Probing the hidden gauge symmetry breaking through the phase transition gravitational waves (Postprint)

Authors: Fa Peng Huang, Xinmin Zhang

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Abstract

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Full Text

Preamble

Probing Hidden Gauge Symmetry Breaking Through Phase-Transition Gravitational Waves

Fa Peng Huang* and Xinmin Zhang
Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918-4, Beijing 100049, P.R. China

Motivated by the discovery of gravitational waves (GWs) at aLIGO and the absence of new physics signals at the current LHC, we discuss how generic classes of extended new physics models with hidden gauge groups could undergo one or several first-order phase transitions associated with gauge group symmetry breaking during the evolution of the universe. These transitions might produce detectable phase-transition GW signals at future GW experiments such as eLISA and BBO.

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INTRODUCTION

The observation of gravitational waves by the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) [1] has inaugurated a new era of exploring cosmology, the nature of gravity, and fundamental particle physics through GW detectors [2-8]. In particular, due to the energy limitations of colliders, GW detectors can serve as novel tools to probe symmetry-breaking patterns and phase-transition histories for a broad class of new physics models featuring hidden gauge group extensions of the Standard Model (SM). These models are motivated by mysterious experimental results in particle cosmology—such as the dark matter problem and the observed baryon asymmetry of the universe—as well as by the lack of new physics signals at current collider experiments. Many increasingly compelling new physics models with hidden gauge group extensions introduce numerous new particles that leave no observable imprints at present-day particle colliders. However, GW experiments may provide a viable approach to test their existence. For example, explaining the baryon asymmetry of the universe via electroweak baryogenesis in hidden gauge group extended models requires a strong first-order phase transition to realize departure from thermal equilibrium [9–11]. During such first-order phase transitions, detectable GWs are produced through three mechanisms: collisions of expanding bubbles, sound waves, and magnetohydrodynamic turbulence in the hot plasma [12–19]. Phase transitions in particle physics and cosmology are typically associated with symmetry breaking, where the universe transitions from a symmetric phase to a symmetry-broken phase as the temperature drops below the corresponding critical temperature.

For the first time following aLIGO' s discovery, we have the opportunity to explore hidden gauge symmetry breaking through phase-transition GW signals —a particularly exciting prospect. In this paper, we investigate the possibility of probing hidden gauge symmetry-breaking patterns via phase-transition GW signals, focusing our analysis on GW detection in non-Abelian gauge group extended models, where symmetry breaking at each energy scale may be associated with a first-order phase transition, as illustrated in Fig. 1. The hidden group G_{Hidden} can spontaneously break into the SM gauge group G_{SM} : $SU(3)_c \otimes SU(2)_L \otimes U(1)_X$. During hidden gauge symmetry breaking, a strong first-order phase transition can occur, producing detectable phase-transition GWs. For instance, the hidden gauge group G_{Hidden} could be the non-Abelian group $SU(3)_c \otimes SU(3)_L \otimes U(1)_Y$, known as the 3-3-1 model [20, 21]. We demonstrate that many versions of the 3-3-1 model can produce at least one strong first-order phase transition at energies of several TeV within certain parameter spaces, generating GW spectra detectable by the Evolved Laser Interferometer Space Antenna (eLISA) [22] and the Big Bang Observer (BBO) [23].

In general, multiple spontaneous symmetry-breaking events may occur, potentially accompanied by several first-order phase transitions during the universe' s evolution, as shown in Fig. 1. If the energy scale of the symmetry breaking and the associated first-order phase transition ranges from 10^7 to 10^8 GeV, triggered by the hidden sector, the resulting phase-transition GW spectrum may fall within the sensitivity of future aLIGO experiments. Other compelling examples of GW detection in non-Abelian gauge group extended models include first-order dark QCD phase-transition GWs in the relaxion mechanism [24], which could be tested by pulsar timing arrays (PTAs) at the Square Kilometre Array (SKA) [25] or the Five-hundred-meter Aperture Spherical Telescope (FAST) [26] in China. Another example is the Nnaturalness mechanism [27], which may also produce observable phase-transition GW signals.

This paper is organized as follows: In Section II, we schematically discuss GW detection of hidden gauge group symmetry breaking and present the calculation of phase-transition GWs during first-order phase transitions. In Section III, we study phase-transition GW spectra in concrete hidden gauge group extended models. In Section IV, we present our final discussions and conclusions.

II. FIRST-ORDER PHASE-TRANSITION GW SPECTRUM

In a broad class of new physics models with extended non-Abelian hidden gauge groups, one or more cosmological phase transitions can occur during each step of hidden gauge symmetry breaking. In general, the gauge symmetry-breaking patterns with extended hidden gauge groups at various scales can be represented as shown in Fig. 1. For example, the hidden symmetry-breaking pattern may follow:

$$G(\text{Hidden } N)\cdots \to G(\text{Hidden}_1) \to G(SU(3)_C \otimes SU(3)_L \otimes U(1)_Y) \to G(SU(3)_C \otimes SU(2)_L \otimes U(1)_X) \to G(SU(3)_C$$

As the universe evolves, symmetry breaking occurs at the corresponding energy scale, where a strong first-order phase transition may take place. Detailed models are provided in Section III.

During the transition from a "false" vacuum to a "true" vacuum, a strong first-order phase transition occurs if a sufficient potential barrier exists between them. This process can produce observable stochastic GW signals detectable by various GW detectors such as aLIGO, eLISA, BBO, SKA, FAST, and others. Their sensitivity ranges for certain critical temperatures depend on the energy scale of the first-order phase transition for different hidden gauge group extended models, as discussed in Section III.

To discuss the GW spectrum from first-order phase transitions, we begin with the one-loop finite-temperature effective potential:

$$V_{\text{eff}}(\Phi, T) = V_{\text{tree}}(\Phi) + V_{\text{CW}}(\Phi) + V_{\text{thermal}}(\Phi, T) + V_{\text{daisy}}(\Phi, T),$$

where Φ represents the order parameter of the phase transition (a real scalar field), $V_{\text{CW}}(\Phi)$ is the one-loop Coleman-Weinberg potential at $T = 0$, and

$V_{\text{thermal}}(\Phi, T) + V_{\text{daisy}}(\Phi, T)$ represents the thermal contribution including daisy resummation [28].

During each step of symmetry breaking in hidden gauge group extended models, a strong first-order phase transition may occur. During such transitions, bubbles nucleate via quantum tunneling or thermal fluctuations over the potential barrier. The bubble nucleation rate per unit volume Γ is given by $\Gamma = \Gamma_0(T)e^{-S_E(T)}$ with $\Gamma_0(T) \propto T^4$ [29], where $S_E(T)$ is the Euclidean action [30, 31] defined as

$$S_E(T) = \int d\tau d^3x \left[\left(\frac{d\Phi}{d\tau} \right)^2 + (\nabla\Phi)^2 + V_{\text{eff}}(\Phi, T) \right].$$

Here, $S_E(T) \simeq S_3(T)/T$, and $\Gamma = \Gamma_0 e^{-S_3/T}$ [29] where

$$S_3(T) = \int d^3x \left[\frac{1}{2}(\nabla\Phi)^2 + V_{\text{eff}}(\Phi, T) \right].$$

From these equations, to obtain the bubble nucleation rate, the scalar field profile Φ during bubble nucleation must be calculated by solving the bounce equation:

$$\frac{d^2\Phi}{dr^2} + \frac{2}{r}\frac{d\Phi}{dr} = \frac{\partial V_{\text{eff}}(\Phi, T)}{\partial \Phi},$$

with boundary conditions $\frac{d\Phi}{dr}(r = 0) = 0$ and $\Phi(r = \infty) = \Phi_{\text{false}}$.

The bounce equation can be solved numerically using the overshoot/undershoot method. The first-order phase transition terminates when the nucleation probability of one bubble per horizon volume is of order unity, i.e., $\Gamma(T_*)/H_*^4 \sim \mathcal{O}(1)$. This condition translates to $S_3(T_*)/T_* = 4\ln(T_*/100 \text{ GeV}) + 137$.

Three major sources produce GWs during first-order phase transitions: vacuum bubble collisions [15], sound waves [16], and turbulence [17, 18] in the plasma after collisions.

The most well-understood source is bubble collisions. The first-order phase-transition GW spectrum depends on four parameters. The first is the ratio α of the vacuum energy density released in the phase transition to that of the thermal bath, defined as

$$\alpha = \frac{\epsilon(T_*)}{\rho_{\text{rad}}(T_*)},$$

where the false vacuum energy density $\epsilon(T_*) = \left[T \frac{dV_{\text{eff}}^{\text{min}}(T)}{dT} \right]_{T=T_*}$ is the latent heat density, and the plasma thermal energy density $\rho_{\text{rad}}(T_*) = \frac{\pi^2}{30} g_* T_*^4$. Here

$V_{\rm eff}^{\rm min}(T)$ is the temperature-dependent true minimum of the effective potential of the scalar field responsible for the phase transition. The parameter α measures the strength of the phase-transition GWs; larger values of α correspond to stronger first-order phase transitions.

The second parameter is the inverse time duration of the phase transition β^{-1}, defined as

$$\beta \equiv -\left.\frac{dS_E}{dt}\right|_{t=t_*} \simeq T\left.\frac{d(S_3/T)}{dt}\right|_{t=t_*}.$$

In other words, β^{-1} corresponds to the typical time scale of the phase transition. Since $\beta = \dot{\Gamma}/\Gamma$ during the phase transition by definition, we have

$$\frac{\beta}{H_*} = T_*\left.\frac{d(S_3/T)}{dT}\right|_{T=T_*}.$$

The third parameter is the efficiency factor κ, which characterizes the fraction of energy density converted into the motion of colliding bubble walls, and the fourth is the bubble wall velocity v_b. The energy released into GWs at the peak frequency is then given by [32]:

$$\Omega_{\rm GW}^{\rm co}h^2 \simeq 1.67\times10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}\frac{(0.11v_b^3)}{(0.42+v_b^2)}.$$

The second and third sources arise from matter fluid effects, which can further contribute to the total energy released in gravitational radiation during the phase transition. We adopt the formulae given in [33]. One source originates from sound waves in the fluid, where a fraction κ_v of the bubble wall energy (after collision) is converted into fluid motion (dissipating only later), with contribution

$$\Omega_{\rm GW,sw}h^2 \simeq 2.65\times10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}\frac{(f/f_{\rm sw})^3}{(4+3(f/f_{\rm sw})^2)^{7/2}}.$$

The other source comes from turbulence in the fluid, where a fraction $\kappa_{\rm tu}$ of the wall energy is converted into turbulence, with contribution

$$\Omega_{\rm GW,turb}h^2 \simeq 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{1/3}\frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f a_0/(a_*H_*))}.$$

Notably, these two contributions from matter fluid effects depend linearly on H_*/β and are not fully understood. In some cases, these effects may dominate over bubble collisions.

The peak frequency produced by bubble wall collisions at T_* during the first-order phase transition is given by [36, 37]:

$$f_*^{\rm co} = 0.62 \frac{\beta}{1.8 - 0.1 v_b + v_b^2}.$$

Considering the adiabatic expansion of our universe from the early to the present epoch, the ratio of scale factors at the time of the first-order phase transition and today can be written as

$$\frac{a_*}{a_0} = 1.65 \times 10^{-5}\ {\rm Hz} \times \left(\frac{100\ {\rm GeV}}{T_*}\right) \left(\frac{g_*}{100}\right)^{1/6}.$$

Thus, the peak frequency today is $f_{\rm co} = f_*^{\rm co} a_*/a_0$, and the corresponding GW intensity is given by [36]

$$\Omega_{\rm co}(f)h^2 \simeq 1.67 \times 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \frac{(f/f_{\rm co})^{2.8}}{0.42 + v_b^2} \left[\frac{3.8 (f/f_{\rm co})^{2.8}}{1 + 2.8 (f/f_{\rm co})^{3.8}}\right].$$

The peak frequency of GW signals from sound wave effects is approximately $f_*^{\rm sw} = 2\beta/(3v_b)$ [16, 33], and its present value is $f_{\rm sw} = f_*^{\rm sw} a_*/a_0$. In this case, the GW intensity is expressed as [16, 33]

$$\Omega_{\rm sw}(f)h^2 \simeq 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \frac{(f/f_{\rm sw})^3}{(4 + 3(f/f_{\rm sw})^2)^{7/2}},$$

where $\kappa_v \simeq \alpha(0.73 + 0.083\sqrt{\alpha} + \alpha)^{-1}$ for relativistic bubbles [34].

GW signals produced by turbulence in the plasma peak at approximately $f_*^{\rm tu} = 1.75\beta/v_b$ [33], which determines the present value as $f_{\rm tu} = f_*^{\rm tu} a_*/a_0$ after accounting for redshift. The GW intensity from turbulence is given by [18, 35]

$$\Omega_{\rm tu}(f)h^2 \simeq 3.35 \times 10^{-4} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_{\rm tu}\alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_*}\right)^{1/3} \frac{(f/f_{\rm tu})^3}{(1 + f/f_{\rm tu})^{11/3} (1 + 8\pi f a_0/(a_* H_*))}.$$

The final phase-transition spectrum consists of the sum of these three contributions.

III. PHASE-TRANSITION GWS FROM NON-ABELIAN GAUGE GROUP EXTENDED MODELS

In this section, we discuss phase-transition GWs in specific non-Abelian gauge group extended models in detail, where one or multiple symmetry-breaking events and first-order phase transitions may occur at certain critical temperatures during the universe' s evolution. First, we investigate GW spectra in hidden gauge group extended models based on the $SU(3)_c \otimes SU(3)_L \otimes U(1)_Y$ gauge symmetry, commonly known as the 3-3-1 model [20, 21].

The 3-3-1 models can explain electric charge quantization and the existence of three fermion generations [20, 21]. The collider phenomenology of 3-3-1 models has been extensively studied (see recent Ref. [38] and references therein), and phase transitions in some versions have been examined in Refs. [39–41]. Here, we explore possible phase-transition patterns associated with the symmetry breaking $SU(3)_L \otimes U(1)_Y \to SU(2)_L \otimes U(1)_X \to U(1)_{\text{EM}}$ using phase-transition GWs in various 3-3-1 models, where scalar fields are accommodated in specific representations of the $SU(3)_L$ gauge group in each version.

Below, we present three versions of 3-3-1 models (the minimal, economical, and reduced minimal 3-3-1 models) [39–41], where very strong first-order phase transitions can occur at the TeV scale [39–41] and produce detectable phase-transition GWs for eLISA and BBO. For simplicity, we limit our discussion to the thermal barrier case, where the potential barrier in the finite-temperature effective potential originates from thermal loop effects. In this scenario, bosonic fields contribute to the thermal effective potential in the high-temperature expansion limit as $V_{\text{eff}} \sim (-T/12\pi) \sum_{\text{bosons}} (m^2_{\text{boson}}(X,T))^{3/2}$.

To make concrete predictions for GWs in the following examples, we first discuss the general effective potential near the symmetry-breaking and phase-transition temperature, which can be approximated by

$$V_{\text{eff}}(X,T) \approx (-\mu^2 + cT^2)\, X^2 - e(X^2)^{3/2} + \lambda (X^2)^2.$$

Here, X represents the order parameter field for the phase transition. For the electroweak phase transition in the SM, the X field is simply the Higgs field. The parameter e quantifies interactions between the X field and light bosons, schematically written as $e \sim \sum_{\text{light bosonic fields}}(\text{degrees of freedom}) \times (\text{coupling to } X)^{3/2}$. The parameter c depends on interactions between X and light bosons and fermions. Heavy fields with masses much larger than the critical temperature can be omitted due to Boltzmann suppression, which helps simplify discussions when models contain many new fields at different energy scales. Thus, in this qualitative analysis, the washout parameter can be obtained as

$$\frac{\langle X \rangle (T_c)}{T_c},$$

where the angle brackets denote the vacuum expectation value (VEV) of the field X at the critical temperature T_c.

From this qualitative analysis, we see that introducing new light bosonic fields (compared to the corresponding critical temperature) helps produce or enhance first-order phase transitions. The 3-3-1 models introduce sufficient bosonic fields to generate detectable phase-transition GWs.

A. Phase-Transition GW Spectrum in the Economical 3-3-1 Model and the Reduced Minimal 3-3-1 Model

We consider the first-order phase-transition GW spectrum in the so-called economical 3-3-1 model [40]. In this version, one chooses the simplest $SU(3)_L$ representations for the scalar fields that spontaneously break symmetry: two complex scalar triplets with different hypercharge are required:

$$\chi = \left(\chi_1^0, \chi_2^-, \chi_3^0\right)^T, \quad \phi = \left(\phi_1^+, \phi_2^0, \phi_3^+\right)^T.$$

The scalar potential is written as

$$V(\chi,\phi) = \mu_1^2\chi^\dagger\chi + \lambda_1(\chi^\dagger\chi)^2 + \mu_2^2\phi^\dagger\phi + \lambda_2(\phi^\dagger\phi)^2 + \lambda_3(\chi^\dagger\chi)(\phi^\dagger\phi) + \lambda_4(\chi^\dagger\phi)(\phi^\dagger\chi).$$

The $SU(3)_L \otimes U(1)_Y$ gauge group breaks spontaneously in two steps. In the first step, $SU(3)_L \otimes U(1)_Y \to SU(2)_L \otimes U(1)_X$ occurs when the scalar triplet χ acquires a VEV given by $\langle\chi\rangle = (u, 0, \omega)^T$. In the final step, to break to the SM $U(1)_{\text{EM}}$ gauge group via $SU(2)_L \otimes U(1)_X \to U(1)_{\text{EM}}$, another scalar triplet ϕ must acquire the VEV $\langle\phi\rangle = (0, v, 0)^T$.

In this version of the 3-3-1 model, two neutral scalars exist: one is the SM Higgs boson h, and the other is the heavy scalar H_1. In this paper, we use the package 'CosmoTransitions' [42] to numerically calculate the first-order phase transition. During the first symmetry-breaking step $SU(3)_L \otimes U(1)_Y \to SU(2)_L \otimes U(1)_X$, the order parameter field for the phase transition is approximately the H_1 scalar field (i.e., $X = H_1$ when compared to Eq. (14)). A strong first-order phase transition at the energy scale of several TeV can be induced by new bosons and exotic quarks in this model if their masses range from 10^2 GeV to several TeV. During the final symmetry-breaking step $SU(2)_L \otimes U(1)_X \to U(1)_{\text{EM}}$, the order parameter field is approximately the Higgs field (i.e., $X = h$ when compared to Eq. (14)). A first-order phase transition at the electroweak scale can be triggered by new bosons, though it is weaker than the first step.

For the benchmark point with $m_{H_1} = 1.4$ TeV and $m_{H^\pm} = 3.2$ TeV, using the methods and formulae from Section II and the 'CosmoTransitions' package [42], these two first-order phase transitions produce two distinct GW spectra with different characteristic peak frequencies and amplitudes, as shown in Fig.

2 [Figure 2: see original paper]. The figure demonstrates that phase-transition GWs can be used to explore symmetry-breaking and phase-transition patterns with eLISA and BBO.

The GW spectrum of the reduced minimal 3-3-1 model is similar to that of the economical 3-3-1 model, as their symmetry-breaking and phase-transition patterns are comparable. The reduced minimal 3-3-1 model primarily contains neutral scalars h, H_1, a doubly charged scalar h^{++}, two SM-like bosons Z_1, $W^{\pm}$, a new heavy neutral boson Z_2, and singly and doubly charged bosons $U^{\pm}$, $U^{\pm\pm}$. These new particles and exotic quarks can trigger first-order phase transitions [41]. Using the methods and formulae from Sec. II and the 'CosmoTransitions' package [42], for the benchmark point $m_{H_1} = 1.3$ TeV and $m_{h^{++}} = 3.3$ TeV, two distinct GW spectra are produced during the two first-order phase transitions, as shown in Fig. 3 [Figure 3: see original paper], which can also be detected by eLISA and BBO.

B. Phase-Transition GW Spectrum in the Minimal 3-3-1 Model

The minimal 3-3-1 model [39] corresponds to the parameter $\beta = -\sqrt{3}$ [39] in the definition of the electric charge operator. The gauge bosons associated with the $SU(3)_L \otimes U(1)_Y$ gauge symmetry consist of an octet W_i^{μ} $(i = 1, \cdots, 8)$ and a singlet B^{μ}. In this version, three $SU(3)_L$ triplet scalars are needed to break the symmetry and generate masses for gauge bosons and exotic quarks:

$$\eta = \left(\eta_1^0, \eta_2^-, \eta_3^0\right)^T, \quad \rho = \left(\rho_1^+, \rho_2^0, \rho_3^{++}\right)^T, \quad \chi = \left(\chi_1^-, \chi_2^{--}, \chi_3^0\right)^T.$$

The scalar potential for ρ, η, and χ is [39, 44]

$$\begin{aligned} V(\rho,\eta,\chi) =& \mu_1^2\eta^\dagger\eta + \lambda_1(\eta^\dagger\eta)^2 + \mu_2^2\rho^\dagger\rho + \lambda_2(\rho^\dagger\rho)^2 + \mu_3^2\chi^\dagger\chi + \lambda_3(\chi^\dagger\chi)^2 \\ &+ \lambda_4(\eta^\dagger\eta)(\rho^\dagger\rho) + \lambda_5(\eta^\dagger\eta)(\chi^\dagger\chi) + \lambda_6(\rho^\dagger\rho)(\chi^\dagger\chi) \\ &+ \lambda_7(\chi^\dagger\eta)(\eta^\dagger\chi) + \lambda_8(\rho^\dagger\eta)(\eta^\dagger\rho) + \lambda_9(\rho^\dagger\chi)(\chi^\dagger\rho) \\ &+ \left(f_1\epsilon_{ijk}\eta_i\rho_j\chi_k + \text{H.c.}\right). \end{aligned}$$

New gauge bosons acquire masses at the several-TeV scale when the $SU(3)_L \times U(1)_Y$ group breaks down to $SU(2)_L \times U(1)_X$, triggered by the $SU(3)_L$ scalar triplet χ, while ordinary quarks and SM gauge bosons obtain their masses during the final symmetry-breaking step triggered by the triplets η and ρ. Three neutral scalars exist: h, H_1^0, and H_2^0, with the lightest corresponding to the SM Higgs boson h and the others being heavier scalar bosons.

By calculating the one-loop effective potential based on Eq. (1) and using the 'CosmoTransitions' package [42] for this minimal 3-3-1 model, we find parameter regions allowed by collider constraints that can accommodate a strong first-order phase transition when the gauge group spontaneously breaks from $SU(3)_L \times U(1)_Y$ to $SU(2)_L \times U(1)_X$, as shown in Ref. [39]. During this phase transition, the X field is the H_1^0 field. The resulting phase-transition GW spectrum can be obtained from the above formulae. Since this model has many free parameters, making a complete study of the allowed parameter space very complicated, we present only one benchmark point. For example, with $v_{\chi^0} = 4$ TeV and $M_{H_1^0} = 0.8$ TeV, the corresponding GW spectrum is shown in Fig. 4 [Figure 4: see original paper], which lies within the sensitivities of eLISA and BBO.

C. Phase-Transition GW Spectrum in Other Hidden Gauge Group Extended Models

In general, if the SM is extended by a hidden non-Abelian gauge group, strong first-order phase transitions may occur associated with symmetry breaking at each symmetry-breaking scale, potentially producing phase-transition GWs. Thus, phase-transition GWs can test hidden gauge symmetry breaking. Beyond the 3-3-1 models discussed above, we first examine the relaxion mechanism [24] proposed in 2015, where the light Higgs mass arises from dynamical cosmological evolution in the early universe. The relaxion mechanism can technically relax the electroweak hierarchy [24, 45], with the highest cutoff relaxed in Ref. [24] being about 10^8 GeV. The original relaxion mechanism requires an inflation sector and a QCD-like sector. In particular, to avoid the strong CP problem in the simplest relaxion model, a dark QCD gauge group is needed, which also includes new dark fermions. In some allowed parameter space, the dark $SU(3)_{\text{dark}}$ can undergo a first-order QCD phase transition at the dark QCD scale. If the dark QCD scale is $\mathcal{O}(100)$ MeV, the first-order phase transition can produce GWs with peak frequencies in the $10^{-9} - 10^{-7}$ Hz range, which can be probed by PTA experiments such as the planned SKA or FAST in China. A schematic GW spectrum for the dark QCD phase transition is shown in Fig. 5 [Figure 5: see original paper].

Very recently, a novel mechanism called "N-naturalness" [27] has been proposed to solve the electroweak hierarchy problem by introducing N copies of the SM with varying Higgs boson mass parameters in a single universe. Although a special reheating particle has been added to the N-naturalness mechanism to suppress baryogenesis from other copies with $v \neq 246$ GeV, first-order phase transitions may still occur in some parameter spaces and produce detectable GW signals, which will be carefully examined in future work [46]. However, we note that if a first-order phase transition occurs at a critical temperature of $\mathcal{O}(10^7 - 10^8)$ GeV [4, 47], as in some grand unified models, this could potentially produce a detectable GW spectrum in future aLIGO experiments, providing a unique probe of hidden gauge symmetry breaking at high energy scales beyond the reach of particle colliders.

IV. DISCUSSIONS AND CONCLUSIONS

Figure 5 [Figure 5: see original paper] shows first-order phase-transition GW spectra $h^2\Omega_{\text{GW}}$ during the universe' s evolution for generic classes of hidden gauge group extended models at different energy scales. The colored regions represent the expected sensitivities of GW detectors SKA, BBO, eLISA, and aLIGO, respectively. The red line depicts the possible GW spectrum from a first-order phase transition at $\mathcal{O}(100)$ MeV in some dark QCD models. GWs produced in dark QCD models can be detected by PTA experiments such as the planned SKA or FAST in China. The black line represents the GW spectrum for a first-order phase transition at about 4 TeV in some dark gauge group extended models, such as certain 3-3-1 models. We have shown that all three versions of the 3-3-1 models discussed above could produce strong first-order phase-transition GWs at the TeV scale when the dark gauge symmetry $SU(3)_L \otimes U(1)_Y$ breaks to $SU(2)_L \otimes U(1)_X$. Particularly, in the economical and reduced minimal 3-3-1 models, two first-order phase transitions may occur, producing two GW spectra with different characteristic peak frequencies. In general, phase-transition GWs produced at scales from $\mathcal{O}(100)$ GeV to several TeV can be tested by future space-based laser interferometer GW detectors such as eLISA, BBO, Taiji, and Tianqin [48]. The purple line corresponds to the GW spectrum from a first-order phase transition at $\mathcal{O}(10,000)$ TeV in some high-scale models, which may fall within the sensitivity of future aLIGO experiments and provide unique detection of hidden gauge symmetry breaking at high energy scales beyond collider capabilities. Beyond these schematic models, many other hidden gauge group extended models may also undergo one or multiple first-order phase transitions at different energy scales, as shown in Fig. 1, producing corresponding phase-transition GW spectra testable by appropriate GW detectors.

In conclusion, phase-transition GWs represent a new and realistic approach to exploring particle cosmology and fundamental physics. From a cosmological perspective, our universe may have undergone one or multiple phase transitions during its early evolution, and we can "hear" these cosmological phase transitions through first-order phase-transition GWs. From a particle physics perspective, this GW approach can complement collider experiments in exploring hidden gauge group extended models and provide a novel method to probe symmetry-breaking and phase-transition patterns. More detailed studies will be discussed in future work.

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