Probing the symmetry breaking patterns of the early universe and new physics by the phase transition gravitational waves

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Motivated by the observation of gravitational waves (GWs) by aLIGO, and the absence of dark matter an other new physics signals at current experiments, we study the possibility to explore the nature of Higgs boson, the baryon asymmetry of the universe, dark matter, new physics models, symmetry breaking history of the early universe by the phase transition GWs if a strong first-order phase transition can be induced therein.

1 Introduction

The observation of gravitational waves (GWs) by aLIGO has initiated a new era of exploring the nature of gravity, cosmology as well as the fundamental particle physics by the GWs. Obvious shortcomings in our understanding of particle cosmology (such as the baryon asymmetry of the universe and the dark matter) and no evidence of new physics at current experiments may just point us towards the novel universe with hidden new physics, which might only be visible for GWs detection. GWs may helps to probing the nature of Higgs boson, the baryogenesis, dark matter, new physics models, symmetry breaking patters of the universe since they may be the triggers for a strong first-order phase transition (FOPT). Then a strong FOPT can produce detectable phase transition GWs.

2 Phase transition gravitational waves in a nutshell

A strong FOPT can drive the plasma of the early universe out of thermal equilibrium, and then bubble nucleate during it, which will produce GWs through three mechanisms: the well-known bubble collision, turbulence in the plasma fluid (a fraction of the bubble wall energy converted into turbulence) and sound wave in the plasma fluid (after the collision a fraction of bubble wall energy converted into motion of the fluid, and is only later dissipated). The phase transition GWs spectrum depend on four parameters. The first parameter is $\alpha \equiv \frac{\epsilon(T_*)}{\rho_{\rm rad}(T_*)}$, which represents the strength the FOPT, namely, a larger value of α produces stronger GWs signature. The second parameter is $\frac{\beta}{H_*} = T\frac{d(S_3/T)}{dT}\Big|_{T=T_*}$, where one has $\beta \equiv -\frac{dS_E}{dt}|_{t=t_*} \simeq \frac{1}{\Gamma}\frac{d\Gamma}{dt}|_{t=t_*}$, namely, β^{-1} corresponds to the typical time scale of the phase transition. The third parameter is the efficiency factor λ_i (i=co,tu,sw), and the last parameter is the bubble wall velocity v_b. Especially, electroweak phase transition GWs becomes more interesting and realistic after the discovery of Higgs boson by LHC and GWs by aLIGO.

3 GWs related to Higgs nature and baryogenesis

A long standing problem in particle cosmology is to unravel the origin of baryon asymmetry of the universe (BAU). After the discovery of the 125 GeV Higgs boson, electroweak baryogenesis becomes a interesting and testable scenario for explaining the BAU. (To produce the observed BAU, three necessary conditions are needed: baryon number violation, C and CP violation, departure from thermal equilibrium or CPT violation.) A strong FOPT can provide the departure from thermal equilibrium, which can be realized in various of new physics models by modify the standard model(SM) Higgs potential. And probing the true Higgs potential is the urgent scientific goal after the discovery of Higgs boson. Instead of investigating the Higgs nature or electroweak phase baryogenesis in a UV-complete theory, which is difficult to make experimental predictions from unknown model parameters, we take a bottom-up approach to explain the BAU and study the possible collider and GWs signals with the effective Lagrangian of the Higgs doublet ϕ as $\delta\mathcal{L} = -\frac{\kappa}{\Lambda^2}(\phi^\dagger\phi)^3$. These effective operators could come from various renormalizable extensions of the SM. Thus, the combined results are shown in Fig.3 with the details in Ref.[1] and references therein. We conclude that the GWs interferometers can provide a complementary approach to probe the nature of the electroweak phase transition alternative to particle colliders, and vice versa.

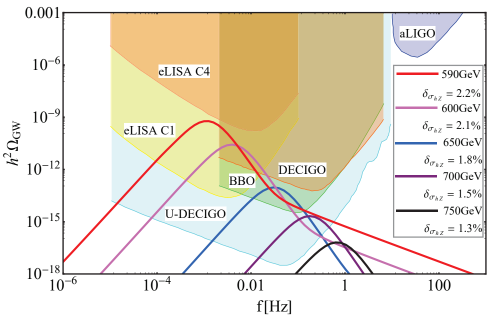

Figure 1 – The phase transition GWs spectra $h^2\Omega_{\rm GW}$ from FOPT during the evolution of our universe. The colored regions represent the expected sensitivities of GWs detectors aLIGO, eLISA, BBO and SKA, respectively. The red line depicts the possible GWs spectrum where the FOPT occurs at the energy scale of $\mathcal{O}(100)$ MeV in some dark QCD models. The black line represents the GWs spectrum for the FOPT at about 4 TeV in some hidden gauge group models, such as some 3-3-1 models. The purple line corresponds to the GWs spectrum when the FOPT takes place at the energy scale of $\mathcal{O}(10000)$ TeV in some models with high symmetry breaking scale.

4 GWs induced by dark matter

Motivated by the absence of dark matter signals in direct detection experiments (such as the recent LUX and PandaX-II experiments) and the discovery of gravitational waves (GWs) at aLIGO, we discuss the possibility to explore a generic classes of scalar dark matter models using the complementary searches via phase transition GWs and the future lepton collider signatures. We focus on the inert scalar multiplet dark matter models and the mixed inert scalar dark matter models, which could undergo a strong FOPT during the evolution of the early universe, and might produce detectable phase transition GWS signals at future GWs experiments, such as eLISA, DECIGO and BBO. We find that the future GWs signature, together with circular electron-positron collider (CEPC), could further explore the model's *blind spot* parameter region, at which the dark matter-Higgs coupling is identically zero, thus avoiding the dark matter spin-independent direct detection constraints. One example is the inert doublet model (IDM) with the relevant tree-level potential

$$\begin{aligned} V_0(\Phi, H_2) &= V(\Phi) + M_D^2 H_2^2 + \lambda_2 H_2^4 \\ &+ \lambda_3 \Phi^2 H_2^2 + \lambda_4 |\Phi^\dagger H_2|^2 + \lambda_5/2 \left[(\Phi^\dagger H_2)^2 + h.c. \right]. \end{aligned}$$

Another exmaple is the mixed singlet-doublet model(MSDM) with the tree-level potential

$$V_0 = \frac{1}{2} M_S^2 S^2 + M_D^2 H_2^\dagger H_2 + \frac{1}{2}\lambda_S S^2 \left|\Phi\right|^2 + \lambda_3 \Phi^\dagger \Phi H_2^\dagger H_2$$

$$+ \quad \lambda_4|\Phi^\dagger H_2|^2 + \frac{\lambda_5}{2}[(\Phi^\dagger H_2)^2 + h.c.] + A\left[S\Phi H_2^\dagger + h.c.\right] .$$

The final results are shown in Fig.2 with the details in the Ref.[2] and references therein.

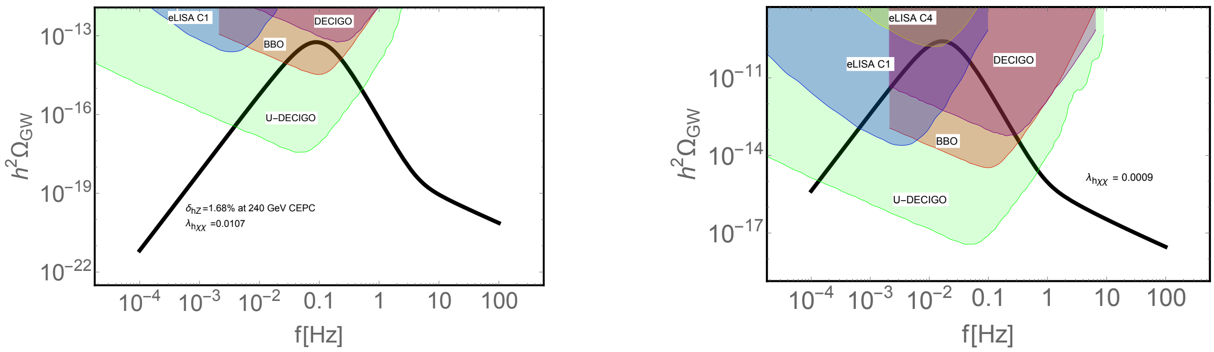

Figure 2 – The phase transition GWs spectra $h^2\Omega_{\rm GW}$ in the IDM (left) and MSDM (right). The colored regions represent the expected sensitivities of GWs interferometers U-DECIGO, DECIGO, BBO and eLISA, respectively. The black line depicts the GWs spectra in the IDM for the set of benchmark points, which also represents the corresponding hZ cross section deviation at the 240 GeV CEPC and the corresponding dark matter coupling.

5 GWs in 3-3-1 models and general new phyics models

In a generic classes of extended new physics models with hidden gauge group could undergo one or several times FOPT associated with the gauge group symmetry breaking during the evolution of the universe as shown in Fig.3, which might produce detectable phase transition GWs signals at future GWs experiments.

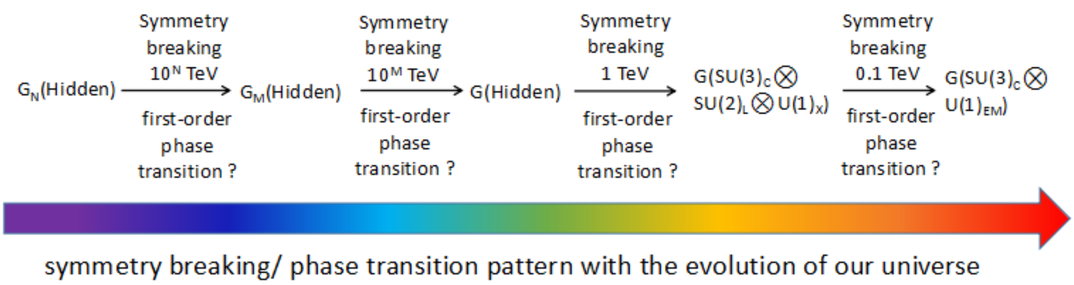

Figure 3 – Symmetry breaking (phase transition) patterns for the non-Abelian gauge group extended models with the evolution of our universe, where the first-order phase transitions may happen.

In Fig. 4, the FOPT GWs spectra $h^2\Omega_{\rm GW}$ during the evolution of our universe are shown for a generic classes of hidden gauge group extended models at the different energy scales. The colored regions represent the expected sensitivities of GWs detectors SKA, BBO, eLISA and aLIGO, respectively. The red line depicts the possible GWs spectrum where the FOPT occurs at the energy scale of $\mathcal{O}(100)$ MeV in some dark QCD models (such as the famous relaxion model), which can be detected by the pulsa timing array (PTA) experiments, such as the planned SKA or the FAST. The black line represents the GWs spectrum for the FOPT at about 4 TeV in some hidden gauge group extended models, such as some versions of 3-3-1 models. We have shown that all the three versions of the 3-3-1 models discussed above could produce FOPT GWs at TeV scale when the hidden gauge symmetry $SU(3)_L \otimes U(1)_Y$ breaks to $SU(2)_L \otimes U(1)_X$. Especially, in the economical and reduced minimal 3-3-1 models two times FOPT may take place, which will produce two GWs spectra with different characteristic peak frequencies. In general, the phase transition GWs produced at the scale from $\mathcal{O}(100)$ GeV to several TeV can be tested at future laser interferometer GWs detectors in space, such as the planned eLISA, BBO, Taiji and

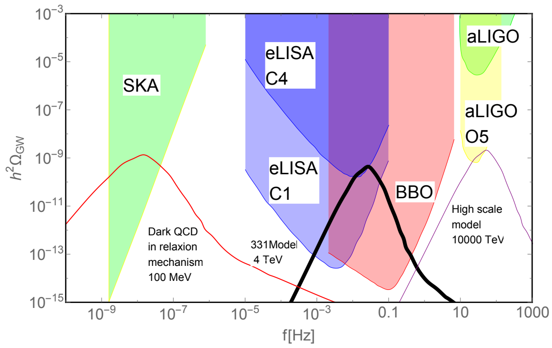

Figure 4 – The phase transition GWs spectra $h^2\Omega_{\rm GW}$ from FOPT during the evolution of our universe. The colored regions represent the expected sensitivities of GWs detectors aLIGO, eLISA, BBO and SKA, respectively. The red line depicts the possible GWs spectrum where the FOPT occurs at the energy scale of $\mathcal{O}(100)$ MeV in some dark QCD models. The black line represents the GWs spectrum for the FOPT at about 4 TeV in some hidden gauge group models, such as some 3-3-1 models. The purple line corresponds to the GWs spectrum when the FOPT takes place at the energy scale of $\mathcal{O}(10000)$ TeV in some models with high symmetry breaking scale.

Tianqin. The purple line corresponds to the GWs spectrum when the FOPT takes place at the energy scale of $\mathcal{O}(10000)$ TeV in some high scale models, which may be within the sensitivity of the future aLIGO and provide us with a unique detection of the hidden gauge symmetry breaking at high energy scales beyond the abilities of particle colliders. Besides these schematic models, many other hidden gauge group extended models may also undergo one or several FOPT at different energy scale as shown in Fig.4, where the corresponding phase transition GWs spectra can be produced and tested at the corresponding GWs detectors. The details are given in Ref.[3] and references therein.

6 summary and outlook

For cosmology, our universe may undergo one or several times phase transition during the early evolution of the universe. And we can hear the cosmological phase transition using GWs if there exists FOPT. For particle physics, this phase transition GWs approach can compensate for the collider experiments to explore the new physics models(especially the hidden sector) and provide a novel approach to probe the symmetry breaking or phase transition patterns. For particle cosmology, GWs provides a unique way to unravel the dark matter, baryogenesis and so so. New physics models in particle physics can provide abundant GWs sources. GWs becomes a new and realistic approach to explore the particle cosmology and fundamental physics, such as probing the extra dimension through gravitational wave observations of compact binaries and their electromagnetic counterparts [4]. Let us ski on the exciting journey of GWs physics.

Acknowledgments

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References

1. Fa Peng Huang, Youping Wan, Dong-Gang Wang, Yi-Fu Cai, Xinmin Zhang, *Phys. Rev.* D **94**, 041702 (2016).
2. Fa Peng, Jiang-hao Yu, arXiv:1704.04201
3. Fa Peng Huang, Xinmin Zhang, arXiv:1701.04338
4. Hao Yu, Bao-Min Gu, Fa Peng Huang, Yong-Qiang Wang, Xin-He Meng, Yu-Xiao Liu, JCAP 1702 (2017) no.02, 039.