

Generating enhanced parity-violating gravitational waves during inflation with violation of the null energy condition

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A violation of the null energy condition (NEC) during inflation in a single-field inflation model will naturally enhance the amplitude of the parity-violation effect (defined by $\Delta\chi$) of inflationary primordial gravitational waves (GWs), provided the inflaton is nonminimally coupled to a gravitational Chern-Simons term. After going through the NEC-violating phase, the Universe enters subsequent slow-roll inflation with a higher energy scale (i.e., a greater Hubble parameter H), which results in an enhanced nearly scale-invariant power spectrum (i.e., P_T) of inflationary primordial GWs in the high-frequency band, while P_T remains consistent with observations in the frequency band of the cosmic microwave background. Therefore, the violation of NEC during inflation will amplify the observability (i.e., $P_T \cdot \Delta\chi$) of the parity-violation effect on small scales. Intriguingly, our model has particular oscillatory features on $\Delta\chi$ that may not be mimicked by others.

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I. INTRODUCTION

The inflation scenario [1–4] has achieved tremendous success in simultaneously solving several puzzles of the hot big bang cosmology. The nearly scale-invariant power spectrum of the primordial scalar perturbations predicted by inflation has been confirmed by observations of the temperature anisotropy of cosmic microwave background (CMB) [5,6], while the primordial gravitational waves (GWs) predicted by inflation remains undetermined. For a scale-invariant power spectrum of the primordial GWs, the tensor-to-scalar ratio is bounded to be $r_{0.002} < 0.035$ at 95% confidence level [7] in the observational window of CMB. In recent years, the detections of GWs from binary black holes [8] and a binary neutron star inspiral [9] by the LIGO and Virgo collaborations have opened a new window for gravitational physics.

The inflationary primordial GWs background [10,11], which spans a broad frequency band (about 10^{-18} – 10^{10} Hz), may bring us a wealth of information about gravity and the early Universe in light of the recent and future observations in a wide multifrequency range, including those of the Pulsar Timing Array (PTA) [12–15], SKA [16], LISA [17], Taiji [18], TianQin [19], DECIGO [20], and BBO [21]. In contrast to primordial scalar perturbations, primordial GWs possess a distinct characteristic, namely, chirality, which can be manifested in parity-violating theories of gravity in the primordial universe; see, e.g., Refs. [22–56] for some of the recent studies, and see also Refs. [57–66]. A dynamical coupling of the inflaton or a spectator field to

a parity-violating term, such as the gravitational Chern-Simons (gCS) term [67,68], which is well motivated [69], is able to produce asymmetric right- and left-handed circularly polarized isotropic GWs; see also Ref. [28] for the chirality oscillation. Notably, a hint of parity-violating physics in the CMB (i.e., the cosmic birefringence) was recently extracted from the polarization data of Planck and WMAP [70–72], which may require further verification. This signal of birefringence (if confirmed by more evidence) must have been generated by some mechanism beyond the slow-roll inflation; see, e.g., Ref. [73].

In single-field inflationary models, the effect of parity violation is proportional to $\dot{\phi} \equiv d\phi/dt$ (where ϕ is the inflaton), which is suppressed by the slow-roll condition ($\dot{\phi} \ll H$), unless a delicate design of the coupling is introduced. Furthermore, the stringent bound on the tensor-to-scalar ratio in the observational window of CMB makes the situation even worse. Consequently, the parity violation of primordial GWs generated in single-field models of slow-roll inflation can hardly be observed in general situations. However, the approximate 60 e -folds inflationary expanding history could be more complicated than that described by the slow-roll inflation; see, e.g., Refs. [74–85]. As can be inferred, the scale invariance of the GW power spectrum could be broken in such a broad frequency band through many different ways [86–94]. Recently, the NANOGrav Collaboration reported evidence for a stochastic common-spectrum process [12], which might be interpreted as a stochastic GW background with a spectrum tilt $-1.5 \lesssim n_T \lesssim 0.5$. If this result could be attributed to the primordial GWs, it would mean that we

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may need new physics beyond the slow-roll inflation; see, e.g., Ref. [95].

One possibility is when there is a violation of the null energy condition (NEC) during inflation, which might play a significant role in the evolution history of the Universe; see Ref. [96] for a review. Implementing a fully stable NEC violation in cosmology is a challenging task [96–100]; see also Refs. [101–109]. It has been demonstrated with the effective field theory method that a fully stable NEC violation can be realized in “beyond Horndeski” theory [110–114]; see also Refs. [115–131] for recent studies. The violation of NEC is able to enhance the power spectrum of primordial GWs in the higher frequency band [78,132], where the scale invariance is recovered due to the recovery of slow-roll condition in the subsequent inflationary phase, which has a larger Hubble parameter H . Furthermore, the slow-roll condition will be inevitably violated around the NEC-violating phase, which is able to naturally enhance the amplitude of the parity-violation effect of inflationary primordial GWs in single-field inflationary models, as we will show in the following. To our knowledge, the enhanced parity-violating GWs produced by a NEC-violating phase during inflation has not been investigated so far.

In this paper, we illustrate the ability of a NEC violation in generating enhanced parity-violating primordial GWs during inflation with a (noncanonical) single-field model of inflation, in which the inflaton is nonminimally coupled to the gCS term. We show that the violation of NEC during inflation will naturally amplify the observability of the parity-violation effect, which might be detectable at scales much smaller than the CMB scale in the future.

II. NEC VIOLATION AND PARITY VIOLATION OF INFLATIONARY GRAVITATIONAL WAVES

The gCS term is the leading-order parity-violating correction to general relativity motivated by the anomaly cancellation in particle physics and string theory; see, e.g., Ref. [68] for a review. In this section, we consider a nonminimal coupling of the inflaton to the gCS term, while setting the background evolution to the same as that introduced in Ref. [78].

Initially, the canonical scalar field ϕ (i.e., the inflaton) slowly rolls down a nearly flat potential $V(\phi)$, so the Universe undergoes a period of slow-roll inflation, which is NEC preserving. The primordial scalar perturbation and GWs generated in this period should be consistent with observations in the window of the CMB. As the field ϕ becomes noncanonical and climbs up the potential rapidly such that $\dot{H} > 0$, the NEC and the slow-roll condition are violated. After exiting the NEC-violating phase, the Universe gradually enters a subsequent slow-roll inflationary phase (NEC preserving) with higher energy scale (i.e., a greater Hubble parameter), during which the inflaton ϕ becomes canonical again.

A. Setup

The action of our single-field model can be given as

$$S = \int d^4x \sqrt{-g} \left[\frac{M_p^2}{2} R - M_p^2 \frac{g_1(\phi)}{2} X + \frac{g_2(\phi)}{4} X^2 - M_p^4 V(\phi) + \frac{g_3(\phi)}{8} R \wedge R + L_{\text{HD}} \right], \quad (1)$$

where the inflaton ϕ is dimensionless, $X = \nabla_\mu \phi \nabla^\mu \phi$, $g_n(\phi)$ are dimensionless functions, the gCS term $R \wedge R = \epsilon^{\alpha\beta\gamma\delta} R_{\alpha\beta\mu\nu} R_{\gamma\delta}{}^{\mu\nu}$, $\epsilon^{\alpha\beta\gamma\delta}$ is the four-dimensional Levi-Civita tensor with $\epsilon^{0123} = -1/\sqrt{-g}$, and L_{HD} represents some higher derivative terms which are assumed to have negligible contributions to the background evolution and the tensor perturbations at quadratic order; see, e.g., Ref. [113] for $L_{\delta g^{00}R^{(3)}}$. In this paper, we will focus on the primordial tensor perturbations. The dangerous ghost or gradient instabilities (see, e.g., Refs. [97,98,106,107]) of the scalar perturbations around the NEC-violating phase are assumed to be cured by L_{HD} (see, e.g., Refs. [110–114], for $L_{\text{HD}} = L_{\delta g^{00}R^{(3)}}$), for simplicity. A detailed study of the scalar sector of this theory will be carried out separately.

With the flat Friedmann-Robertson-Walker metric, i.e., $ds^2 = -dt^2 + a^2(t)d\vec{x}^2$, the background equations can be found as

$$3H^2 M_p^2 = \frac{M_p^2}{2} g_1 \dot{\phi}^2 + \frac{3}{4} g_2 \dot{\phi}^4 + M_p^4 V, \quad (2)$$

$$\dot{H} M_p^2 = -\frac{M_p^2}{2} g_1 \dot{\phi}^2 - \frac{1}{2} g_2 \dot{\phi}^4, \quad (3)$$

where $\dot{\phi} \equiv d/d\phi$. The background evolution is unaffected by the gCS term or L_{HD} . By choosing the functions $g_1(\phi)$, $g_2(\phi)$, and $V(\phi)$ appropriately, we can realize the background evolution of intermittent NEC violation during inflation; see Ref. [78].

In the unitary gauge, we will set the tensor perturbation as $h_{ij} = a^2(\epsilon^\gamma)_{ij}$, where $\gamma_{ii} = 0 = \partial_i \gamma_{ij}$. The quadratic action of tensor perturbation can be given as

$$S_\gamma^{(2)} = \frac{M_p^2}{8} \int d\tau d^3x \left\{ a^2 [\gamma'_{ij}]^2 - (\partial_k \gamma_{ij})^2 - \frac{g'_3}{M_p^2} \epsilon^{ijk} [(\partial_i \gamma_{jl})' (\gamma'_k) - \partial_i \partial_l \gamma_{jq} \partial^l \gamma'_k] \right\}, \quad (4)$$

where $' = d/d\tau$ and $\tau = \int dt/a$, $\epsilon^{ijk} = \epsilon^{0ijk}$ is the three-dimensional Levi-Civita symbol and the higher-derivative terms proportional to g'_3 are the parity-violating corrections contributed by the gCS term. During the slow-roll inflation, the effect of parity violation could be suppressed by $\dot{\phi}$ since $g'_3 = a g_{3,\phi} \dot{\phi}$, unless a delicate design of $g_3(\phi)$ is adopted.

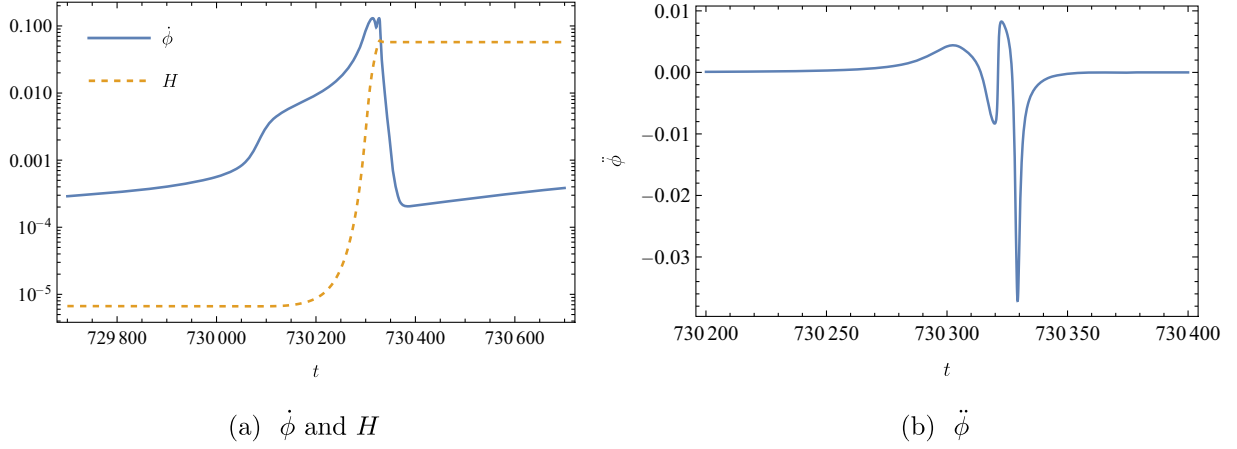


FIG. 1. Evolution of the background. Approximately, $|\dot{\phi}|$ and $|\ddot{\phi}|$ reach their maximum values around the end of the NEC-violation phase.

However, the parity violation during inflation could be greatly enhanced by an intermediate NEC violation, during which $\dot{\phi}$ can naturally and significantly violate the slow-roll condition.

In the Fourier space, we have $\gamma_{ij}(\tau, \mathbf{x}) = \sum_{s=L,R} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \gamma_{\mathbf{k}}^{(s)}(\tau) p_{ij}^{(s)}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}}$, where $p_{ij}^{(s)}$ is the circular polarization tensor which satisfies $p_{ij}^{(R)} p^{ij(R)} = p_{ij}^{(L)} p^{ij(L)} = 0$, $p_{ij}^{(R)} p^{ij(L)} = 2$ and $ik_l e^{nlj} p_{ij}^{(s)} = k\lambda^{(s)} p_i^{(s)}$. The parameters $\lambda^{(L)} = -1$ and $\lambda^{(R)} = 1$ correspond to the left- and right-handed modes, respectively. For convenience, we also define $\lambda^{(N)} = 0$, which corresponds to the situation where there is no violation of parity.

From Eq. (4), we can obtain the equation of motion of $\gamma_{\mathbf{k}}^{(s)}$ as

$$u_{\mathbf{k}}^{(s)''} + \left[(c_{T\mathbf{k}}^{(s)})^2 k^2 - \frac{z_T^{(s)''}}{z_T^{(s)}} \right] u_{\mathbf{k}}^{(s)} = 0, \quad (5)$$

where we have defined $u_{\mathbf{k}}^{(s)} \equiv z_T^{(s)} \gamma_{\mathbf{k}}^{(s)}$ and $z_T^{(s)} = \frac{a}{2} \sqrt{1 - \lambda^{(s)} \frac{k}{a^2} \frac{g_3}{M_p^2}}$, and the effective sound speed is $c_{T\mathbf{k}}^{(s)} = 1$ for both the left- and the right-handed GW modes; see, e.g., Ref. [36]. To avoid the appearance of the ghost modes, we require that $\frac{k}{a^2} \frac{g_3}{M_p^2} < 1$; see, e.g., Ref. [133].

The perturbation modes are deep inside their horizon initially, i.e., $k^2 \gg z_T^{(s)''}/z_T^{(s)}$, which indicates $u_{\mathbf{k}}^{(s)} \simeq e^{-ik\tau}/\sqrt{2k}$ for $\tau \rightarrow -\infty$. The power spectrum of primordial GWs is $P_T^{(s)} = \frac{k^3}{2\pi^2} |\gamma_{\mathbf{k}}^{(s)}|^2$ for $k \ll aH$, where $s = L, R$, and N .¹ To evaluate the intensity of parity violation of

¹Note that $P_T^{(N)} = P_T/2$ in the situation where there is no parity violation.

primordial GWs, it is convenient to define the chiral parameter

$$\Delta\chi = \frac{P_T^{(L)} - P_T^{(R)}}{P_T^{(L)} + P_T^{(R)}}. \quad (6)$$

From an observational point of view, what we really care about is the difference between the power spectra of the left- and right-handed GW modes, i.e., $P_T^{(L)} - P_T^{(R)}$. With a sufficient large $P_T = P_T^{(L)} + P_T^{(R)}$, a $\Delta\chi$ as small as a few percent in the GW background might be detectable for future observations. Furthermore, the peculiar features on $\Delta\chi$ may encode the characteristic of our model.

B. Model and numerical solution

We adopt the phenomenological model proposed in Ref. [78], in which we set

$$g_1(\phi) = \frac{2}{1 + e^{-q_1(\phi-\phi_0)}} + \frac{1}{1 + e^{q_2(\phi-\phi_3)}} - \frac{f_1 e^{2\phi}}{1 + f_1 e^{2\phi}}, \quad (7)$$

$$g_2(\phi) = \frac{f_2}{1 + e^{-q_2(\phi-\phi_3)}} \frac{1}{1 + e^{q_3(\phi-\phi_0)}}, \quad g_3(\phi) = \phi, \quad (8)$$

$$V(\phi) = \frac{1}{2} m^2 \phi^2 \frac{1}{1 + e^{q_2(\phi-\phi_2)}} + \frac{\lambda}{1 + e^{-q_4(\phi-\phi_1)}} \left[1 - \frac{(\phi - \phi_1)^2}{\sigma^2} \right]^2, \quad (9)$$

where $m, \lambda, f_{1,2}$, and $q_{1,2,3,4}$ are some positive constants. We set $\phi_3 < \phi_2 < 0 < \phi_1 < \phi_0$ for convenience.

In the limit $\phi \ll \phi_3$, we have $g_1 = 1, g_2 = 0$, and $V = V_{\text{inf1}} \simeq m^2 \phi^2/2$, which is responsible for the first stage of slow-roll inflation. Apparently, the inflaton is canonical when $\phi \ll \phi_3$. For $\phi \gg \phi_0$, we have $g_1 = 1$,

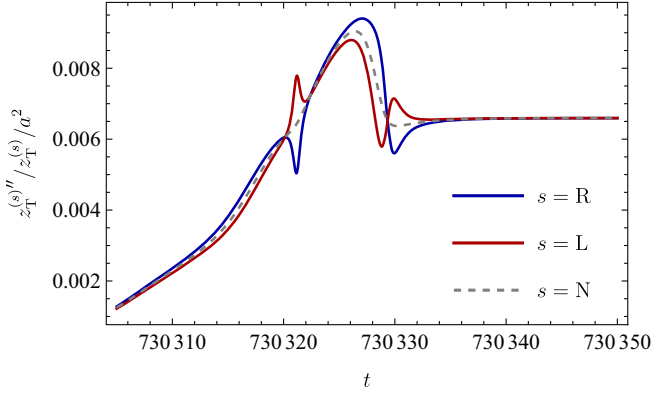


FIG. 2. Comparison of the evolutions of $z_T^{(s)''}/z_T^{(s)}/a^2$ for $s = R$ ($\lambda_s = 1$), $s = L$ ($\lambda_s = -1$) and $s = N$ ($\lambda_s = 0$), where $s = N$ corresponds to a''/a^3 . We have set $k = 8.8 \times 10^5 \text{ Mpc}^{-1}$.

$g_2 = 0$, and $V = V_{\text{inf}2} \simeq \lambda[1 - \frac{(\phi - \phi_1)^2}{\sigma^2}]^2 \gg V_{\text{inf}1}$, which is responsible for the subsequent slow-roll inflation with a higher energy scale (or equivalently, a greater Hubble parameter H). Again, the inflaton becomes canonical in this stage. In these two NEC-preserving regimes (i.e., $\phi \ll \phi_3$ and $\phi \gg \phi_0$), the potential is nearly flat, so the

predicted primordial scalar perturbations are consistent with the observations in the window of CMB.

We numerically solve Eqs. (2) and (3) using (7) to (9) and show the evolutions of H , $\dot{\phi}$ and $\ddot{\phi}$ around the NEC-violating phase in Fig. 1. Apparently, the slow-roll condition is strongly violated around the NEC-violating phase. More details about the background evolution can be found in Ref. [78]. The evolution of $z_T^{(s)''}/z_T^{(s)}$ is displayed in Fig. 2. Actually, it is mainly the nontrivial evolutions of $\dot{\phi}$ and $\ddot{\phi}$ that cause $z_T^{(s)''}/z_T^{(s)}$ to deviate greatly from a''/a , where a''/a corresponds to the situation in which parity is preserved (i.e., $\lambda^{(s)} = 0$). Therefore, the NEC violation during inflation is able to naturally enhance the parity violation, compared with the case where the slow-roll condition is preserved, as can be inferred.

We also numerically solve Eq. (5) and plot the evolutions of perturbation modes $|u|_{\mathbf{k}}^{(s)}$ and $|\gamma|_{\mathbf{k}}^{(s)}$ for $s = L, R$, and N in Fig. 3, in which we set the comoving wave number $k = 8.8 \times 10^6 \text{ Mpc}^{-1}$. Basically, the chirality asymmetry of GW modes becomes relatively apparent when $|\dot{\phi}|$ and $|\ddot{\phi}|$ become sufficient large, as we can see from Figs. 1–3. The left- and right-handed GW modes oscillate with each other and eventually arrive at different values after exiting their

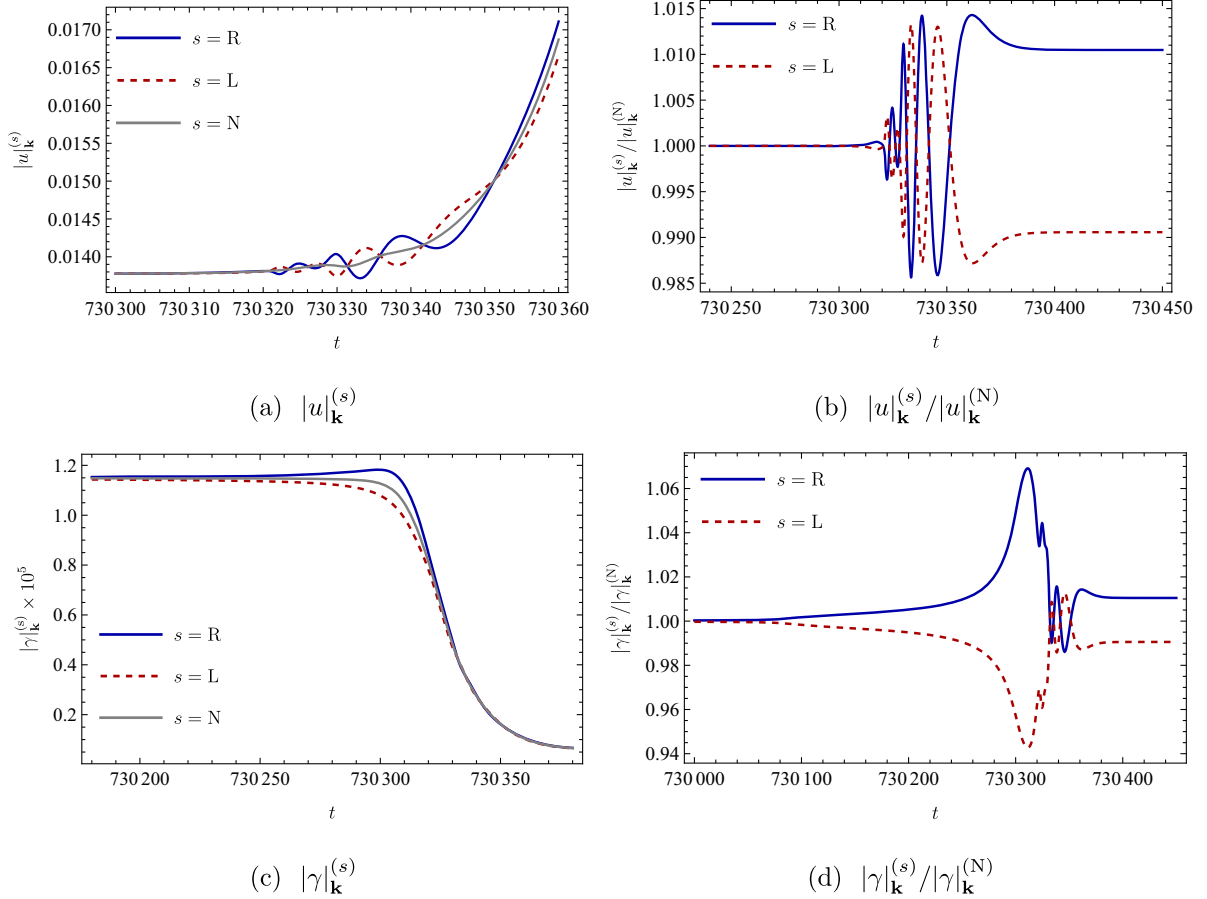


FIG. 3. Evolution of the GW mode with comoving wave number $k = 8.8 \times 10^6 \text{ Mpc}^{-1}$.

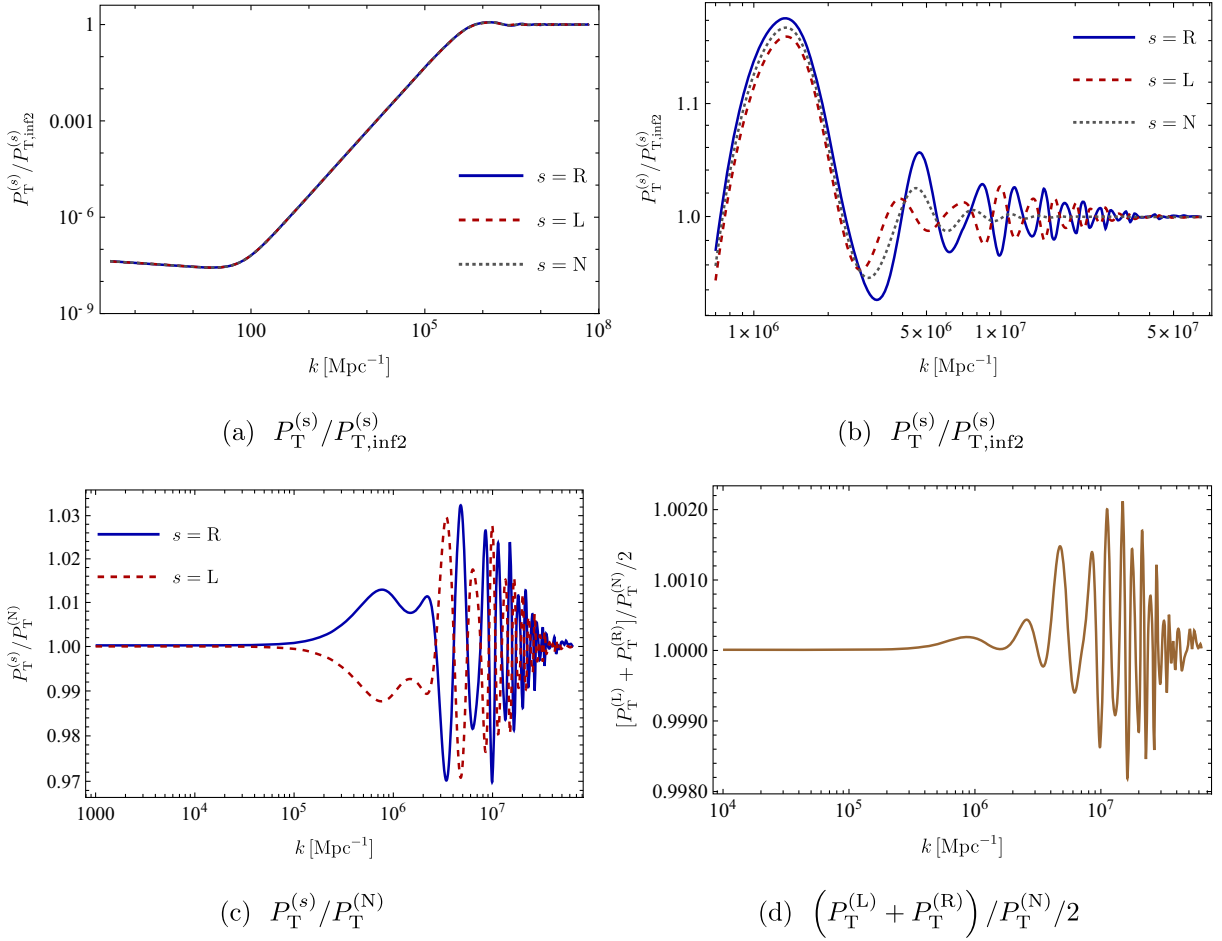


FIG. 4. Comparisons of the power spectra of the left-handed ($\lambda^{(s)} = -1, s = L$), right-handed ($\lambda^{(s)} = 1, s = R$), and parity-preserving ($\lambda^{(s)} = 0, s = N$) primordial GWs modes which exited their horizon around the NEC-violating phase (part a) and that around the end of the NEC-violating phase (part b). The ratios of the power spectra of the chiral GW modes to that of the parity-preserving ones (parts c and d). Here, the power spectra are nearly scale invariant on both large and small scales, which may be distinctive from that produced by other mechanism.

horizon. As a result, the parity violation of primordial GWs enhanced by NEC violation during inflation will be encoded in the power spectra; see also Ref. [28] for the chirality oscillation.

The power spectra and the chiral parameter $\Delta\chi$ are displayed in Figs. 4 and 5, respectively. We can see that the parity violation becomes evident in the range $10^5 \text{ Mpc}^{-1} \lesssim k \lesssim 10^8 \text{ Mpc}^{-1}$. This range corresponds to those GW modes exiting horizon around the end of the NEC-violating phase, around which $|\dot{\phi}|$ and $|\ddot{\phi}|$ reach their maximum values. It should be pointed out that the specific relation between the comoving wave number k and the time t depends on the choice of parameters in the numerical calculation. For example, with a different normalization of the scale factor, we can obtain a shift of the power spectra as well as $\Delta\chi$ with respect to k .

Notably, we can see in Fig. 5 that there are some peculiar oscillatory features on $\Delta\chi$ at small scales. These features

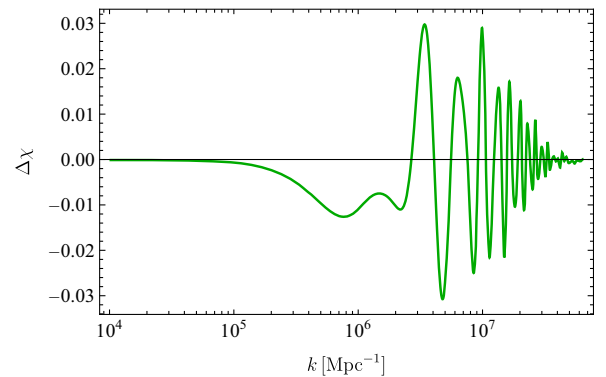


FIG. 5. The chiral parameter $\Delta\chi$ is defined by Eq. (6). These nontrivial oscillations of $\Delta\chi$ become evident in the range $10^5 \text{ Mpc}^{-1} \lesssim k \lesssim 10^8 \text{ Mpc}^{-1}$, which corresponds to those GW modes exiting horizon around the end of the NEC-violating phase.

together with the peculiar power spectra (as shown in Fig. 4) make our model characteristic with respect to others in the literature (e.g., Refs. [31,45,50,52,53]).

III. PARITY-VIOLATING GRAVITATIONAL WAVE BACKGROUND AND OBSERVATIONS

The energy density spectrum of GWs is defined as [134,135] (see also Ref. [86])

$$\Omega_{\text{GW}} = \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \ln k} = \frac{k^2}{12a_0^2 H_0^2} P_{\text{T}} \mathcal{T}^2(k, \tau_0), \quad (10)$$

where the critical energy density of the Universe is $\rho_c = 3M_p^2 H_0^2$, $H_0 = 67.8 \text{ km/s/Mpc}$, $\tau_0 = 1.41 \times 10^4 \text{ Mpc}$, $a_0 = 1$, the reduced Hubble parameter $h = H_0/(100 \text{ km/s/Mpc})$, ρ_{GW} is the energy density of GWs at present, and the wave number relates to the frequency as $k = 2\pi f$. The transfer function can be given as

$$\mathcal{T}(k, \tau_0) = \frac{3\Omega_m j_1(k\tau_0)}{k\tau_0} \sqrt{1.0 + 1.36 \frac{k}{k_{\text{eq}}} + 2.50 \left(\frac{k}{k_{\text{eq}}}\right)^2}, \quad (11)$$

where $k_{\text{eq}} = 0.073\Omega_m h^2 \text{ Mpc}^{-1}$ is the comoving wave number of the perturbation mode that entered the horizon at the equality of matter and radiation and Ω_m is the density fraction of matter today.

Currently, the bound on the tensor to scalar ratio put by data of CMB [7] indicates that $\Omega_{\text{GW}} < 10^{-15}$ at $f \sim 10^{-16} \text{ Hz}$. The 12.5 yr data of NANOGrav [12] suggest $\Omega_{\text{GW}} \sim 10^{-9}$ at $f \sim 10^{-8} \text{ Hz}$, provided the stochastic common-spectrum process can be interpreted as a stochastic GW background. The observations in the frequency

band of LIGO and Virgo [8,9] put the bound $\Omega_{\text{GW}} < 10^{-7}$ at $f \simeq 30 \text{ Hz}$.

We plot $\Omega_{\text{GW}}^{(s)} h^2 \sim P_{\text{T}}^{(s)}$ with respect to the physical frequency f for left-handed, right-handed, and parity-preserving GW modes in Fig. 6. We use the 12.5 yr data of NANOGrav and the future sensitivity curves of SKA, LISA, Taiji, TianQin, DECIGO, and BBO to compare the theoretical predictions with experimental projections. In Fig. 6, the largest parity-violation effect appears in the observational window of PTA. We also choose a different normalization of the scale factor in our numerical calculation so that we can shift the largest parity-violation effect to the band of space-based interferometers, as displayed in Fig. 7.

Additionally, with a different choice of the parameter space, we should obtain a larger effect of parity violation, i.e., a larger maximum value of $|\Delta\chi|$. Here, for simplicity and to show that the NEC violation during inflation can naturally enhance the effect of parity violation in primordial GWs, we have chosen the same model parameters in the numerical calculation as in Ref. [78]. Furthermore, since the GW power spectra P_{T} (or $\Omega_{\text{GW}} h^2$) are greatly enhanced for more than seven orders by the NEC violation, the absolute value of $|P_{\text{T}}^{(L)} - P_{\text{T}}^{(R)}|$ (or $\Omega_{\text{GW}}^{(L)} h^2 - \Omega_{\text{GW}}^{(R)} h^2$) could become quite substantial, even though the maximum value of $|\Delta\chi|$ is only a few percent. Therefore, the NEC violation is able to amplify the observability of parity violation in the GW background. It is also interesting to note that observations of an enhanced P_{T} and the peculiar oscillatory features on $\Delta\chi$ might distinguish our model from others in the literature (e.g., Refs. [31,45,50,52,53]).

We did not extend the curve to higher frequencies in Figs. 6 and 7 because there is a cutoff to avoid the appearance of ghost modes [133] in gCS theory, as can be seen from the expression of $z_{\text{T}}^{(s)}$. It is also because we did not deal with the exit of the second inflationary phase,

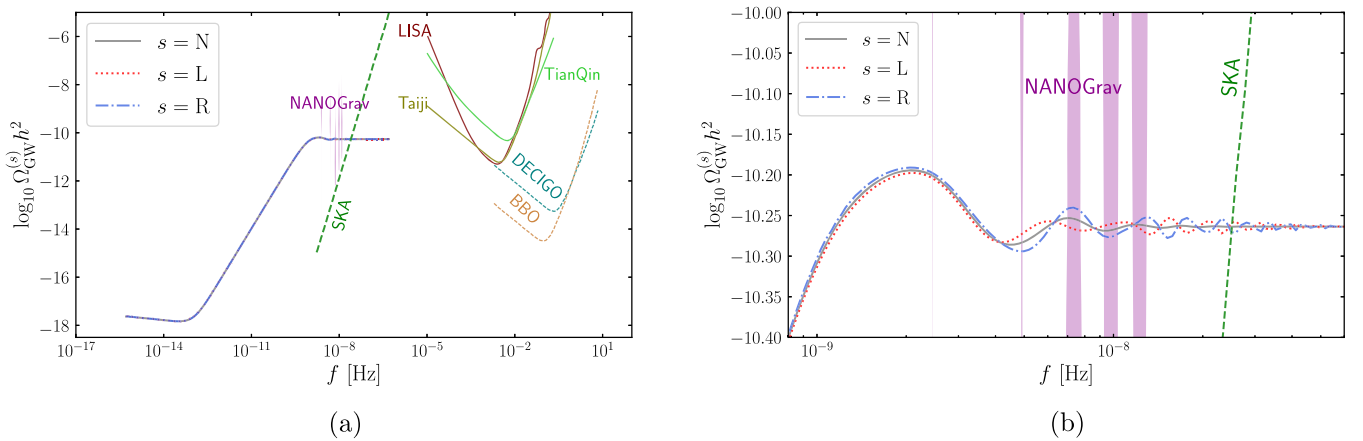


FIG. 6. The energy density spectrum of GWs $\Omega_{\text{GW}}^{(s)} h^2$ with respect to the physical frequency f , where $h = H_0/(100 \text{ km/s/Mpc})$; $s = L$ and R correspond to the left- and right-handed GW modes, respectively; $s = N$ corresponds to the parity-preserving mode. The largest parity-violation effect appears in the band of PTA.

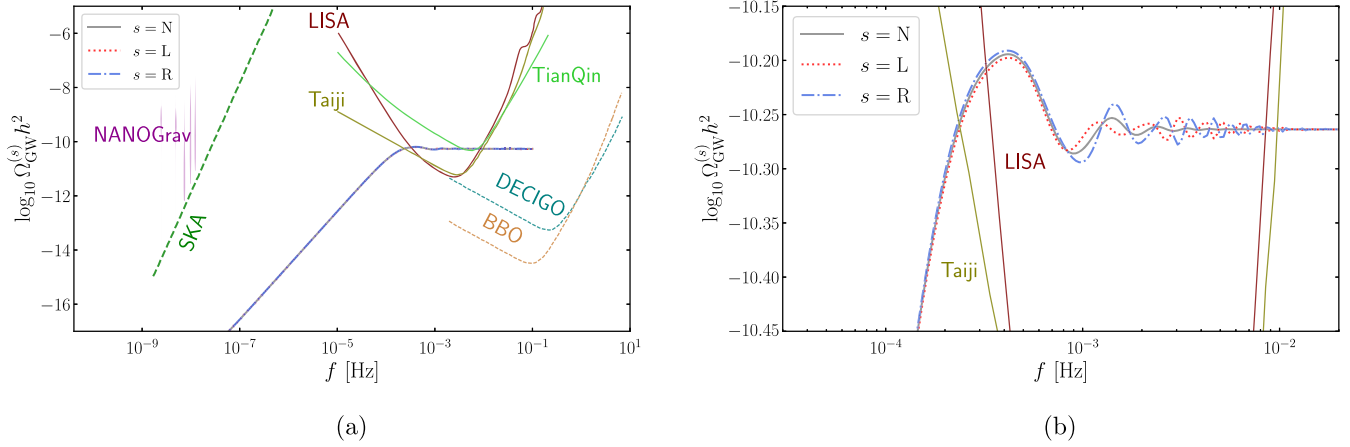


FIG. 7. The energy density spectrum of GWs $\Omega_{\text{GW}}^{(s)} h^2$ with respect to the physical frequency f , where $h = H_0/(100 \text{ km/s/Mpc})$; $s = \text{L}$ and R correspond to the left- and right-handed GW modes, respectively; $s = \text{N}$ corresponds to the parity-preserving mode. The largest parity-violation effect appears in the band of space-based interferometers.

which is an open question. Interestingly, there might be multistage inflation with intermittent NEC violations and short periods of decelerated expansion, as has been discussed in Ref. [78]. As a result, the GW spectra might look like the Great Wall while satisfying constraints in the band of CMB.

IV. CONCLUSION

Chirality might be an intrinsic characteristic of GWs. We have shown that a violation of the NEC during inflation is able to naturally enhance the parity-violating primordial GWs such that the chirality asymmetry of GWs can be observable at scales much smaller than the CMB scale. We have illustrated this new mechanism with a single-field inflationary model, in which the inflaton ϕ is nonminimally coupled to a gravitational Chern-Simons term.

The enhancement of parity-violating GWs in our model is twofold. First, because of the strong violation of the slow-roll condition induced by the violation of NEC, $\Delta\chi$ is naturally enhanced compared with that in the case where the slow-roll condition is preserved, though $\Delta\chi$ cannot approach $|\Delta\chi| \sim 1$ in the current model. Second, the power spectrum of parity-violating GWs (i.e., P_{T}) can be enhanced for more than seven orders in higher frequency band by the NEC violation during inflation, which might be detectable at small scales in the future, while the

power spectrum remains consistent with constrains in the observational window of CMB. Therefore, the violation of NEC will amplify the observability of the parity-violation effect in the GW background, since $P_{\text{T}} \cdot \Delta\chi$ is the difference between the power spectrum of the left- and right-handed GWs.

An enhanced nearly scale-invariant power spectrum of the parity-violating inflationary primordial GWs in the high-frequency band with peculiar oscillatory features on $\Delta\chi$ could be distinguishable from that generated by other mechanism (e.g., Refs. [31,45,50,52,53]). A wide range of multifrequency observations aimed at searching for GW signals will bring us rich information about the gravity and the early Universe. A signal of parity-violating GW background found by future observations could be attributed to that generated by our mechanism.

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