Collider tests of nanohertz gravitational waves

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Abstract. Recently, compelling evidence of nanohertz gravitational waves is indicated by the pulsar timing array collaborations. We present an MeV-scale first-order phase transition from a minimal dark sector to explain the gravitational waves, with a focus on the collider tests via the Higgs portal interaction. We demonstrate that to explain the observed gravitational waves, the Higgs portal coupling should be so sizable that it can be probed through Higgs invisible decay at the LHC and future colliders such as HL-LHC, CEPC, ILC, and FCC-ee. It opens up a promising avenue to uncover the physical origin of the nanohertz gravitational waves via colliders and to hear and see the minimal dark sector.

1 Introduction

Gravitational waves (GW) from the merger of binary black hole observed in 2015 has opened the gate of GW astronomy, greatly inspiring the exploration of the Universe through GW messengers. If GW were produced in the very early Universe, the exceedingly weak interaction ensures that information from the very early stage can be maintained, therefore opening the window to detect the important processes prior to the Big Bang nucleosynthesis and Cosmic Microwave Background. Recently, pulsar timing array (PTA) collaborations from NANOGrav [1], CPTA [2], EPTA [3] and PPTA [4] have released their new datasets, showing compelling evidence of a stochastic GW background that peaks at nanohertz frequency. New physics beyond the inspiraling supermassive black hole binaries can provide attractive explanations, which is further supported by Bayesian analysis of the PTA data [5].

A promising new physics explanation of the nanohertz GW is first-order phase transition (FOPT) that happens when the temperature of the early Universe drops to the MeV scale [6]. Here, we consider a minimal FOPT scenario that can generate the nanohertz GW, where the hidden sector only contains a scalar and a dark gauge boson charged under a gauged $U(1)_{\rm D}$ symmetry. The only connection between the Standard Model (SM) and the dark world is via the Higgs portal interaction. We highlight the connection between the GW and particle collider physics, demonstrating the importance of collider detection as a complementary probe to identify the physical origin of the nanohertz GW.

Being the unique connection, the Higgs portal interaction has two important effects. On the one hand, a sizable portal coupling can enhance the production and detection signals of the dark sector at colliders, creating more opportunities to search for the dark world. On the other hand, a larger portal coupling helps to thermalize the dark sector such that the SM and the dark sectors can share a common temperature at early times. As will be shown later, a

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larger temperature ratio of the dark to the SM sector can lead to a larger energy fraction of the dark FOPT in the early Universe and hence enhance the GW signals. Consequently, the GW signal has a positive correlation with collider detection: stronger GW signals imply a larger coupling which will enhance the collider detection signals. Especially, we find that the recently reported stochastic GW background requires a sizable portal coupling that can be probed by Higgs invisible decay at the LHC and be fully tested by future colliders such as HL-LHC, CEPC, ILC and FCC-ee.

2 GW from MeV-scale FOPT in a dark gauge $U(1)$ scenario

The basic Lagrangian for a dark gauge $U(1)_D$ boson plasma, minimally coupled to the SM via the Higgs portal is given by

$$\mathcal{L} = D_\mu S^\dagger D^\mu S - \mu_h^2|H|^2 - \mu_s^2|S|^2 - \lambda_h|H|^4 - \lambda_s|S|^4 - \lambda_{hs}|H|^2|S|^2\,, \tag{1}$$

where $H = (G^+, (h+iG^0)/\sqrt{2})$ is the SM Higgs doublet, and $S = (\phi+i\eta)/\sqrt{2}$ is the dark scalar field which is a singlet under the SM gauge group but carries unit charge under the dark gauge $U(1)_D$. The dark interaction is described by gauge covariant derivative $D_\mu = \partial_\mu - ig_D A'_\mu$, with g_D being the dark gauge coupling and A'_μ the dark gauge boson.

For MeV-scale FOPT in the dark sector, the SM electroweak gauge symmetry is spontaneously broken first, so one can focus on the ϕ-direction when studying the dark FOPT dynamics. However, it is not guaranteed that the two sectors still maintain the same temperature at this epoch. Using T and T' for the SM and dark temperatures respectively, with a temperature ratio $\xi \equiv T'/T$, we can write down the effective ϕ-potential at finite temperatures as

$$V_{\rm eff}(\phi, T') = V_0(\phi) + V_{\rm CW}(\phi) + V_T(\phi, T')\,, \tag{2}$$

where $V_0(\phi)$ is the tree-level potential from Eq. (1), and $V_{\rm CW}(\phi)$ is the Coleman-Weinberg potential at zero temperature. $V_T(\phi, T')$ is the one-loop thermal correction plus the daisy resummation term at finite temperatures:

$$V_{\rm CW} = \sum_{i=\phi,A'} \frac{n_i M_i^4(\phi)}{64\pi^2}\left(\log\frac{M_i^2(\phi)}{\mu_R^2} - C_i\right), \tag{3}$$

$$V_T(\phi, T') = \sum_{i=\phi,\eta,A'} \frac{n_i T'^4}{2\pi^2} J_B\left(\frac{M_i^2(\phi)}{T'^2}\right) - \frac{g_D^3 T'}{12\pi}\left((\phi^2 + T'^2)^{3/2} - \phi^3\right), \tag{4}$$

where the renormalization scale is set by $\mu_R = 10$ MeV, $n_{\phi,\eta,A'} = 1, 1, 3$, $C_{\phi,A'} = 3/2, 5/6$, the field-dependent masses read

$$M_\phi^2(\phi) = -\frac{m_\phi^2}{2} + \frac{3m_\phi^2}{2v_\phi^2}\phi^2\,, \quad M_{A'}(\phi) = g_D\phi\,, \quad M_\eta^2(\phi) = -\frac{m_\phi^2}{2}\left(1 - \frac{\phi^2}{v_\phi^2}\right), \tag{5}$$

and the Bose thermal integral is defined as

$$J_B(y) \equiv \int_0^\infty x^2 {\rm d}x \log(1 - e^{-\sqrt{x^2+y}})\,.$$

We apply the above effective potential in the Python package `cosmoTransitions` [7] to compute the FOPT parameter α, which is the ratio of the FOPT latent heat to the radiation

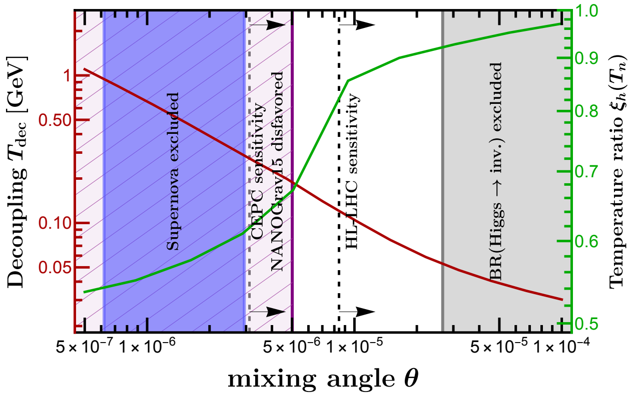

Figure 1. Collider tests of the favored parameter space that generates the nanohertz GW from the dark FOPT. By fitting the observed GW signals, we have used the following benchmark point: $m_\phi = 31.5$ MeV, $v_\phi = 133.2$ MeV, $g_D = 1.1$, $\alpha = 1.3$, and $\beta/H_n = 16.8$. The blue band is excluded by supernova observations and the gray band is excluded by current limits on Higgs invisible decay.

energy, and β/H_n, which is the inverse ratio of the FOPT duration β^{-1} to the Hubble expansion at the dark nucleation temperature T_n'.

The GW from the dark FOPT is sound-wave dominated, where the GW spectrum today can be fitted by the FOPT parameters $\alpha, \beta/H_n, T_n'$ and the wall velocity v_w [8]. In particular, the peak of the sound-wave dominated GW amplitude, $\Omega_{\rm sw}^{\rm peak}$, is proportional to the temperature ratio at nucleation $\xi_n \equiv T_n'/T_n$, with

$$\Omega_{\rm sw}^{\rm peak} \propto \xi_n^l \propto \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{l/3}, \tag{6}$$

where $8 \lesssim l \lesssim 16$ denotes a constant power [9], and g_* denotes the effective degrees of freedom in the SM plasma, with $T_{\rm dec}$ the decoupling temperature of the dark sector from the SM plasma. We can see that a temperature ratio at 0.1 will lead to strong suppression of the GW amplitude by orders of magnitude. To avoid such suppression, the Higgs portal coupling should be large enough such that $T_{\rm dec}$ is sufficiently low, thereby enhancing the ratio $g_*(T_n)/g_*(T_{\rm dec})$.

We have learned from Eq. (6) that a large Higgs portal coupling is required to avoid the strong suppression of GW signals. Since the dark FOPT occurs at the MeV scale, it implies that the dark scalar would also have an MeV-scale mass. The Higgs portal coupling then indicates that the SM Higgs has an invisible decay channel to two dark scalars $h \to 2\phi$. In the limit of $m_h \gg m_\phi$, the invisible decay width reads

$$\Gamma(h \to 2\phi) = \frac{\theta^2 m_h^3}{32\pi v_\phi^2}, \tag{7}$$

where $v_{\rm EW} = 246$ GeV corresponds to the electroweak vacuum, $m_h = 125$ GeV the SM Higgs mass, and we have used a $h-\phi$ mixing angle $|\theta| \equiv v_{\rm EW} v_\phi |\lambda_{hs}|/m_h^2$ to describe the decay width. Currently, the CMS collaboration sets an upper bound on the portal coupling at $\lambda_{hs} < 0.014$ [10]. Future detection from the HL-LHC, CEPC, ILC or FCC-ee can further increase the sensitivity by at least an order of magnitude. Remarkably, these collider experiments will probe the parameter space favored by the nanohertz GW signals indicated by the PTA data, which will be shown below.

In Fig. 1, we first fit the nanohertz GW from the PTA data, and then choose a benchmark parameter set to illustrate how collider detection of Higgs invisible decay can help to identify the GW origin from the dark FOPT. It is seen that a large portion of the parameter space favored by the NANOGrav observation (the white band) can be probed by experiments at the HL-LHC, and the favored parameter space can be fully tested by future experiments at the CEPC. Note that the future ILC and FCC-ee experiments have a sensitivity of the Higgs portal coupling similar to the CEPC. It is also seen that within the white band, the decoupling temperature of the dark sector is below the QCD phase transition epoch ($T_{\rm QCD} \simeq$ 200 MeV) when $g_*(T)$ drastically decreases. Such a low decoupling temperature implies that the temperature ratio at nucleation ξ_n is not far away from unity, as can be seen by the green curve, avoiding the strong suppression of GW signals.

3 Conclusion

We have shown that a minimal dark plasma consisting of a scalar and a gauge boson can realize an MeV-scale FOPT. The stochastic GW background induced by such a dark FOPT can explain the data observed recently by the PTA collaborations. The crucial element for generating a strong enough GW spectrum at nanohertz is a large Higgs portal coupling at order 10^{-3} , which leads to thermalization between the SM and the dark sectors before the QCD temperature. Remarkably, the favored parameter space of the Higgs portal coupling can be fully tested by future collider experiments through Higgs invisible decay.

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