbingers of Cosmic Strings Diluted by Inflation. *Phys. Rev. Lett.*, 125(21):211302, 2020. arXiv:1912.08832, doi:10.1103/PhysRevLett.125.211302

[O5] L. Badurina et al. AION: An Atom Interferometer Observatory and Network. *JCAP*, 05:011, 2020. arXiv:1911.11755, doi:10.1088/1475-7516/2020/05/011

[O6] Pierre Auclair et al. Probing the gravitational wave background from cosmic strings with LISA. *JCAP*, 04:034, 2020. arXiv:1909.00819, doi:10.1088/1475-7516/2020/04/034

[O7] Yousef Abou El-Neaj et al. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quant. Technol.*, 7:6, 2020. arXiv:1908.00802, doi:10.1140/epjqt/s40507-020-0080-0

[O8] Luc Darmé, Joerg Jaeckel, and Marek Lewicki. Generalized escape paths for dynamical tunneling in QFT. *Phys. Rev. D*, 100(9):096012, 2019. arXiv:1907.04865, doi:10.1103/PhysRevD.100.096012

[O9] John Ellis, Malcolm Fairbairn, Marek Lewicki, Ville Vaskonen, and Alastair Wickens. Intergalactic Magnetic Fields from First-Order Phase Transitions. *JCAP*, 09:019, 2019. arXiv:1907.04315, doi:10.1088/1475-7516/2019/09/019

[O10] Tomasz Krajewski, Zygmunt Lalak, Marek Lewicki, and Paweł Olszewski. Higgs domain walls in the thermal background. *Phys. Dark Univ.*, 26:100347, 2019. arXiv:1902.05560, doi:10.1016/j.dark.2019.100347

[O11] Ankit Beniwal, Marek Lewicki, Martin White, and Anthony G. Williams. Gravitational waves and electroweak baryogenesis in a global study of the extended scalar singlet model. *JHEP*, 02:183, 2019. arXiv:1810.02380, doi:10.1007/JHEP02(2019)183

[O12] Yanou Cui, Marek Lewicki, David E. Morrissey, and James D. Wells. Probing the pre-BBN universe with gravitational waves from cosmic strings. *JHEP*, 01:081, 2019. arXiv:1808.08968, doi:10.1007/JHEP01(2019)081

[O13] Michal Artymowski, Olga Czerwinska, Zygmunt Lalak, and Marek Lewicki. Gravitational wave signals and cosmological consequences of gravitational reheating. *JCAP*, 04:046, 2018. arXiv:1711.08473, doi:10.1088/1475-7516/2018/04/046

[O14] Yanou Cui, Marek Lewicki, David E. Morrissey, and James D. Wells. Cosmic Archaeology with Gravitational Waves from Cosmic Strings. *Phys. Rev. D*, 97(12):123505, 2018. arXiv:1711.03104, doi:10.1103/PhysRevD.97.123505

[O15] Tomasz Krajewski, Zygmunt Lalak, Marek Lewicki, and Paweł Olszewski. Domain walls in the extensions of the Standard Model. *JCAP*, 05:007, 2018. arXiv:1709.10100, doi:10.1088/1475-7516/2018/05/007

[O16] Luc Darmé, Joerg Jaeckel, and Marek Lewicki. Towards the fate of the oscillating false vacuum. *Phys. Rev. D*, 96(5):056001, 2017. arXiv:1704.06445, doi:10.1103/PhysRevD.96.056001

[O17] Ankit Beniwal, Marek Lewicki, James D. Wells, Martin White, and Anthony G. Williams. Gravitational wave, collider and dark matter signals from a scalar singlet electroweak baryogenesis. *JHEP*, 08:108, 2017. arXiv:1702.06124, doi:10.1007/JHEP08(2017)108

[O18] Michał Artymowski, Marek Lewicki, and James D. Wells. Gravitational wave and collider implications of electroweak baryogenesis aided by non-standard cosmology. *JHEP*, 03:066, 2017. arXiv:1609.07143, doi:10.1007/JHEP03(2017)066

[O19] Tomasz Krajewski, Zygmunt Lalak, Marek Lewicki, and Paweł Olszewski. Domain walls and gravitational waves in the Standard Model. *JCAP*, 12:036, 2016. arXiv:1608.05719, doi:10.1088/1475-7516/2016/12/036

[O20] Michal Artymowski, Zygmunt Lalak, and Marek Lewicki. Multi-phase induced inflation in theories with non-minimal coupling to gravity. *JCAP*, 01:011, 2017. arXiv:1607.01803, doi:10.1088/1475-7516/2017/01/011

[O21] Olga Czerwińska, Zygmunt Lalak, Marek Lewicki, and Paweł Olszewski. The impact of non-minimally coupled gravity on vacuum stability. *JHEP*, 10:004, 2016. arXiv:1606.07808, doi:10.1007/JHEP10(2016)004

[O22] Zygmunt Lalak, Marek Lewicki, and Paweł Olszewski. Gauge fixing and renormalization scale independence of tunneling rate in Abelian Higgs model and in the standard model. *Phys. Rev. D*, 94(8):085028, 2016. arXiv:1605.06713, doi:10.1103/PhysRevD.94.085028

[O23] Michal Artymowski, Zygmunt Lalak, and Marek Lewicki. Implications of extreme flatness in a general $f(R)$ theory. *Phys. Lett. B*, 760:432–437, 2016. arXiv:1604.02470, doi:10.1016/j.physletb.2016.07.027

[O24] Marek Lewicki, Tanja Rindler-Daller, and James D. Wells. Enabling Electroweak Baryogenesis through Dark Matter. *JHEP*, 06:055, 2016. arXiv:1601.01681, doi:10.1007/JHEP06(2016)055

[O25] Michal Artymowski, Zygmunt Lalak, and Marek Lewicki. Saddle point inflation from higher order corrections to Higgs/Starobinsky inflation. *Phys. Rev. D*, 93(4):043514, 2016. arXiv:1509.00031, doi:10.1103/PhysRevD.93.043514

[O26] Michal Artymowski, Zygmunt Lalak, and Marek Lewicki. Saddle point inflation from $f(R)$ theory. *Phys. Lett. B*, 750:595–600, 2015. arXiv:1508.05150, doi:10.1016/j.physletb.2015.09.076

[O27] Zygmunt Lalak, Marek Lewicki, Moritz McGarrie, and Paweł Olszewski. Features of electroweak symmetry breaking in five dimensional SUSY models. *JHEP*, 11:137, 2015. arXiv:1508.05105, doi:10.1007/JHEP11(2015)137

[O28] Zygmunt Lalak, Marek Lewicki, and James D. Wells. Higgs boson mass and high-luminosity LHC probes of supersymmetry with vectorlike top quark. *Phys. Rev. D*, 91(9):095022, 2015. arXiv:1502.05702, doi:10.1103/PhysRevD.91.095022

[O29] Michal Artymowski, Zygmunt Lalak, and Marek Lewicki. Inflationary scenarios in Starobinsky model with higher order corrections. *JCAP*, 06:032, 2015. arXiv:1502.01371, doi:10.1088/1475-7516/2015/06/032

[O30] Michal Artymowski, Zygmunt Lalak, and Marek Lewicki. Inflation and dark energy from the Brans-Dicke theory. *JCAP*, 06:031, 2015. arXiv:1412.8075, doi:10.1088/1475-7516/2015/06/031

[O31] Marcin Badziak, Zygmunt Lalak, Marek Lewicki, Marek Olechowski, and Stefan Pokorski. Upper bounds on sparticle masses from muon g − 2 and the Higgs mass and the complementarity of future colliders. *JHEP*, 03:003, 2015. arXiv:1411.1450, doi:10.1007/JHEP03(2015)003

[O32] Zygmunt Lalak, Marek Lewicki, and Paweł Olszewski. Higher-order scalar interactions and SM vacuum stability. *JHEP*, 05:119, 2014. arXiv:1402.3826, doi:10.1007/JHEP05(2014)119

[O33] Zygmunt Lalak and Marek Lewicki. Fine-tuning in GGM and the 126 GeV Higgs particle. *JHEP*, 05:125, 2013. arXiv:1302.6546, doi:10.1007/JHEP05(2013)125

5.5 Bibliometric data

From Web of Science:	
Publications:	41
Citations:	945
Citations without self-citations:	826
h-index:	17
From Inspire:	https://inspirehep.net/authors/1259434
Publications:	41
Citations:	1,525
Citations without self-citations:	1,220
h-index:	20

6 Other achievements

6.1 Grants

1. NAWA Polish Returns 2020 (1.12.2020-30.11.2024).
   Principal investigator.

Title: *Auscultation of the Universe: search for new physics through primordial gravitational waves.*
Grant number: PPN/PPO/2020/1/00013.
Funding: 2 031 997 PLN.

2. NCN SONATA (24.07.2019-23.07.2023)
   Principal investigator.
   Title: *Exploring the early universe with gravitational waves.*
   Grant number: 2018/31/D/ST2/02048
   Funding: 1 059 600 PLN.

3. Iuventus plus (21.10.2016-21.10.2018)
   Principal investigator.
   Title: *Phase transitions in the early Universe and their consequences for baryon asymmetry in the context of new data from the LHC.*
   Grant number: 0431/IP3/2016/74.
   Funding: 140 000 PLN.

4. NCN ETIUDA (1.10.2015-30.09.2016)
   Principal investigator.
   Title: *Aspects of electroweak symmetry breaking in light of new data from the LHC.*
   Grant number: 2015/16/T/ST2/0052,
   71 270 PLN.

5. NCN PRELUDIUM (24.02.1015-12.02.2017).
   Principal investigator.
   Title: *Precision corrections to expected lifetime of vacuum in the Standard Model and its extensions.*
   Principal investigator.
   Grant number: 2014/13/N/ST2/02712,
   Funding: 99 320 PLN.

6.2 Awards

- 2015/2016 PhD scholarship for outstanding achievements from Polish Minister of Higher Education

6.3 Teaching and Supervision

I have supervised one master's student Mr. Mateusz Zych who successfully defended his thesis in September 2021. He was admitted to the PhD programme in Warsaw and began his doctoral studies in October 2021 with me acting as his secondary supervisor. I have also lead the exercise sessions for the following subjects during my PhD studies:

2012/2013	Classical Mechanics 1100-2AF13
	Electrodynamics 1100-3005
2013/2014	Analysis 1100-1INZ21

6.4 Organisation

- 2021 – 2023 Elected member of RND (Council of the Scientific Discipline: Physics) Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Poland
- 2019 – 2020 Organization of the Theoretical Particle Physics and Cosmology seminars at King's College London.
- 12-16 VII 2021 Conference Gravitational Wave Probes of Physics Beyond Standard Model

6.5 Talks and Seminars

2013 *Fine-tuning in GGM and the 126 GeV Higgs particle*, Seminar for Theoretical Particles Physics and Cosmology, Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, 17 III2013, Warsaw, Poland

Fine-tuning in GGM and the 126 GeV Higgs particle, SUSY 2013, 26—31 August 2013, ICTP Trieste, Italy

Naturalness in General Gauge Mediation SCALARS 2013, 12 – 16 September 2013, Warsaw, Poland

2014 *Higher-order scalar interactions and SM vacuum stability* Seminar for Theoretical Particles Physics and Cosmology, Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, 11.03.2014, Warsaw, Poland

Lifetime of the electroweak vacuum in the presence of nonrenormalizable operators The 20th International Symposium on Particles, Strings and Cosmology, PASCOS 2014, 22 - 27 June 2014, Warsaw, Poland

Higher-order scalar interactions and SM vacuum stability SUSY 2014, 21 - 26 July 2014, Manchester, England

2015 *Standard Model vacuum stability in the presence of gauge invariant nonrenormalizable operators* Planck 2015, 25-29 May 2015, Ioannina, Greece

Constraining new physics with SM effective potential 55. Cracow school of theoretical physics, 20-28 June 2015, Zakopane, Poland,

Vacuum stability in the Standard Model and its extensions Astroparticle physics in Poland,11-13 May 2015, Warsaw, Poland

Constraining new physics with the Standard Model effective potential HEP seminar, 15 December 2015, Argonne national laboratory, USA

2016 *Enabling Electroweak Baryogenesis through Dark Matter* Seminar for Theoretical Particles Physics and Cosmology, Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, 12 April 2016, Warsaw, Poland

Enabling Electroweak Baryogenesis through Dark Matter HEP seminar, 10 May 2016, Krakow, Poland,

Enabling Electroweak Baryogenesis through Dark Matter "Collider Physics" 2nd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society , 14 May 2016, Katowice, Poland,

Enabling Electroweak Baryogenesis through Dark Matter Planck 2016, 23-27 May 2016, Valencia, Spain

Enabling Electroweak Baryogenesis through Dark Matter The 28th Rencontres de Blois 2016 , 29 May 2016 to 3 June 2016, Blois, France

2017 *Electroweak baryogenesis aided by non-standard cosmology*, University of Adelaide HEP seminar, 9 November 2016, Adelaide, Australia

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis , CoEPP Annual Workshop, 23 February 2017,Adelaide, Australia

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis, University of Sydney HEP seminar, 16 March 2017, Sydney, Australia

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis, Melbourne University HEP seminar, 6 April 2017, Melbourne, Australia

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis, PLANCK 2017, 24 May 2017, Warsaw, Poland

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis, PASCOS 2017, 20 June 2017,Madrid, Spain

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis, Kings College London HEP seminar,8 Nov 2017, London, UK

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis, Scalars 2017, 2 December 2017, Warsaw,

2018 *Cosmic Archaeology with Gravitational Wave Signals from Cosmic Strings*, University of Warsaw HEP seminar, 8 March 2018, Warsaw, Poland

Cosmic Archaeology with Gravitational Waves from Cosmic Strings, DAMTP-Cavendish HEP seminar,25 May 2018, Cambridge, UK

Cosmic Archaeology with Gravitational Waves from Cosmic Strings, String Pheno 2018, 2-6 VII 2018, Warsaw, Poland

On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal, University of Sussex Theoretical Particle Physics seminar,25 Oct 2018, Sussex, UK

On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal, Bilbao Early Universe Cosmology Seminar,14 Nov 2018, Bilbao, Spain

On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal, HPP Meeting at NIKHEF,30 Nov 2018, Amsterdam, Netherlands

2019 *On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal*, 6th LISA Cosmology Working Group meeting, 14-18 January 2019, IFT, Madrid , Spain

Cosmic Archaeology with Gravitational Wave Signals from Cosmic Strings, 6th LISA Cosmology Working Group meeting, 14-18 January 2019, IFT, Madrid , Spain

On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal, Winter Mini Workshop on Gravity and Cosmology, 21-23 January 2019, Faculty of Physics, University of Warsaw, Warsaw , Poland

Primordial gravitational waves, First AION Workshop, 25-26 March 2019, CERN, Geneva , Switzerland

Gravitational wave energy budget in strongly supercooled phase transitions, PLANCK 2019, 3-7 June 2019, Granda , Spain

Gravitational wave energy budget in strongly supercooled phase transitions, Beyond General Relativity, Beyond Cosmological Standard Model, 1-5 July 2019, Faculty of Physics, University of Warsaw, Warsaw , Poland

AEDGE: Gravitational Waves, AEDGE workshop, 22-23 July 2019, CERN, Geneva , Switzerland

Gravitational wave energy budget in strongly supercooled phase transitions, 7th LISA Cosmology Working Group meeting, 23-27 September 2019, Padova, Italy

Gravitational wave energy budget in strongly supercooled phase transitions, Theory Institute in Particle Physics and Cosmology, 9-19 October 2019, CERN, Geneva , Switzerland

2020 *Cosmic Archaeology with Gravitational Wave Signals from Cosmic Strings*, From Inflation to Hot Big Bang, 30 I 2020, KITP Santa Barbara , USA

Gravitational waves from first order phase transitions, Cosmology Seminar, 30 VI 2020, NTUA, Athens , Greece

Cosmic String Interpretation of NANOGrav Pulsar Timing Data, HEP Seminar, 11 XII 2020, University of Southampton , UK

2021 *Cosmic String Interpretation of NANOGrav Pulsar Timing Data and its impact on Cosmic Archaeology with Gravitational Waves*, APC Theory Seminar, 20 IV 2021, Paris, France

Cosmic String Interpretation of NANOGrav Pulsar Timing Data and its impact on Cosmic Archaeology with Gravitational Waves, Theory Seminar , 20 V 2021, TU Dresden, Germany

AION and AEDGE: Gravitational physics with atom interferometry 16th Marcel Grossmann Meeting, 7 VII 2021, Virtual Meeting

Gravitational waves from bubble collisions in first order phase transitions, Gravitational Wave Probes of Physics Beyond Standard Model, 13 VII 2021, Warsaw, Poland

Gravitational waves from bubble collisions in first order phase transitions, SUSY 2021, 24 VIII 2021, Shanghai, China

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[1] Marek Lewicki and Ville Vaskonen. Gravitational waves from colliding vacuum bubbles in gauge theories. *Eur. Phys. J. C*, 81(5):437, 2021. arXiv:2012.07826, doi:10.1140/epjc/s10052-021-09232-3.

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[5] Rouzbeh Allahverdi et al. The First Three Seconds: a Review of Possible Expansion Histories of the Early Universe. 6 2020. arXiv:2006.16182, doi:10.21105/astro.2006.16182.

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[8] Yanou Cui, Marek Lewicki, and David E. Morrissey. Gravitational Wave Bursts as Harbingers of Cosmic Strings Diluted by Inflation. *Phys. Rev. Lett.*, 125(21):211302, 2020. arXiv:1912.08832, doi:10.1103/PhysRevLett.125.211302.

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