Probing new physics with multi-vacua quantum tunnelings beyond standard model through gravitational waves

Zihan Zhou, ¹, ², ³, Jun Yan, ¹, ², ³, ‡ Andreas Addazi, ⁴, ⁵, †
Yi-Fu Cai, ¹, ², ³, § Antonino Marciano, ⁶, ⁷, ⁸, and Roman Pasechnik ⁸, **

¹ Department of Astronomy, School of Physical Sciences,
University of Science and Technology of China, Hefei, Anhui 230026, China
² CAS Key Laboratory for Researches in Galaxies and Cosmology,
University of Science and Technology of China, Hefei, Anhui 230026, China
³ School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, China
⁴ Center for Theoretical Physics, School of Physics Science and Technology, Sichuan University, 610065 Chengdu, China
⁵ INFN sezione Roma Tor Vergata, I-00133 Rome, Italy, EU
⁶ Department of Physics & Center for Field Theory and Particle Physics, Fudan University, Shanghai 200433, China
⁷ Laboratori Nazionali di Frascati INFN, Frascati (Rome), Italy, EU
⁸ Department of Astronomy and Theoretical Physics, Lund University, 221 00 Lund, Sweden, EU

We report on a novel phenomenon of particle cosmology, which features specific cosmological phase transitions via quantum tunnelings through multiple vacua. This is inspired by the axion(-like) scalar potential, and enables to probe the associated new physics models, constraining these from the stochastic gravitational waves background. Multiple vacua may induce the nucleation of multiple co-existing bubbles over the phase transition epoch, hence enhancing the overall process of bubbles’ nucleation. Our detailed analysis of semi-analytical and numerical solutions to the bounce equations of the path integral, enabled us to determine the existence of three most probable escape paths towards a local maximum of the Euclidean action. These generate non-negligible contributions to the overall decay rate to the true vacuum. This new mechanism of cosmological phase transitions naturally yields multiple vacua for a single scalar field. Inspired by this innovative phenomenology, we propose in this Letter to study quantum tunneling transitions, within the case of non-degenerate multiple vacua in a simple model with a single axion-inspired scalar field. Besides, we illustrate the possibility of probing new physics scenarios of this type by analysing the signals of the primordial GWs spectra generated by such transitions.

Instanton methods, initially developed in [47–49] to investigate quantum tunnelings in a gravitational environment, are nowadays widely exploited in the community. Even the functional Schrödinger equation, supplied with the WKB approximation, was established to gain further insights into fields’ potentials endowed with multi-vacua [50–52]. The path integral over the quantum field configurations is addressed in terms of the most probable escape paths (MPEP) dominating it in the classically forbidden region. In this Letter, we perform a complete analysis of quantum tunnelings for the non-degenerate multi-vacua case, which preserves the major characteristics of the cosmological relaxation, and can yield well-behaved approximate solutions to the so-called bounce equations of the path integral. Around the reheating epoch, multiple types of bubbles would run away in a cosmic medium, naturally yielding multiple vacua for a single scalar field. Inspired by this innovative phenomenology, we propose in this Letter to study quantum tunneling transitions, within the case of non-degenerate multiple vacua in a simple model with a single axion-inspired scalar field. Besides, we illustrate the possibility of probing new physics scenarios of this type by analysing the signals of the primordial GWs spectra generated by such transitions.

Insta

Introduction. – Cosmological phase transitions (PTs) offer an inspiring possibility to probe physics beyond the Standard Model (SM). If first-order PTs took place at early cosmological times, a gravitational waves (GWs) spectrum can be induced, with crucial observational consequences for current and future GW experiments [1–4]. Such a scenario is traditionally considered in the hot cosmological plasma characterized by a scalar-field effective potential accounting for both the loop and thermal corrections. In such a thermal system, the quantum tunneling is either ignored or only considered as happening between two vacua at a typical time scale of a given PT. [5]. However, in order to realize strong enough first-order PTs, several extended models of particle physics were considered that involve more than two vacua in the effective potential at a given temperature. These are models with extra scalar singlets [6–11] and doublets [12–16], dimensional six effective operators [17–21], as well as supersymmetric models [22–24], hidden dark sectors [25–36], and other SM extensions. [37–40].

Nonetheless, new physics beyond the SM may arise for example by invoking the axion, originally postulated in Ref. [41–43] to address the strong CP problem in quantum chromodynamics (QCD), or axion-like particles. The axion was recently revitalized in the cosmological relaxation model, to dynamically address the electroweak (EW) hierarchy problem [44–46], which also

¹ Several scalar fields can be accounted for giving rise to cosm-
and generate GWs that are expected to be examined in various observational windows, including GW astronomy and cosmic microwave background (CMB) signals [60].

**Multi-vacua quantum tunnelings.** – According to the relaxation model, the inspired scalar field $\sigma$ evolves into the classically stable but quantum metastable regions where quantum fluctuations would become dominant in its subsequent evolution. For simplicity, we illustrate the three vacua case, assuming the decay through the four-vacua configuration in a single transition to be exponentially suppressed. Capturing the essence for multi-vacua quantum tunnelings, we consider the scalar potentials as

$$V(\sigma) = \begin{cases} 
\frac{1}{4}(\sigma - 2a_1)^2\sigma^2 - b_1\Lambda^3(\sigma - 2a_1) & |\sigma| < 0 , \\
\frac{1}{4}(\sigma - 2a_2)^2\sigma^2 + \Lambda^2(2b_1a_1 - 2b_2\sigma) & |\sigma| \geq 0 .
\end{cases} \tag{1}$$

In Eq. (1), four parameters were introduced, $a_1$ and $a_2$ roughly denoting the expectation value of the false vacuum and of the true vacuum, respectively, while $b_1$ and $b_2$ realizing the energy differences among the three vacua; $\Lambda$ is an effective energy scale, which, in an axion-inspired model, may be identified as $\Lambda_{QCD} \approx 200$ MeV. In our analysis, we impose matching conditions, between the two sides of the potential, on the parametric space $(a_1, b_1, a_2, b_2)$ of our model, avoiding any discontinuities.

Since this axion-inspired scalar field $\sigma$ was practically decoupled from any other SM fermions and bosons, while having suppressed scalar self-interactions, the bubble nucleation temperature $T_n$ of early Universe would just provide the average kinetic energy available for the scalar fields, without any significant modifications to the potential barrier shape. On the other hand, in our case, it is difficult to find such $T_n$ satisfying strong first order PTs condition $S_3(T_n)/T_n \sim 140$ in hot Universe. Then the dominant PTs contribution will be realized by quantum tunnelings with $T_n \approx 0$. The small thermal fluctuations estimated by $T^2(\sigma - 2a_1)^2$ here reduce the energy difference in Eq. (1), thus leading to the secondary effect against quantum tunnelings. As an example, we choose the parameters so that the effective mass of $\sigma$ satisfies $m_\sigma \lesssim O(10)$ GeV. This typically corresponds to some moment after inflation, but before reheating with small thermal corrections.

The profile of the potential is sketched in the left top panel of Fig. 1. Ignoring thermal perturbations, quantum tunnelings originate from the homogeneous Universe within a false vacuum, and eventually terminate at a homogeneous Universe within a true vacuum.

The semiclassical equation of motion can be both numerically and analytically solved. After inflation, we approach the lower energy scale $\Lambda$, for which suppressed interaction terms of the form $\sigma^n$, with $n > 4$, can be ignored. With the functional Schrödinger equation for $H = \int d^4x \left( -\frac{\hbar^2}{2m_\sigma} \frac{\delta^2}{\delta \sigma^2} + \frac{1}{2}(\nabla\sigma)^2 + V(\sigma) \right)$, namely

$$H\Psi(\sigma, x) = E\Psi(\sigma, x),$$

and the WKB approximation $\Psi(\sigma) = \mathcal{A}\mathcal{E}^{\pm S(\sigma)}$, with $S(\sigma) = S(0) + \hbar S(1)(\sigma) + \cdots$, one may derive the MPEP semi-classical bounce equation

$$\frac{\partial^2 \sigma(x, \tau)}{\partial \tau^2} + \mathcal{V}^2\sigma(x, \tau) - \frac{\partial V(\sigma(x, \tau))}{\partial \sigma} = 0 \bigg|_{\tau < 0},$$

$$\frac{\partial^2 \sigma(x, \tau)}{\partial \tau^2} - \mathcal{V}^2\sigma(x, \tau) + \frac{\partial V(\sigma(x, \tau))}{\partial \sigma} = 0 \bigg|_{\tau \geq 0}, \tag{2}$$

where $\tau$ is the parameter of MPEP, ranging from $-\infty$ to $+\infty$, with the critical point, separating the classically forbidden region ($\tau < 0$) and the classically allowed region ($\tau \geq 0$), being fixed exactly at $\tau = 0$. For cosmological PTs, the former equation can be recognized to describe the bubble nucleation processes, while the latter one drives the bubble evolutions, during which the energy-momentum tensor of the field can evolve and generate GWs.

Following [61], the MPEP solutions to the first bounce equation ought to obey the $O(4)$ invariance and satisfy $\frac{\partial \sigma}{\partial \tau} = 0$ as well as $\sigma(\tau \to -\infty) = \sigma_F$, with $\sigma_F$ value of the false vacuum, as depicted in Fig. 1. The analytical solutions can be derived through the variational method:

$$\sigma(\rho) = \frac{1}{2}\sigma_F \tanh\left( \frac{\mu_1}{2}(\rho - R_1) \right) + \frac{1}{2}\sigma_F$$

$$- \frac{1}{2}\sigma_T \tanh\left( \frac{\mu_2}{2}(\rho - R_2) \right) + \frac{1}{2}\sigma_T,$$

with $\rho = \sqrt{x^2 + \tau^2}$, $\mu_1 = \sqrt{2a_1^2}$ and $\mu_2 = \sqrt{2a_2^2}$. $R_1$, $R_2$ are the variational parameters. Then, the Euclidean action can be expressed as

$$S_E[\sigma] = 2\pi^2 \int_0^{+\infty} \rho^3 \left( \frac{1}{2} \left( \frac{d\sigma}{d\rho} \right)^2 + V(\sigma) \right) d\rho , \tag{4}$$

Varying the action with respect to $R_1$ and $R_2$, one can get the estimated solutions. Numerical computation can be derived via the Runge-Kutta algorithm for nonlinear ODE based on the package of CosmoTransitions [62]. The process involving three vacua provides us with a novel picture of tunneling transitions. In the previous literature, authors considered only one solution to the bounce equation, which allowed to denote only one MPEP. Our model can now lead up to three MPEPs at most. If we further require that $\sigma|_{\tau = 0} = \sigma_M$, we can get a trivial solution which is ‘Bubble3’ in the right small panel in Fig. 1. The existence of this solution is independent on the model parameters $a_1$, $a_2$, $b_1$ and $b_2$, while the other two are model-dependent.

All numerical solutions to the bounce equation are shown in the small panel at the middle top region of Fig. 1, having fixed the values of the four parameters.
The three tunneling processes depicted can occur simultaneously in the Universe, at an estimated rate per volume $\Gamma \sim e^{-S_E}$. In our case, ‘Bubble1’ and ‘Bubble2’ solutions are driven by quantum effects, adding two new MPEPs which can not appear in the classical case. Since the length of bubble walls is small enough $\delta l/l \ll 1$, the solutions can be further simplified in thin-wall approximation with the tanh function, in analogy with the solution of the quartic potential with degenerate vacua. Additionally, we see that the two radii of ‘Bubble1’ are nearly the same, rendering negligible the existence of $\sigma_M$; while, for ‘Bubble2’, one can simply sum together the two parts of the contributions, which arise from $(\sigma_F, \sigma_M)$ and $(\sigma_M, \sigma_T)$ respectively. Although we can also get more complicated cases like nested and recoucurring [63] bubble profiles by only preserving $O(3)$ symmetry and solving both of the two equations in Eq.(2) simultaneously, these solutions are not from pure quantum effects, inconsistent with our main consideration. Note that the Universe was extremely empty after inflation and before reheating. In this epoch, the plasma effect is negligible, and the bubbles expand and collide with each other to reach thermal equilibrium. Since both ‘Bubble1’ and ‘Bubble2’ trigger the tunnelings towards $\sigma_T$, the whole Universe shall reach the final state represented by the true vacuum, eventually.

Astonishingly, for specific model parameters, ‘Bubble1’ and ‘Bubble2’ can vanish at the same time, and then ‘Bubble3’ is the only solution. We name this novel phenomenon as “Two Step Tunneling” (TST). This is the first time that someone realized TST in cosmological PTs within the context of single field models.2 Looking at the ‘Bubble1’ and ‘Bubble2’ solutions in Fig. 1, the radii $R_1$ and $R_2$ show a decreasing behaviour when $\Delta b$, which controls the energy difference separation between vacua, decreases. Numerically, we scan the $\Delta b$ parameter space from 0.014 GeV$^3/\Lambda$ to 0.043 GeV$^3/\Lambda$. Below this range both the solutions vanish. The variation of $R_1$ and $R_2$ provides the solutions to Eq. (2). Then $S_E$ approaches its static points, of which ‘Bubble2’ corresponds to the maximum point and ‘Bubble1’ to the saddle point. This implies $\frac{\delta S_E[\sigma]}{\delta R_1} = \frac{\delta S_E[\sigma]}{\delta R_2} = 0$. When the action of each of the two bubbles reaches the same value, the maximum point and the saddle point coincide. Afterwards, for smaller $\Delta b$, there is no static point for any bubble radius, and then, ‘Bubble3’ is the only MPEP ensuring the quantum decay. The false vacuum $\sigma_F$ would first tunnel to the intermediate vacuum $\sigma_M$, and then experience the second tunneling to reach the true vacuum $\sigma_T$.

The occurrence of TST can actually impose very strict constraints on the model parameters. For instance, in the very early Universe the curvaton could decay into radiation, and hence raise the temperature of the Universe thus approaching the reheating regime. In this case, a finite temperature correction $\sim T^2 \sigma^2$ should be taken into account in the effective potential. After its quantum decay into the intermediate vacuum $\sigma_M$, along with the increase of the temperature, the true vacuum $\sigma_T$ would become degenerate with $\sigma_M$, and then even vanish. If one still requires TST to occur in the specific example of Fig. 1, the reheating temperature is expected to be below 0.5 GeV, so that $\sigma_M$ and $\sigma_T$ would not be degenerate. As in this Letter we focus on a preliminary analysis of quantum tunnelings via multiple vacua, we leave to forthcoming studies more detailed investigations.

**GW signals.** – For ‘Bubble1’ and ‘Bubble2’ solutions, tunneling rates increase when the energy difference separation $\Delta b$ becomes smaller. The magnitude of $S_E$ stays of the same order for ‘Bubble1’ and drops down an order of magnitude for ‘Bubble2’. This effect becomes important for an efficient generation of GWs. In general, there exist three major sources for GWs from cosmological PTs [67, 68], which respectively are collisions of vacuum bubbles [69, 70], sound waves [71–73] due to bubbles’ expansions inside the plasma, and MHD turbulence [74–76] after collisions. Concerning the PTs dynamics of axion-inspired model in the vacuum-dominated epoch, which is not significantly affected by the thermal corrections we have discussed, we naturally explore bubbles dynamics in run-away regime, where it is very well known that

\[ \text{GW signals.} \]

---

2 We refer to [34] for the realization with a two-field model and [63–66] for more exotic situations.
contributions to GWs spectrum from MHD turbulence and sound waves are negligible compared to collisional contributions [67, 68]. Nevertheless, the multi-nucleation phenomena may be recast in a more general context, well far from the run-away condition, as understood. As for the GWs production, it is sensitive to the temperature at reheating due to those different types of bubble dynamics and cosmological background. We assume that the GWs are produced in a thermal bath at temperature $T_*$ which approximately equals the reheating temperature $T_{\text{reh}} \sim T_*$.

Recall that, the observational constraint upon reheating temperature is pretty loose, namely, the Big Bang Nucleosynthesis (BBN) yields a lower bound $T_{\text{reh}} > 1 \text{ MeV}$ [77, 78]. In this case, the GW intensity $\Omega_\sigma$ and the related peak frequency $f_\sigma$ caused by $\sigma$ can be approximated as follows,

$$
\Omega_\sigma h^2 \approx 1.67 \times 10^{-5} \left( \frac{1}{\beta} \right)^2 \left( \frac{\kappa_\sigma \alpha}{1 + \alpha} \right)^2 \frac{1}{g_\ast} \times \left( \frac{0.11 \nu_u^3}{0.42 + \nu_u^2} \right) \frac{3.8}{1 + 2.8 \frac{f}{f_\sigma}} \frac{1}{1.8 - 0.11 \nu_u + \nu_u^2} \frac{1}{\beta} f_\sigma \approx 1.65 \times 10^{-5} \text{Hz} \left( \frac{g_\ast}{100} \right) \left( \frac{T_\ast}{100 \text{ GeV}} \right) \left( \frac{T_{\text{reh}}}{14 \text{ GeV}} \right),
$$

with the two key parameters $\alpha$ and $\beta$. The former one, $\alpha$, is defined at the PT temperature $T_n$ by $\alpha \equiv \kappa(T_n)/\rho_{rad}(T_n)$, and introduces the ratio between the energy difference among two vacua and the thermal energy density of the plasma $\rho_{rad}(T_n) \propto T_n^4$. The latter one, $\beta$, is the bubbles nucleation rate parameter, captured by $\beta \equiv -dS_E/dt|_{t_n} \simeq 1/\Gamma (d\Gamma/dt)|_{t_n}$, which is often rescaled by $\bar{\beta} \equiv \beta/\bar{H}_n = T_n (dS_E/dt)|_{T=T_n}$, so to account for the concurring expansion of the Universe. Finally, $\kappa_\sigma$ characterizes the fraction of the latent heat for the energy transfer.

PTs driven by $\sigma$ in our model are due to quantum mechanical effects, implying $T_n \approx 0$ and thus $\alpha \rightarrow \infty$. In this limit, one gets $\Omega_{GW} \approx \Omega_\sigma$, with $\kappa_\sigma \sim 1$ and $\nu_u \sim 1$. We present the results in Fig. 2. The total GW signals can be separated into three components, corresponding to the contributions of three types of vacuum bubbles in Fig. 2(a). For relatively large energy difference separations, i.e. $\Delta b > 0.035 \text{ GeV}^3/\Lambda^3$, the signals from ‘Bubble2’ and ‘Bubble3’ are severely suppressed, resulting in the fact that the total spectrum is given by the ‘Bubble1’ contribution. Indeed, a large energy difference separation implies an enhanced $S_E$ value in ‘Bubble2’, and similarly in ‘Bubble3’, which then leads to a rather low tunneling rate. When the energy difference separation is around $0.020 \text{ GeV}^3/\Lambda^3$, and above $0.014 \text{ GeV}^3/\Lambda^3$, $S_{E1}$ and $S_{E2}$ decrease, and their ratio $S_{E1}/S_{E2}$ is order of unity. The related tunneling rates will be of the same magnitude, giving rise to similar contributions from ‘Bubble1’ and ‘Bubble2’. The tiny differences between these three contributions can only influence the fine structure of the GW spectra, which could be examined thanks to data from the future GW interferometers. Since $S_E$ significantly depends on $\Delta b$, the amplitude of GW spectra can vary up to $O(10^2)$ in the considered example. We emphasize that, the result predicted in our case is fundamentally different from other cosmological PTs, due to the fact that the profile of the GW spectrum is unique. For instance, in the standard case of thermal PTs there are extra contributions from sound waves and MHD turbulence, but...
Conclusions.—In this Letter we put forward a novel mechanism to generate cosmological PTs via quantum tunneling transitions that may arise due to new physics described in terms of axion-inspired scalar field models with multiple vacua. Accounting for a specific parameterization of the field potential, we made first semi-analytical and numerical analyses, providing an explicit solution involving three MPEPs, and calculating the quantum decay rates. Our mechanism provides a platform for phenomenological investigations of the rich structure of quantum tunnelings, namely, an innovative realization of the TST phenomenon within the single field scenario in cosmology. This process can lead to a spectrum of induced stochastic GWs, of which the profile is uniquely predicted. Due to the fact that its origin is different from those arisen from sound waves and MHD turbulence, this newly proposed GW source is observationally distinguishable in the future GW astronomy.

We end by discussing several implications of the novel mechanism that could inspire forthcoming studies. From theoretical perspective, our study illustrates that new physics beyond SM could be accessible through cosmological PTs if multiple vacua are allowed. This may be also related to the SM hierarchy problem, through embedding into the relaxation model. Phenomenologically, we report a new paradigm of quantum tunnelings, leading to fruitful phenomena in cosmological PTs. We have neglected tunnelings along more consecutive vacua, but this theoretical possibility deserves further investigations, as a pathway to get better understanding on the new physics related to axion(-like) particles. Furthermore, the physical picture of quantum tunnelings depicted in our mechanism can be also related to the inhomogeneous initial conditions that arise because of thermal perturbations, which may result in resonant tunnelings with higher decay rates. Although it may be challenging to test the heuristic example we are focused on within this Letter, with the resolutions of current GW experiments, our study can either be extended to several theoretical scenarios, or provide detection targets for the next generation of GW instruments.

Acknowledgments.—We are grateful to Peter Graham, Misao Sasaki, and Hao Yang for valuable comments. YFC is supported in part by the NSFC (Nos. 11722327, 11653002, 11961130107, 11421303), by the CAST-YESS (2016QNR001), by the National Youth Talents Program of China, and by the Fundamental Research Funds for Central Universities. AM is supported in part by the NSFC (No. 11875113), by Shanghai Municipality (No. KBH1512299), and by Fudan University (No. JH1512105). RP is supported in part by the Swedish Research Council (No. 621-2013-4287). All numerics were operated on the computer clusters LINDA & JUDY in the particle cosmology group at USTC.

References:

1. E. Witten, “Cosmic Separation of Phases,” Phys. Rev. D 30, 272 (1984).
2. C. J. Hogan, “Nucleation Of Cosmological Phase Transitions,” Phys. Lett. 133B, 172 (1983).
3. C. J. Hogan, “Gravitational radiation from cosmological phase transitions,” Mon. Not. Roy. Astron. Soc. 218, 629 (1986).
4. M. S. Turner and F. Wilczek, “Relic gravitational waves and extended inflation,” Phys. Rev. Lett. 65, 3080 (1990).
5. M. Quiros, “Finite temperature field theory and phase transitions,” Proceedings, Summer School in high-energy physics and cosmology: Trieste, Italy, June 29-July 17, 1998 hep-ph/9903132.
6. G. W. Anderson and L. J. Hall, “The Electroweak phase transition and baryogenesis,” Phys. Rev. D 45, 2685 (1992).
7. J. R. Espinosa and M. Quiros, “The Electroweak phase transition with a singlet,” Phys. Lett. B 305, 98 (1993) [hep-ph/9301285].
8. J. R. Espinosa and M. Quiros, “Novel Effects in Electroweak Breaking from a Hidden Sector,” Phys. Rev. D 76, 075004 (2007) [hep-ph/0701145].
9. S. Profumo, M. J. Ramsey-Musolf and G. Shaughnessy, “Singlet Higgs phenomenology and the electroweak phase transition,” JHEP 0708, 010 (2007) [arXiv:0705.2425 [hep-ph]].
10. J. R. Espinosa, T. Konstandin and F. Riva, “Strong Electroweak Phase Transitions in the Standard Model with a Singlet,” Nucl. Phys. B 854, 592 (2012) [arXiv:1107.5441 [hep-ph]].
11. F. P. Huang and C. S. Li, “Electroweak baryogenesis in the framework of the effective field theory,” Phys. Rev. D 92, no. 7, 075014 (2015) [arXiv:1507.08168 [hep-ph]].
12. J. M. Cline and P. A. Lemieux, “Electroweak phase transition in two Higgs doublet models,” Phys. Rev. D 55, 3873 (1997) [hep-ph/9609240].
13. G. C. Dorsch, S. J. Huber and J. M. No, “A strong electroweak phase transition in the 2HDM after LHC8,” JHEP 1310, 029 (2013) [arXiv:1305.6610 [hep-ph]].
14. P. Basler, M. Krause, M. Mühleitner, J. Wittbrodt and A. Wlotzka, “Strong first-order Electroweak Phase Transition in the CP-Conserving 2HDM Revisited,” JHEP 1702, 121 (2017) [arXiv:1612.04086 [hep-ph]].
15. G. C. Dorsch, S. J. Huber, K. Mimatsu and J. M. No, “The Higgs Vacuum Uplifted: Revisiting the Electroweak Phase Transition with a Second Higgs Doublet,” JHEP 1712, 086 (2017) [arXiv:1705.09186 [hep-ph]].
16. P. Basler, M. Mühleitner and J. Wittbrodt, “The CP-Violating 2HDM in Light of a Strong first-order Electroweak Phase Transition and Implications for Higgs Pair Violation,” Phys. Rev. D 96, 015005 (2017) [arXiv:1610.01849 [hep-ph]].
Production," JHEP 1803, 061 (2018) [arXiv:1711.04097 [hep-ph]].
[17] X. M. Zhang, “Operators analysis for Higgs potential and cosmological bound on Higgs mass,” Phys. Rev. D 47, 3065 (1993) [hep-ph/9301277].
[18] C. Grojean, G. Servant and J. D. Wells, “First-order electroweak phase transition in the standard model with a low cutoff,” Phys. Rev. D 71, 036001 (2005) [hep-ph/0407019].
[19] C. Delaunay, C. Grojean and J. D. Wells, “Dynamics of Non-renormalizable Electroweak Symmetry Breaking,” JHEP 0804, 029 (2008) [arXiv:0711.2511 [hep-ph]].
[20] F. P. Huang, Y. Wan, D. G. Wang, Y. F. Cai and X. Zhang, “Hearing the echoes of electroweak baryogenesis with gravitational wave detectors,” Phys. Rev. D 94, no. 4, 041702 (2016) [arXiv:1601.01640 [hep-ph]].
[21] R. G. Cai, M. Sasaki and S. J. Wang, “The gravitational waves from the first-order phase transition with a dimension-six operator,” JCAP 1708, no. 08, 004 (2017) [arXiv:1707.03001 [astro-ph.CO]].
[22] R. Aprea, M. Maggiore, A. Nicolis and A. Riotto, “Gravitational waves from electroweak phase transitions,” Nucl. Phys. B 841, 342 (2002) [gr-qc/0107033].
[23] S. J. Huber and T. Konstandin, “Production of gravitational waves in the nMSSM,” JCAP 0805, 017 (2008) [arXiv:0709.2091 [hep-ph]].
[24] S. J. Huber, T. Konstandin, G. Nardini and I. Rues, “Detectable Gravitational Waves from Very Strong Phase Transitions in the General NMSSM,” JCAP 1603 (2016) no.03, 036 [arXiv:1512.06357 [hep-ph]].
[25] J. R. Espinosa, T. Konstandin, J. M. No and M. Quiros, “Some Cosmological Implications of Hidden Sectors,” Phys. Rev. D 78, 123528 (2008) [arXiv:0809.3215 [hep-ph]].
[26] P. Schwaller, “Gravitational Waves from a Dark Phase Transition,” Phys. Rev. Lett. 115, no. 18, 181101 (2015) [arXiv:1504.07263 [hep-ph]].
[27] P. S. B. Dev and A. Mazumdar, “Probing the Scale of New Physics by Advanced LIGO/VIRGO,” Phys. Rev. D 93, no. 10, 104001 (2016) [arXiv:1602.04203 [hep-ph]].
[28] A. Addazi, “Limiting First Order Phase Transitions in Dark Gauge Sectors from Gravitational Waves experiments,” Mod. Phys. Lett. A 32 (2017) no.08, 1750049 [arXiv:1607.08057 [hep-ph]].
[29] W. Chao, H. K. Guo and J. Shu, “Gravitational Wave Signals of Electroweak Phase Transition Triggered by Dark Matter,” JCAP 1709, no. 09, 009 (2017) [arXiv:1702.02698 [hep-ph]].
[30] A. Addazi and A. Marciano, “Gravitational waves from dark first order phase transitions and dark photons,” Chin. Phys. C 42 (2018) no.2, 023107 [arXiv:1703.03248 [hep-ph]].
[31] F. P. Huang and J. H. Yu, “Exploring inert dark matter blind spots with gravitational wave signatures,” Phys. Rev. D 98, no. 9, 095022 (2018) [arXiv:1704.04201 [hep-ph]].
[32] A. Addazi and A. Marciano, “Limiting majoron self-interactions from gravitational wave experiments,” Chin. Phys. C 42 (2018) no.2, 023105 [arXiv:1705.08346 [hep-ph]].
[33] A. Addazi, Y. F. Cai and A. Marciano, “Testing Dark Matter Models with Radio Telescopes in light of Gravitational Wave Astronomy,” Phys. Lett. B 782, 732 (2018) [arXiv:1712.03798 [hep-ph]].
[34] B. Imtiaz, Y. F. Cai and Y. Wan, “Two-field cosmological phase transitions and gravitational waves in the singlet Majoron model,” Eur. Phys. J. C 79, no. 1, 25 (2019) [arXiv:1804.05835 [hep-ph]].
[35] A. Ahriche, K. Hashino, S. Kanemura and S. Nasri, “Gravitational Waves from Phase Transitions in Models with Charged Singlets,” Phys. Lett. B 789, 119 (2019) [arXiv:1809.09883 [hep-ph]].
[36] W. Yang, S. Vagnozzi, E. Di Valentino, R. C. Nunes, S. Pan and D. F. Mota, “Listening to the sound of dark sector interactions with gravitational wave standard sirens,” JCAP 1907, 037 (2019) [arXiv:1905.08286 [astro-ph.CO]].
[37] P. Huang, A. J. Long and L. T. Wang, “Probing the Electroweak Phase Transition with Higgs Factories and Gravitational Waves,” Phys. Rev. D 94, no. 7, 075008 (2016) [arXiv:1608.06619 [hep-ph]].
[38] Y. F. Cai and X. Zhang, “Probing the origin of our universe through primordial gravitational waves by Ali CMB project,” Sci. China Phys. Mech. Astron. 59, no. 7, 670431 (2016) [arXiv:1605.01840 [astro-ph.IM]].
[39] Y. Chen, M. Huang and Q. S. Yan, “Gravitational waves from QCD and electroweak phase transitions,” JHEP 1805, 178 (2018) [arXiv:1712.03470 [hep-ph]].
[40] K. Hashino, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, “Selecting models of first-order phase transitions using the synergy between collider and gravitational-wave experiments,” Phys. Rev. D 99, no. 7, 075011 (2019) [arXiv:1809.04904 [hep-ph]].
[41] R. D. Peccei and H. R. Quinn, “CP Conservation in the Presence of Instantons,” Phys. Rev. Lett. 38, 1440 (1977).
[42] S. Weinberg, “A New Light Boson?,” Phys. Rev. Lett. 40, 223 (1978).
[43] F. Wilczek, “Problem of Strong P and T Invariance in the Presence of Instantons,” Phys. Rev. Lett. 40, 279 (1978).
[44] P. W. Graham, D. E. Kaplan and S. Rajendran, “Cosmological Relaxation of the Electroweak Scale,” Phys. Rev. Lett. 115, no. 22, 221801 (2015) [arXiv:1504.07551 [hep-ph]].
[45] J. R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolas and G. Servant, “Cosmological Higgs-Axion Interplay for a Naturally Small Electroweak Scale,” Phys. Rev. Lett. 115, no. 25, 251803 (2015) [arXiv:1506.09217 [hep-ph]].
[46] R. S. Gupta, Z. Komargodski, G. Perez and L. Ublaldi, “Is the Relaxion an Axion?,” JHEP 1602, 166 (2016) [arXiv:1509.00047 [hep-ph]].
[47] S. R. Coleman, “The Fate of the False Vacuum. 1. Semi-classical Theory,” Phys. Rev. D 15, 2929 (1977).
[48] C. G. Callan, Jr. and S. R. Coleman, “The Fate of the False Vacuum. 2. First Quantum Corrections,” Phys. Rev. D 16, 1762 (1977).
[49] S. R. Coleman and F. De Luccia, “Gravitational Effects on and of Vacuum Decay,” Phys. Rev. D 21, 3305 (1980).
[50] S. Sarangi, G. Shiu and B. Shlaer, “Rapid Tunneling and Percolation in the Landscape,” Int. J. Mod. Phys. A 24, 741 (2009) [arXiv:0708.4375 [hep-th]].
[51] E. J. Copeland, A. Padilla and P. M. Saffin, “No resonant tunneling in standard scalar quantum field theory,” JHEP 0801, 066 (2008) [arXiv:0709.0261 [hep-th]].
[52] S.-H. H. Tye and D. Wolns, “Resonant Tunneling in Scalar Quantum Field Theory,” arXiv:0910.1088 [hep-ph].
A. P. Morais, R. Pasechnik and T. Vieu, “Multi-peaked…

B. Feng and M. z. Li, “Curvaton reheating in nonoscillatory inflationary models,” Phys. Lett. B 522, 215 (2001) [hep-ph/0110096].

K. Enqvist and M. S. Sloth, “Adiabatic CMB perturbations in pre-big bang string cosmology,” Nucl. Phys. B 626, 395 (2002) [hep-ph/0109214].

B. Feng and M. Li, “Curvaton reheating in nonoscillatory inflationary models,” Phys. Lett. B 564, 169 (2003) [hep-ph/0212213].

A. R. Liddle and L. A. Urena-Lopez, “Curvaton reheating: An Application to braneworld inflation,” Phys. Rev. D 68, 043517 (2003) [astro-ph/0302054].

C. Gordon and A. Lewis, “Observational constraints on the curvaton model of inflation,” Phys. Rev. D 67, 123513 (2003) [astro-ph/0212248].

S. R. Coleman, V. Glaser and A. Martin, “Action Minima Among Solutions to a Class of Euclidean Scalar Field Equations,” Commun. Math. Phys. 58, 211 (1978).

C. L. Wainwright, “CosmoTransitions: Computing Cosmological Phase Transition Temperatures and Bubble Profiles with Multiple Fields,” Comput. Phys. Commun. 183, 2006 (2012) [arXiv:1109.4189 [hep-ph]].

A. P. Morais, R. Pasechnik and T. Vieu, “Multi-peaked signatures of primordial gravitational waves from multi-step electroweak phase transition,” arXiv:1802.10109 [hep-ph].

A. Addazi, A. Marciano, A. P. Morais, R. Pasechnik, R. Srivastava and J. W. F. Valle, “Gravitational footprints of massive neutrinos and lepton number breaking,” arXiv:1909.09740 [hep-ph].

A. P. Morais and R. Pasechnik, “Probing multi-step electroweak phase transition with multi-peaked primordial gravitational waves spectra,” arXiv:1910.00717 [hep-ph].

D. Croon and G. White, “Exotic Gravitational Wave Signatures from Simultaneous Phase Transitions,” JHEP 1805, 210 (2018) [arXiv:1803.05438 [hep-ph]].

C. Caprini et al., “Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions,” JCAP 1604, 001 (2016) [arXiv:1512.06239 [astro-ph.CO]].

C. Caprini et al., “Detecting gravitational waves from cosmological phase transitions with LISA: an update,” JCAP 2003, no. 03, 024 (2020) [arXiv:1910.13125 [astro-ph.CO]].

M. Kamionkowski, A. Kosowsky and M. S. Turner, “Gravitational radiation from first order phase transitions,” Phys. Rev. D 49, 2837 (1994) [astro-ph/9310044].

S. J. Huber and T. Konstandin, “Gravitational Wave Production by Collisions: More Bubbles,” JCAP 0809, 022 (2008) [arXiv:0806.1828 [hep-ph]].

M. Hindmarsh, S. J. Huber, K. Rummukainen and D. J. Weir, “Gravitational waves from the sound of a first order phase transition,” Phys. Rev. Lett. 112, 041301 (2014) [arXiv:1304.2433 [hep-ph]].

M. Hindmarsh, S. J. Huber, K. Rummukainen and D. J. Weir, “Numerical simulations of acoustically generated gravitational waves at a first order phase transition,” Phys. Rev. D 92, no. 12, 123009 (2015) [arXiv:1504.03291 [astro-ph.CO]].

A. Kosowsky, A. Mack and T. Kahnishihvili, “Gravitational radiation from cosmological turbulence,” Phys. Rev. D 66, 024030 (2002) [astro-ph/0111483].

A. Nicolis, “Relic gravitational waves from colliding bubbles and cosmic turbulence,” Class. Quant. Grav. 21, L27 (2004) [gr-qc/0303084].

C. Caprini, R. Durrer and G. Servant, “The stochastic gravitational wave background from turbulence and magnetic fields generated by a first-order phase transition,” JCAP 0912, 024 (2009) [arXiv:0909.0622 [astro-ph.CO]].

M. Kawasaki, K. Kohri, T. Moroi and Y. Takaesu, “Revisiting Big-Bang Nucleosynthesis Constraints on Long-Lived Decaying Particles,” Phys. Rev. D 97, no. 2, 023502 (2018) [arXiv:1709.01211 [hep-ph]].

J. Mielczarek, “Reheating temperature from the CMB,” Phys. Rev. D 83, 023502 (2011) [arXiv:1009.2359 [astro-ph.CO]].

C. J. Moore, R. H. Cole and C. P. L. Berry, “Gravitational-wave sensitivity curves,” Class. Quant. Grav. 32, no. 1, 015014 (2015) [arXiv:1408.0740 [gr-qc]].

H. Kudoh, A. Taruya, T. Hiramatsu and Y. Himemoto, “Detecting a gravitational-wave background with next-generation space interferometers,” Phys. Rev. D 73, 064006 (2006) [gr-qc/0511145].

X. Gong et al., “Descope of the ALIA mission,” J. Phys. Conf. Ser. 610, no. 1, 012011 (2015) [arXiv:1410.7296 [gr-qc]].

J. Luo et al. [TianQin Collaboration], “TianQin: a space-borne gravitational wave detector,” Class. Quant. Grav. 33, no. 3, 035010 (2016) [arXiv:1512.02076 [astro-ph.IM]].