NANOGrav signal and LIGO-Virgo Primordial Black Holes from Higgs inflation

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We show that the NANOGrav signal can come from the Higgs inflation with a noncanonical kinetic term in terms of the scalar induced gravitational waves. The scalar induced gravitational waves generated in our model are also detectable by space based gravitational wave observatories. Primordial black holes with stellar masses that can explain LIGO-Virgo events are also produced. Therefore, the NANOGrav signal and the BHs in LIGO-Virgo events may both originate from the Higgs field.

I. INTRODUCTION

The North American Nanohertz Observatory for Gravitational Wave (NANOGrav) Collaboration has recently published an analysis of the 12.5 yrs pulsar timing array (PTA) data, where strong evidence of a stochastic process with a common amplitude and a common spectral slope across pulsars was found [1]. Although this process lacks quadrupolar spatial correlations, which should exist for gravitational wave (GW) signals, it is worthwhile to be interpreted as a stochastic GW signal. The GW signal with the amplitude of the energy density \(\Omega_{GW} h^2 \sim 10^{-10}\) at a reference frequency of \(f_s = 1yr^{-1} Hz\) has a flat power spectrum \(\Omega_{GW} h^2 \sim f^\alpha\) with \(\alpha\) from \(-1.5\) to \(0.5\) at \(1\sigma\) confidence level.

The scalar induced gravitational waves (SIGWs) associated with the formation of primordial black holes (PBHs) are the natural sources to explain the NANOGrav signal [2–8]. (For other explanations for the sources of the NAGrav signal, see Ref. [9–24].) The nanohertz frequencies of SIGWs constrain the masses of PBHs to stellar mass, and these stellar mass PBHs, on the other hand, may be the sources of the GWs detected by the Laser Interferometer Gravitational Wave Observatory (LIGO) Scientific Collaboration and the Virgo Collaboration [25–38]. Therefore, PBHs with stellar mass can be related to both the LIGO-Virgo events and the NANOGrav signal. The PBHs are also proposed to account for the dark matter (DM) [39–48] and explain the Planet 9 which is a hypothetical astrophysical object in the outer solar system used to interpret the anomalous orbits of trans-Neptunian objects [49].

PBHs will be formed from the gravitational collapse if the density contrasts of overdense regions exceed the threshold value at the horizon reentry during radiation domination [50, 51]. The initial conditions for the overdense regions are from the inflation. Enough abundance of PBHs needs the amplitude of the power spectrum of the primordial curvature perturbations reach \(A_\zeta \sim 0(0.01)\) at small scales, and this condition is also required to explain the NANOGrav signal if it is regarded as a SIGW. The constraint on the amplitude of the power spectrum at large scales from the cosmic microwave background (CMB) anisotropy measurements is \(A_s = 2.1 \times 10^{-9}\) [52]. Therefore, to produce enough abundance of PBH DM, the amplitude of the power spectrum should be enhanced at least seven orders of magnitude to reach the threshold at small scales [53–55].

The traditional slow-roll inflation is unable to enhance the power spectrum to produce PBHs while keeping the model consistent with the CMB constraints. To overcome this, the ultra-slow-roll inflation [56–58] is then considered [53, 59–73]. Among them, the inflation model with a noncanonical kinetic term can successfully enhance the power spectra, produce PBHs, and generate SIGWs [74–76]. In this mechanism, there are no restrictions on the potential, both sharp and broad peaks in the power spectrum can be generated, the masses of the PBHs and the frequencies of the SIGWs can be adjusted as we want. In this paper, we will show that under this mechanism, the NANOGrav signal and the BHs in the LIGO-Virgo events can both come from the Higgs inflation.

The paper is organized as follows. In Sec. II, we give a brief review of the PBHs and SIGWs. We introduce our model and produce PBHs with stellar mass and generate SIGWs consistent with the NANOGrav signal in Sec. III. We conclude the paper in Sec. IV.

II. THE PBHS AND SCALAR INDUCED GWS

If the energy density contrast of overdensity regions is large enough during the radiation domination, the PBHs will be formed from gravitational collapse, and the seed of the overdensity regions is from the primordial curvature perturbations generated during inflation. The mass fraction of the Universe that collapses to form PBHs at formation is

\[
\beta = \frac{\rho_{PBH}}{\rho_b},
\]

where \(\rho_b\) is the energy density of the background and \(\rho_{PBH}\) is the energy density of the PBHs at formation, which can be obtained by the peak theory [77–82],

\[
\rho_{PBH} = \int_{\nu_c}^{\infty} M_{PBH} N_p k(\nu) d\nu,
\]
where the number density of the PBHs at formation in physical space is
\[
N_{ph}(\nu) = \frac{1}{a^3} \frac{1}{\langle 2\pi \rangle^2} \left( \frac{\sigma_1}{\sqrt{3\sigma_0}} \right)^3 \nu^3 \exp \left( -\frac{\nu^2}{2} \right).
\] (3)

\[\nu_c = \delta_c/\sigma_0 \text{ and } \delta_c \text{ is the threshold for the formation of PBHs, } \sigma_0 \text{ is the variance of the smoothed density contrast and } \sigma_1 \text{ is the moment of the smoothed density power spectrum with the definition,}

\[
\sigma_n^2 = \int_0^\infty \frac{dk}{k} k^{2n} T^2(k, R_H) W^2(k, R_H) \mathcal{P}_\delta(k).
\] (4)

The relation between the power spectrum of the density contrast \( \mathcal{P}_\delta \) and the power spectrum of primordial curvature perturbations \( \mathcal{P}_\zeta \) is
\[
\mathcal{P}_\delta(k) = \frac{4(1+w)^2}{(5+3w)^2} \left( \frac{k}{aH} \right)^4 \mathcal{P}_\zeta(k),
\] (5)

with the state equation \( w = 1/3 \) during the radiation domination. For more precise results, the non-linearities between the Gaussian disturbance of curvature and density contrast should be considered [83–85], for simplicity, we just consider the linear relationship in this work. The window function we choose in this paper is the real space top-hat window function
\[
W(k, R_H) = 3 \left[ \sin(kR_H) - (kR_H) \cos(kR_H) \right] \left( kR_H \right)^3,
\] (6)

with the smoothed scale \( R_H \sim 1/aH \). The threshold \( \delta_c \) is dependent on the choice of the window function and the shape of the density perturbation [80, 81, 86]. For the real space top-hat window function, we choose the threshold as \( \delta_c = 0.51 \) [86, 87]. During radiation domination with constant degrees of freedom, the transfer function is
\[
T(k, R_H) = 3 \left[ \sin\left( \frac{kR_H}{\sqrt{3}} \right) - \frac{kR_H}{\sqrt{3}} \cos\left( \frac{kR_H}{\sqrt{3}} \right) \right] \left( \frac{kR_H}{\sqrt{3}} \right)^3.
\] (7)

The masses of the PBHs obey the critical scaling law [88–90],
\[
M_{PBH} = \kappa M_H (\delta - \delta_c) \gamma,
\] (8)

with \( \kappa = 3.3 \) for the real space top-hat window function and \( \gamma = 0.36 \) in the radiation domination [88, 89]. The horizon mass related to the horizon scale is
\[
M_H \approx 13 \left( \frac{g_*}{106.75} \right)^{-1/6} \left( \frac{k}{10^9 \text{Mpc}^{-1}} \right)^{-2} M_\odot,
\] (9)

where \( g_* \) is the number of relativistic degrees of freedom at the formation. The density parameter of the PBHs expressed by the \( \beta \) is [91]
\[
\Omega_{PBH} = \int_{M_{\text{min}}}^{M_{\text{max}}} d\ln M_H \left( \frac{M_{eq}}{M_H} \right)^{1/2} \beta(M_H),
\] (10)

where we use the relation \( \rho_k \propto a^{-4} \) and \( \rho_{PBH} \propto a^{-3} \) during radiation domination, and \( M_{eq} = 2.8 \times 10^{17} M_\odot \) is the horizon mass at the matter-radiation equality. Because of \( \beta(M_H) \rightarrow 0 \) at the condition \( M_H \rightarrow 0 \) or \( M_H \rightarrow \infty \), for the sake of simplicity, we choose the interval of the integration as \( M_{\text{min}} = 0 \) and \( M_{\text{max}} = \infty \). The fraction of the PBHs in the dark matter is
\[
f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{DM}} = \int f(M_{PBH}) d\ln M_{PBH},
\] (11)

where the definition of the PBHs mass function is
\[
f(M_{PBH}) = \frac{1}{\Omega_{DM}} \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dM_{PBH}}{M_{PBH}} \Gamma_{PBH} \sqrt{M_{eq}/M_H}
\times \frac{1}{3\pi} \left( \frac{\sigma_1}{\sqrt{3\sigma_0 aH}} \right)^3 \frac{1}{\sigma_0} \left( \mu^{1/\gamma} + \delta_c \right)^3
\times \mu^{1/\gamma} \exp \left( -\frac{(\mu^{1/\gamma} + \delta_c)^2}{2\sigma_0^2} \right),
\] (12)

Combining Eq. (10) and Eq. (12) and using the relation (8), the mass function becomes [91]
\[
f(M_{PBH}) = \frac{1}{\Omega_{DM}} \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dM_{PBH}}{M_{PBH} \Gamma_{PBH} \sqrt{M_{eq}/M_H}} \times \frac{1}{3\pi} \left( \frac{\sigma_1}{\sqrt{3\sigma_0 aH}} \right)^3 \frac{1}{\sigma_0} \left( \mu^{1/\gamma} + \delta_c \right)^3
\times \mu^{1/\gamma} \exp \left( -\frac{(\mu^{1/\gamma} + \delta_c)^2}{2\sigma_0^2} \right),
\] (13)

where \( \mu = M_{PBH}/(\kappa M_H) \) and we have used \( d\delta/d\ln M_{PBH} = \mu^{1/\gamma}/\gamma \).

Associating with the formation of PBHs, the large scalar perturbations induce the gravitational waves during radiation domination. These SIGWs belonging to the stochastic background can account for the NANOGrav signal with frequencies around \( 10^{-9} \) Hz [2–4] and can also be detected by the space based GW detectors like LISA [92, 93], Taiji [94] and TianQin [95] with frequencies around \( 10^{-3} \) Hz in the future. In the cosmological background and the Newtonian gauge and neglecting the anisotropic stress, the perturbed metric is
\[
ds^2 = -a^2(\eta)(1 + 2\Phi) d\eta^2
+ a^2(\eta) \left[ (1 - 2\Phi) \delta_{ij} + \frac{1}{2} h_{ij} \right] dx^i dx^j,
\] (14)

where \( \eta \) is the conformal time, \( \Phi \) is the Bardeen potential. In the Fourier space, the tensor perturbations \( h_{ij} \) can be expressed as
\[
h_{ij}(x, \eta) = \int \frac{d^3k}{(2\pi)^{3/2}} e^{i k \cdot x} \left[ h_{k}(\eta) e_{ij}(k) + \tilde{h}_{k}(\eta) \tilde{e}_{ij}(k) \right],
\] (15)

where \( e_{ij}(k) \) and \( \tilde{e}_{ij}(k) \) are the plus and cross polarization tensors,
\[
e_{ij}(k) = \frac{1}{\sqrt{2}} \left[ e_{i}(k)e_{j}(k) - \tilde{e}_{i}(k)\tilde{e}_{j}(k) \right],
\] (16)

\[
\tilde{e}_{ij}(k) = \frac{1}{\sqrt{2}} \left[ e_{i}(k)\tilde{e}_{j}(k) + \tilde{e}_{i}(k)e_{j}(k) \right],
\] (17)
with \( \mathbf{e} \cdot \mathbf{e} = \mathbf{e} \cdot \mathbf{k} = \mathbf{e} \cdot \mathbf{k} \). Focusing on the source at second order from the linear scalar perturbations, the tensor perturbations in the Fourier space with either polarization satisfy [96, 97]

\[
h'_{k} + 2\mathcal{H}h_{k} + k^{2}h_{k} = 4S_{k},
\]

where a prime denotes the derivative with respect to the conformal time, \( h'_{k} = dh_{k}/d\eta \), and \( \mathcal{H} = a'/a \) is the conformal Hubble parameter. The second order source from the linear scalar perturbations is

\[
S_{k} = \int \frac{d^{3}k}{(2\pi)^{3/2}} c_{ij}(k)\bar{k}^{i}k^{j} \left[ 2\Phi_{k} \Phi_{k} - \frac{1}{\mathcal{H}^{2}}(\Phi'_{k} + \mathcal{H}\Phi_{k}) \right],
\]

where \( \Phi_{k} \) is Bardeen potential in Fourier space, and related to the primordial curvature perturbation \( \zeta_{k} \) by the transfer function,

\[
\Phi_{k} = \frac{3 + 3w}{5 + 3w} T(k\eta)\zeta_{k}.
\]

The power spectrum \( P_{h}(k, \eta) \) for the SIGWs is

\[
\langle h_{k}(\eta)h_{\bar{k}}(\eta) \rangle = \frac{2\pi^{2}}{k^{3}}\delta^{(3)}(k + \bar{k})P_{h}(k, \eta),
\]

which is found to be [96–99]

\[
P_{h}(k, \eta) = 4\int_{-\infty}^{\infty} dv \int_{-u}^{u} du \left[ 4v^{2} - \left( 1 - u^{2} + v^{2} \right) \right]^{2} 4uv
\times I_{RD}^{2}(u, v, x)P_{\zeta}(kv)P_{\zeta}(ku),
\]

where \( u = |k - \bar{k}|/k, v = \bar{k}/k, x = k\eta \) and the integral kernel \( I_{RD} \) is

\[
I_{RD}(u, v, x) = \int_{1}^{x} dy y\sin(x - y) \left\{ 3\Psi(uy)\Psi(vy) + y\Psi(vy)u\Psi(uy) + y^{2}w\Psi'(vy)\Psi(uy) \right\} + y^{2}w\Psi'(vy)\Psi'(vy).
\]

The energy density of the SIGWs is [54, 99]

\[
\Omega_{GW}(k, \eta) = \frac{1}{6} \left( \frac{k}{aH} \right)^{2} \int_{0}^{\infty} dv \int_{-u}^{u} du \left[ 4v^{2} - \left( 1 - u^{2} + v^{2} \right) \right]^{2}
\times I_{RD}^{2}(u, v, x)P_{\zeta}(kv)P_{\zeta}(ku),
\]

where \( I_{RD}^{2} \) is the oscillation time average of the integral kernel. After formation, the SIGWs behave like radiation, so the energy density of the SIGWs at present is

\[
\Omega_{GW}(k, \eta_{0}) = c_{g}\Omega_{r,0}\Omega_{GW}(k, \eta),
\]

where \( \Omega_{r,0} \) is the energy density of radiation at present, and [2, 4]

\[
c_{g} = 0.387 \left( \frac{g_{*s}g_{*e}}{166.75} \right)^{-1/3}.
\]

### III. THE MODEL AND RESULTS

To obtain enough abundance of PBH DM and induce secondary GWs with large energy density, the amplitude of the power spectrum of the primordial curvature perturbations should be enhanced about seven order of magnitude at small scales. In this section, we present our model and show that the PBHs that account for LIGO-Virgo events and the SIGWs which are consistent with the NONAgrav signal may come from the Higgs inflation. The model that can enhance the power spectrum is

\[
S = \int dx^{4} \sqrt{-g} \left[ \frac{1}{2} R + X + G(\phi)X - V(\phi) \right],
\]

where \( X = -g_{\mu\nu} \nabla^{\mu}\phi\nabla^{\nu}\phi/2 \) and we take the convention \( 8\pi G = 1 \). The noncanonical coupling function which may arise from scalar-tensor theory of gravity, G inflation [100] or k inflation [101, 102], is [74]

\[
G(\phi) = G_{p}(\phi) + f(\phi).
\]

The first part \( G_{p}(\phi) \) with a peak is used to enhance the power spectrum to produce PBHs at small scales [66, 69], and the second part \( f(\phi) \) is used to dress the noncanonical scalar field to make the model consistent with the CMB observational constraints at large scales [74, 75]. With this mechanism, both sharp and board peaks in the power spectrum can be given, and the inflationary potential does not have any restriction. For example, Higgs inflation, T-model and natural inflation are shown to satisfy the observational constraints at large scales and produce enough abundance of PBH DM at small scales [74–76]. In this paper, the peak function is

\[
G_{p}(\phi) = \frac{d}{1 + (|\phi - \phi_{p}|/w)^{q}},
\]

with \( q = 7/5 \). The Higgs potential is

\[
V(\phi) = \frac{\lambda}{4}\phi^{4},
\]

with the corresponding function \( f(\phi) = \phi^{22} \). The choice of parameter set of the model is shown in table I.

| Parameter | Value |
|-----------|-------|
| \( d \) | \( 3.23 \times 10^{11} \) |
| \( w \) | \( 3.15 \times 10^{-10} \) |
| \( \phi_{p} \) | \( 1.367 \) |
| \( \phi_{s} \) | \( 1.40 \) |
| \( \lambda \) | \( 1.25 \times 10^{-9} \) |

**TABLE I.** The choice of the parameter set.

This parameter set, the numerical solution for the primordial power spectrum is displayed in Fig. 1. The scalar tilt and the tensor-scalar ratio are

\[
n_{s} = 0.9664, \quad r = 0.039,
\]

which are compatible with the Planck 2018 constraints [52], and the e-folding numbers before the end of inflation
at the horizon exit for the pivotal scale $k_*$ is consistent with the constraints from the PTA observations [103], the effect on the ratio between neutron and proton during the big bang nucleosynthesis (BBN) [104] and $\mu$-distortion of CMB [105]. The power spectrum at the peak and the peak scale are

$$P_k(\text{peak}) = 4.63 \times 10^{-3}, \quad k_{\text{peak}} = 5.65 \times 10^5 \text{Mpc}^{-1}. \quad (32)$$

![FIG. 1. The power spectrum from model (27) with the parameter set in table I. The light green shaded region is excluded by the CMB observations [52]. The red, blue and orange regions show the constraints from the PTA observations [103], the effect on the ratio between neutron and proton during the big bang nucleosynthesis (BBN) [104] and $\mu$-distortion of CMB [105], respectively.]

By using the numerical results of the power spectrum of the primordial curvature perturbations, we obtain the PBHs mass function shown in Fig. 2. The PBH mass and the mass function at the peak are

$$M_{\text{PBH}}^{\text{peak}} = 29 M_\odot, \quad f(M_{\text{PBH}}^{\text{peak}}) = 7.40 \times 10^{-4}, \quad (33)$$

and the fraction of the PBHs in dark matter is

$$f_{\text{PBH}} = 1.73 \times 10^{-3}. \quad (34)$$

Therefore, we successfully produce the PBHs which can account for the LIGO-Virgo events, and the mass function is consistent with all the observational constraints. There may be some concern that the large enhancement on the power spectrum causes large non-Gaussianities which affect the formation of PBH DM. It was pointed out in Ref. [106] that non-Gaussianities of Higgs fluctuations are small at both the CMB and peak scales, so the effect of non-Gaussianities in our model is negligible.

The corresponding energy density of the SIGWs as a function of the frequency is displayed in Fig. 3. The frequencies of the SIGWs cover from nanohertz to millihertz. Around the nanohertz, the energy density of the SIGWs is consistent with the 2σ region of the NANOGrav signal; and around the millihertz, the SIGWs can be detected by space based GW detectors such as Taiji and LISA. This means that the NANOGrav signal may also be detected by space based GW detectors in the future.

![FIG. 2. The corresponding PBHs mass function. The shaded regions show the observational constraints on the PBH abundance: the cyan region from accretion constraints by CMB [107, 108], the red region from LIGO-Virgo Collaboration measurements [109–111], the green region from microlensing events with Subaru HSC [112], the blue region from the Kepler satellite [113], the gray region from the EROS/MACHO [114].]

![FIG. 3. The scalar induced secondary GWs for the Higgs model. The black dashed curve denotes the EPTA limit [115–119], the green dot-dashed curve denotes the PPTA limit [120], the gray dotted curve denotes the SKA limit [121], the red dot-dashed curve in the middle denotes the TianQin limit [95], the dotted magenta curve shows the Taiji limit [94], the brown dashed curve shows the LISA limit [93].]

### IV. CONCLUSION

The NANOGrav signal can be explained by the gravitational waves induced from large scalar perturbations at small scales during the radiation dominated epoch. By introducing a noncanonical kinetic term with a high peak in inflation models, the amplitude of the power spectrum of the primordial curvature perturbations can be
enhanced to produce PBHs at small scales while keeping small to satisfy the Planck 2018 observational data at large scales. With this mechanism, the Higgs inflation successfully produces PBHs with peak mass $M_{\text{PBH}}^{\text{peak}} = 29 M_\odot$ and peak mass function $f_{\text{PBH}}(M_{\text{PBH}}^{\text{peak}}) = 7.40 \times 10^{-4}$, the total fraction of the PBHs in dark matter is $f_{\text{PBH}} = 1.74 \times 10^{-4}$, and these PBHs can explain the BHs in the LIGO-Virgo events. The scalar tilt and tensor-to-scalar ratio are $n_s = 0.9664$ and $r = 0.039$ which are consistent with Planck 2018 observational data, the $e$-folds for the pivot scale $k_*=0.05 Mpc^{-1}$ are $N = 63$. The energy density of the corresponding SIGWs is consistent with the $2\sigma$ region of the NANOGrav signal. Besides, these SIGWs can also be detected by the future space based GW detectors such as Taiji and LISA. In conclusion, the NANOGrav signal and the BHs in LIGO-Virgo events can both originate from the Higgs field, and the NANOGrav signal may also be detected by the space based GW detectors in the future.

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