Multi-peaked signatures of primordial gravitational waves from multi-step electroweak phase transition

Thibault Vieu,1,2,3 António P. Morais,1 and Roman Pasechnik4
1Departamento de Física, Universidade de Aveiro and CIDMA, Campus de Santiago, 3810-183 Aveiro, Portugal
2Magistère de Physique Fondamentale, Université Paris-Saclay, Bât. 470, F-91405 Orsay, France
3International Centre for Fundamental Physics, Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France
4Department of Astronomy and Theoretical Physics, Lund University, 221 00 Lund, Sweden

The first-order electroweak phase transition in the early universe could occur in multiple steps leading to specific multi-peaked signatures in the primordial gravitational wave (GW) spectrum. We argue that these signatures are generic phenomena in multi-scalar extensions of the Standard Model particularly relevant for electroweak baryogenesis. In a simple example of such an extension, we have studied the emergence of reoccuring and nested vacuum bubble configurations and their role in the formation of multiple peaks in the GW spectrum. The conditions for potential detectability of these features by the forthcoming generation of interferometers have been studied.

PACS numbers: 12.10.Dm, 12.60.Jv, 12.60.Cn, 12.60.Fr

Introduction. Despite the great success of the Large Hadron Collider (LHC) in the discovery of the Higgs boson [1,2], thus completing the Standard Model (SM), the persistent absence of new physics evidence is driving an increasing discomfort among the particle physics community. The current void of new phenomena either indicates that new physics can only be manifest at a larger energy scale than previously thought, or results from a lack of sensitivity of the current experiments measuring rare events. In fact, the weaker the interaction strength between the SM and new physics, the greater the challenge to probe it.

On the other hand, the recent discovery of a binary neutron star merger, firstly observed by the gravitational waves (GW) interferometers of the LIGO-Virgo collaboration [3,4], a new era of multi-messenger astronomy has begun. Furthermore, the reach of GW observatories is by no means exhausted and larger sensitivities are designed for future space-based interferometers such as those of the eLISA [5,6], DECIGO [7] and BBO [8] collaborations. This opens up the door for a plethora of new studies including connections with both cosmology and particle physics (see e.g. Refs. [9–15]). In particular, the potential observation of a stochastic GW background produced by violent processes in the early universe, e.g. by expanding and colliding vacuum bubbles associated with strong cosmological phase transitions [16,17], may well become a gravitational probe for beyond-the-SM (BSM) physics and a complement for recent and future collider experiments.

The observed baryon asymmetry in nature is a major motivation to consider a strong first-order electroweak (EW) phase transition (EWPT) during the thermal evolution of the universe. This follows from the Sakharov conditions [18] stating that in addition to baryon number, C and CP violation, a strong departure from thermal equilibrium, via e.g. a first-order cosmological phase transition, is required to prevent dilution of the generated asymmetry by means of the CPT-theorem. However, neither a significant CP violation nor a strong EW transition are possible to achieve within the SM framework. Extended scalar sectors containing additional EW doublets and singlets are then needed, and even minimal extensions such as the Two-Higgs Doublet Model [19] and the Singlet-Extended SM [20,21] can successfully fulfill the Sakharov conditions providing the necessary means for efficient EW baryogenesis [22,31].

When extending the SM scalar sector, the underlying vacuum structure exhibits a growing complexity such that a possibility for transition patterns with several successive first-order steps arises. Multi-step transitions were discussed in Refs. [22,32,33] in the context of baryogenesis. In Refs. [22,34,35] it was shown that the EWPT could be very strong when occurring at tree-level. This leads to an amplification of free-energy release thus substantially enhancing the GW signals that emerge from the expanding and colliding bubbles.

We propose a possibility to probe new physics models with non-trivial vacuum structure by means of the GW data. We point out that the GW spectrum produced in multi-step strong EWPTs occurring at distinct temperatures in the early universe exhibits a multi-peaked shape which may be probed by future space-based GW observatories such as BBO and DECIGO. Such an observation would be a signature of multiple symmetry breaking stages, a step forward in our understanding of the EWPT and offer gravitational probes to BSM physics.

Multi-step electroweak phase transition. In cosmology, thermal evolution of the EW-breaking vacuum as the universe cools down is determined by the temperature-dependent part of the one-loop effective potential [36]. Given the field content and its quantum numbers of an underlying multi-scalar fundamental theory, the shape of the potential can be determined at any temperature...
In a configuration of two minima of the effective potential coexisting at the critical temperature $T_c$, by using CosmoTransitions \cite{36,38} one computes numerically the Euclidean action $\tilde{S}_3$ describing transitions between the corresponding phases. The temperature $T_n$, at which the nucleation of vacuum bubbles effectively occurs, is estimated by setting the probability to nucleate one bubble per horizon volume to unity, which translates into $\tilde{S}_3/T_n\sim140$ \cite{36,38}. The sphaleron suppression criterion $v_+/T_c\geq1$, with $v_+=v(T_c)$ the Higgs vacuum expectation value (VEV), defines a strong first-order phase transition. For non-runaway bubbles this typically means that the transition produces strong GW signals detectable by the next generation of interferometers and may be used for constraining BSM scenarios \cite{15,16}. Here we study successive strong first-order EWPTs which we refer to as multi-step transitions. This definition slightly differs from that in the literature, where, at variance with our analysis, the first step does not necessarily need to be strong. An important consequence of this yet unexplored ground is that we can have more than a single transition pattern for a particular point in the parameter space, which results in sequential nucleation of bubbles of different vacua.

A generic BSM scenario typically contains a large number of scalar degrees of freedom which can be advantageous e.g. for EW baryogenesis. Even reducing the scalar sector to a few fields, new unexplored possibilities of transition patterns arise, in particular, transitions in several successive first-order steps. Therefore, a non-trivial EWPT is expected and multi-step transitions may well have occurred in the early universe.

In order to illustrate the generic features of multi-step first-order EW transitions, consider for instance a minimal extension of the SM scalar sector inspired by the high-scale Grand-unified trinification theory \cite{33,35,36}. Besides the SM Higgs field $H_1$, it contains an additional EW doublet $H_2$ and singlet $\varphi$ fields which are charged under a $U(1)$ family symmetry. The resulting potential possesses an approximate discrete Z$_2$ symmetry acting as $H_j\rightarrow-H_j$ $(j=1,2)$ and $\varphi\rightarrow-\varphi$ which significantly simplifies the vacuum structure of the model. An expansion of the scalar fields in terms of real components

$$H_j=\frac{1}{\sqrt{2}}\left(\phi_j+i\chi_j\right), \quad \varphi=\frac{1}{\sqrt{2}}(\phi_s+S_R+iS_I),$$

defines the quantum fluctuations $h_1$, $h_2$ and $S_R$ about the classical field configurations $\phi_\alpha=\{\phi_1,\phi_2,\phi_s\}$, respectively. With this expansion, the classical potential reads

$$V_{cl}(\phi_\alpha)=\frac{1}{2}m_\alpha^2|\phi_\alpha|^2+\frac{1}{4}\lambda_\alpha|\phi_\alpha|^4+\frac{1}{4}\lambda_\alpha\beta|\phi_\alpha|^2|\phi_\beta|^2.$$  

A comprehensive analysis of the tree-level vacuum structure was performed recently in Ref. \cite{35}. It was shown that the basic characteristics of EWPTs in this model, in particular, sequential first-order transitions, are generic for multi-Higgs extensions of the SM. Thus, this model, due to the simplicity of its potential \cite{36}, could serve as a good benchmark scenario for further in-depth explorations of cosmological implications of multi-scalar BSM theories.

We focus on a simple representative configuration of the parameter space \cite{35} where the only existing phases given in terms of the VEVs of the scalar fields $v_\alpha=\langle\phi_\alpha\rangle_{\text{vac}}=\{v_1,v_2,v_s\}$ are $(0,0,0)$, $(v_1,0,0)$, $(0,v_2,0)$ and $(0,0,v_s)$, which we recast as $\{0\}$, $H_1$, $H_2$ and $\Phi$, respectively. The possible first-order transitions were found to be $H_1\leftrightarrow H_2$, $H_1\leftrightarrow \Phi$, $H_2\leftrightarrow \Phi$, which take place readily in the leading $(m/T)^2$ order of the thermal expansion and are expected to be strong.

*FIG. 1:* An illustration of a universe in the $\Phi$-phase filled with coexisting bubbles of new $H_1$ and $H_2$ phases emerging simultaneously (left panel), and also with nested bubbles when $H_1$-bubbles are born inside of $H_2$ ones (middle panel). In the right panel, the nucleation of the $H_1$-bubbles in the $\Phi$ phase causes the previously produced $H_2$-bubbles to contract simultaneously with nucleation of smaller $H_1$-bubbles inside them (reoccuring bubbles).
In what follows, without loss of generality we identify the stable phase at $T=0$ with $H_1$. Note, our current first study of the phase transitions between the $H_1$, $H_2$ and $\Phi$ vacua is simple but represents the basic features of a more involved scenario with the generic EW-breaking ground state $\{v_1,v_2,0\}$ at $T=0$.

**Coexisting, nested and reoccurring bubbles.** Consider first a sequence of phase transitions to the true vacuum $H_1$ with the following two patterns:

$$\Phi \rightarrow H_1, \quad \Phi \rightarrow H_2 \rightarrow H_1.$$  \hspace{1cm} (3)

One could expect several nucleation processes in the same range of temperatures, e.g. $\Phi \rightarrow H_1$ and $\Phi \rightarrow H_2$, meaning that different sequences could be realized during the same cosmological evolution time leading to a universe where coexisting bubbles of different broken phases expand simultaneously (left panel in Fig. 1).

In addition to the coexisting bubbles, more exotic cosmological objects may emerge from multi-step phase transitions. In particular, consider the second and third steps in the pattern $[0] \rightarrow \Phi \rightarrow H_2 \rightarrow H_1$, occurring at typical nucleation temperatures $T_n(\Phi \rightarrow H_2)\geq T_n(H_2 \rightarrow H_1)$. Between $T_n(\Phi \rightarrow H_2)$ and $T_n(H_2 \rightarrow H_1)$, the $H_2$-bubbles nucleate and expand in a universe filled with the $\Phi$-phase. Then at $T_n(H_2 \rightarrow H_1)$, while they are still expanding, the $H_1$-bubbles emerge and nucleate inside the $H_2$-bubbles. As such, the $\Phi$-phase becomes populated with the $H_2$-bubbles containing the $H_1$-bubbles inside. We denote such objects as nested bubbles shown in Fig. 1 (middle panel).

Since the scalar potential keeps evolving as the universe cools down below $T_n(H_2 \rightarrow H_1)$, the initial phase $\Phi$ becomes unstable also along the $H_1$ direction, so both transitions towards $H_1$ and $H_2$ can occur (coexisting bubbles scenario). In particular, if the potential barrier between the phases $\Phi$ and $H_1$ disappears, the new $H_1$-bubbles would nucleate in the parts of the universe that still remain in the $\Phi$-phase i.e. the direct $\Phi \rightarrow H_1$ transition quickly eliminates the $\Phi$-phase outside of the $H_2$-bubbles formed at an earlier time. Such a mixed situation with the coexistence of the ordinary $H_1$ and nested $H_2 \rightarrow H_1$ bubbles is depicted in Fig. 1 (middle panel). In the end of this process, one ends up with the $H_1$-bubbles inside the $H_2$-bubbles which exist in a universe filled with the $H_1$-phase. We denote these exotic cosmological objects as reoccurring bubbles. Since the $H_2$-bubbles cannot expand in a universe filled with the stable $H_1$-phase, they are pushed inwards and collapse while the $H_1$-bubbles nucleate inside them as illustrated in Fig. 1 (right panel).

In Fig. 2 we show three realistic cosmological scenarios where the objects discussed above are expected to occur. In the left column, we plot the evolution of the action $\hat{S}_j/T$ as a function of temperature for all possible transitions. Whenever a curve corresponding to a transition $i \rightarrow j$ crosses the horizontal line $\hat{S}_j/T=140$, a bubble of phase $j$ is nucleated inside the phase $i$, which is denoted as $i(j)$ in what follows. In the right column, we show a diagrammatic representation displaying all types of bubbles (co)existing at a given temperature and corresponding to the plots in the left column. For example, the top panel describes a first-order phase transition $\Phi \rightarrow H_1$ when $H_1$-bubbles nucleate in a universe filled with the $\Phi$-phase (i.e. $\Phi(H_1)$). In particular, a universe in the symmetric phase $[0]$ first collapses to the $\Phi$-phase through a second-order phase transition without generating any bubbles. Then, the $H_1$-bubbles are nucleated at $T \sim 105$ GeV and expand until the $\Phi$-phase becomes unstable at around $T \sim 60$ GeV leaving a universe entirely filled by the true vacuum $H_1$. Provided that the transition occurs over the interval $\Delta T \sim 45$ GeV, it is very likely that the bubbles percolate before this last step, although it also depends on the details of a multi-scalar model as well as on dynamics of the nucleated bubbles which will be discussed elsewhere.

While the graphs on the second line of Fig. 2 represent a scenario where three successive steps lead to the nucleation of a nested bubbles $\Phi(H_2(H_1))$, those on the last line describe reoccurring bubbles that emerges from a nested ones. For instance, after nucleation of nested bubbles $\Phi(H_2(H_1))$, the potential barrier between the phases $\Phi$ and $H_1$ disappears (around $T \sim 60$ GeV), such that the parts of the universe in the $\Phi$-phase collapse to the $H_1$-
phase transforming the nested bubbles $\Phi(H_2(H_1))$ into the reoccurring ones $H_1(H_2(H_1))$. This type of cosmological objects is only possible if the nucleation temperatures of the corresponding steps are not too different (percolation typically occurs in the range of $\Delta T < 10$ GeV), and further likely to occur when symmetries in the potential enforces them to be identical as in e.g. Ref. [41].

**Multi-peaked gravitational-wave spectrum.** As a phenomenological probe, we suggest that multi-step transition patterns such as the ones discussed above leave a characteristic signature in the spectrum of GWs exhibiting a multi-peaked shape. The main idea is that, provided that the properties of the bubble nucleation process are different for successive transitions between distinct phases, we can expect a superposition of GW signals with different frequency peaks, whose positions mostly depend on the inverse time scale of each transition. Typically, the larger the time scale, the smaller the frequency of the corresponding GW signal.

We analyse the multi-peaked signatures in the power spectrum of GWs using the well known formalism of Ref. [11, 42, 43] which describes the energy density per logarithmic frequency of the GW radiation, $h^2\Omega_{GW}$. The GW signal is a linear superposition of three components parameterizing bubble wall collisions, sound waves generated by the phase transitions as well as magnetohydro-dynamics turbulences in the plasma.

Since both transitions $\Phi \to H_1$ and $\Phi \to H_2$ occurring in parallel to each other are the strong first-order ones in the considered model [35], their typical time scale is rather small, $10^{-6}-10^{-5}$s. It is then expected that the three transitions in Eq. (3) share similar properties resulting in a profile for the GW spectrum with peaks likely to be close to each other, as seen in the left panel of Fig. 3 with frequencies of, approximately, $10^{-3}$Hz and $2 \times 10^{-2}$Hz. For the current pattern, depending on the accuracy of the measurement, it may be possible to detect a signature of the second transition as the black curve shows. While the patterns in Eq. (3) may be only partially probed, the peak amplitudes are large enough to be within the reach of planned space based interferometers such as BBO and DECIGO.

Alternatively, well separated peaks can be generated by transitions with very different time scales. Therefore, a multi-peaked GW spectrum of this kind should be produced by another pattern with, at least, one short-lasting and one long-lasting transitions. Let us consider two breaking steps where the first one is generated by thermal loop effects, in the spirit of the models studied in, e.g. Refs. [22, 32, 44]. For instance, the $|0\rangle \to \Phi \to H_1$ pattern, where the first $|0\rangle \to \Phi$ step becomes a first-order transition due to the effect of cubic contributions in the thermal $m/T$ expansion. For such transitions, a sample of the corresponding GW signals are displayed at the right panel of Fig. 3. Here, we observe two well-separated peaks but with amplitudes much smaller than those found in the left panel. This is a consequence of relatively weak first-order phase transitions whose strengths are of the order $v_n/T_n \sim 0.2-0.5$. In particular, the loop-generated ones, which have a much larger time scale than those that are already first-order at tree level, have their
The authors would like to thank Acknowledgments.

Signatures and thus strongly motivating further studies dant leading to potentially observable multi-peaked GW possible and such processes could become more abundant large scalar sectors, a variety of transition patterns is from Grand-unified field theories, which typically offer nucleated. In generic BSM theories emerging bables can be nucleated. In generic BSM theories emerging phase transitions take place at close temperatures, exetered peaks. We have also argued that if different such transitions have a different origin, i.e. one is generated by radiative and thermal corrections while the other more complicated multi-scalar models (e.g. with mixing) where the loop-induced transitions, followed by another strong first-order transition, emerge within the detection limits (e.g. Ref. [23]).

We would like to point out that a complete knowledge of the bubble dynamics is needed in order to precisely describe the phase transitions, from nucleation to percolation. While this is beyond the scope of the present letter, one may raise a few immediate questions that result from our analysis: do we expect new sources of GWs when nested bubbles collide or when a nested bubble expands faster than its “mother bubble” reaching the wall of the latter? Given that in general such objects have no reason to be spherically symmetric, what is their impact on the profile of the GW spectrum? What is the impact of nested vacuum bubbles for baryogenesis? These are important questions for a further deeper analysis.

Conclusions. We have shown how multi-peaked GW spectra can originate from multi-step strong first-order phase transitions in multi-scalar BSM theories. Taking a simple model as an example, we found that when two of such transitions have a different origin, i.e. one is generated by radiative and thermal corrections while the other is present at tree level, the GW spectrum exhibits two well resolved peaks. We have also argued that if different phase transitions take place at close temperatures, exotic cosmological objects like coexisting and nested bubbles can be nucleated. In generic BSM theories emerging from Grand-unified field theories, which typically offer large scalar sectors, a variety of transition patterns is possible and such processes could become more abundant leading to potentially observable multi-peaked GW signatures and thus strongly motivating further studies in this direction.

Acknowledgments. The authors would like to thank C. Herdeiro, M. Sampaio, J. Rosa and M. Ouerfelli for useful discussions in the various stages of this work. A.P.M. is funded by the FCT grant SFRH/BPD/97126/2013. R.P. thanks Prof. C. Herdeiro for support of the project and hospitality during his visits at Aveiro university. R.P. is partially supported by the Swedish Research Council, contract number 621-2013-428 and by CONICYT grant PIA ACT1406. The work in this paper is also supported by the CIDMA project UID/MAT/04106/2013. T. V. received a financial support Erasmus+ for international mobility from Université Paris-Sud.

[1] G. Aad et al. (ATLAS), Phys. Lett. B716, 1 (2012), 1207.7214.
[2] S. Chatrchyan et al. (CMS), Phys. Lett. B716, 30 (2012), 1207.7235.
[3] B. P. Abbott et al. (Virgo, LIGO Scientific), Phys. Rev. Lett. 116, 061102 (2016), 1602.03837.
[4] B. P. Abbott et al. (Virgo, LIGO Scientific), Phys. Rev. Lett. 116, 241103 (2016), 1606.04855.
[5] P. A. Seoane et al. (eLISA) (2013), 1305.5720.
[6] N. Bartolo et al., JCAP 1612, 026 (2016), 1610.06481.
[7] S. Kawamura et al., Class. Quant. Grav. 28, 094011 (2011).
[8] V. Corbin and N. J. Cornish, Class. Quant. Grav. 23, 2435 (2006), gr-qc/0512039.
[9] P. Huang, A. J. Long, and L.-T. Wang, Phys. Rev. D94, 075008 (2016), 1608.06619.
[10] J. M. No, Phys. Rev. D84, 124025 (2011), 1103.2159.
[11] C. Grojean and G. Servant, Phys. Rev. D75, 043507 (2007), hep-ph/0607107.
[12] R. Aprea, M. Maggiore, A. Nicola, and A. Riotto, Nucl. Phys. B631, 342 (2002), gr-qc/0107033.
[13] K. Hashino, M. Kakizaki, S. Kanemura, and T. Matsui, Phys. Rev. D94, 015005 (2016), 1604.02069.
[14] K. Hashino, M. Kakizaki, S. Kanemura, P. Ko, and T. Matsui, Phys. Lett. B766, 49 (2017), 1609.00297.
[15] M. Kakizaki, S. Kanemura, and T. Matsui, Phys. Rev. D92, 115007 (2015), 1509.08394.
[16] M. Hindmarsh, S. J. Huber, K. Rummukainen, and D. J. Weir, Phys. Rev. Lett. 112, 041301 (2014), 1304.2433.
[17] M. Hindmarsh, S. J. Huber, K. Rummukainen, and D. J. Weir, Phys. Rev. D92, 123009 (2015), 1504.03291.
[18] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967), [Usp. Fiz. Nauki161,61 (1991)].
[19] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Phys. Rept. 516, 1 (2012), 1106.0034.
[20] V. Barger, P. Langacker, M. McCaskey, M. J. Ramsey-Musolf, and G. Shaughnessy, Phys. Rev. D77, 035005 (2008), 0706.4311.
[21] V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf, and G. Shaughnessy, Phys. Rev. D79, 015018 (2009), 0811.0393.
[22] V. Vaskonen, Phys. Rev. D95, 123515 (2017), 1611.02073.
[23] A. Beniwal, M. Lewicki, J. D. Wells, M. White, and A. G. Williams (2017), 1702.06124.
[24] J. M. Cline and K. Kainulainen, JCAP 1301, 012 (2013), 1210.4196.
[25] G. Kurup and M. Perelstein, Phys. Rev. D96, 015036 (2017), 1704.03381.
[26] T. Li and Y.-F. Zhou, JHEP 07, 006 (2014), 1402.3087.
[27] M. Jiang, L. Bian, W. Huang, and J. Shu, Phys. Rev. D93, 065032 (2016), 1502.07574.
[28] P. Basler, M. Krause, M. Mühlleitner, J. Wittbrodt, and A. Wlotzka, JHEP 02, 121 (2017), 1612.04086.
[29] P. Basler, M. Muhlleitner, and J. Wittbrodt (2017), 1711.04097.
[30] G. C. Dorsch, S. J. Huber, and J. M. No, JHEP 10, 029 (2013), 1305.6610.
[31] I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, and D. Sokolowska, Phys. Rev. D82, 123533 (2010), 1009.4593.
[32] H. H. Patel and M. J. Ramsey-Musolf, Phys. Rev. D88, 035013 (2013), 1212.5652.
[33] S. Inoue, G. Ovanesyan, and M. J. Ramsey-Musolf, Phys. Rev. D93, 015013 (2016), 1508.05404.
[34] T. Alanne, K. Kainulainen, K. Tuominen, and V. Vaskonen, JCAP 1608, 057 (2016), 1607.03303.
[35] T. Vieu, A. P. Morais, and R. Pasechnik (2018), 1801.02670.
[36] M. Quiros, Proceedings of Summer School in High-Energy Physics and Cosmology: Trieste, Italy, June 29-July 17, 1998 pp. 187–259 (1999), hep-ph/9901312.
[37] C. L. Wainwright, Comput. Phys. Commun. 183, 2006 (2012), 1109.4189.
[38] M. Dine, R. G. Leigh, P. Y. Huet, A. D. Linde, and D. A. Linde, Phys. Rev. D46, 550 (1992), hep-ph/9203203.
[39] J. E. Camargo-Molina, A. P. Morais, A. Ordell, R. Pasechnik, M. O. Sampaio, and J. Wessén, Phys. Rev. D95, 075031 (2017), 1610.03642.
[40] J. E. Camargo-Molina, A. P. Morais, A. Ordell, R. Pasechnik, and J. Wessén (2017), 1711.05199.
[41] I. P. Ivanov, J. Phys. Conf. Ser. 873, 012036 (2017), 1702.07542.
[42] L. Leitao and A. Megevand, JCAP 1605, 037 (2016), 1512.08962.
[43] C. Caprini et al., JCAP 1604, 001 (2016), 1512.06239.
[44] A. Buonanno, G. Sigl, G. G. Raffelt, H.-T. Janka, and E. Muller, Phys. Rev. D72, 084001 (2005), astro-ph/0412277.