## Large Anisotropies in the Gravitational Wave Background from Baryogenesis

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Affleck-Dine (AD) baryogenesis can produce the baryon asymmetry of the Universe through the CP-violating dynamics of AD field. The field generally fragments into Q-balls, whose rapid decay induces enhanced gravitational waves. In this Letter, we investigate the anisotropies in this gravitational wave background as a new essential observable for AD baryogenesis. The evolution of AD field causes non-Gaussian baryonic isocurvature perturbations, and the non-Gaussianity modulates the spatial distribution of Q-balls on large scales, resulting in large-scale anisotropies in the Q-ball-induced gravitational wave background. We present that the anisotropies can be significantly large with a reduced angular power spectrum  $\sim 10^{-2}$ , and can be detected by future experiments like LISA. Moreover, these anisotropies universally reveal the CP-violating dynamics of AD field, opening a novel road to explore the longstanding baryon asymmetry puzzle.

Introduction.— The origin of the baryon asymmetry of our Universe remains a fundamental challenge in particle physics and cosmology, unaddressed in the framework of the Standard Model (SM) [1, 2]. Affleck-Dine (AD) baryogenesis is a well-established mechanism to produce the observed baryon asymmetry, driven by the evolution of an AD field, which can be a flat direction with a non-zero baryon number in extensions of the SM [3-6]. The AD field forms scalar condensates during inflation, and the post-inflationary dynamics of the condensates efficiently generate baryon density through CP-violating interactions. Since this mechanism is expected to happen at high energy scales inaccessible to particle colliders, searching for corresponding cosmological observables becomes a basic task to test AD baryogenesis and to explore the dynamics of AD field.

A promising observational window for AD baryogenesis is Q-balls in the early Universe. Generic models predict that AD condensates fragment into non-topological solitons termed Q-balls [7, 8], whose stability is protected by the conserved charge (i.e., baryon number). Q-balls have garnered increasing attentions for their profound cosmological implications, e.g., they can dominate and reheat the early Universe [9, 10], constitute all the dark matter [11–14], and provide seeds for primordial black holes (PBHs) [15–18]. The properties of Q-balls, which are determined by details of the evolution of AD field, naturally carry rich information about AD baryogenesis.

Gravitational waves (GWs), which propagate almost freely since their generation in the early Universe, offer a direct probe to cosmological scenarios involving Q-balls. Various processes associated with Q-balls can be sources of GWs, including their formation [19–22], decay [23–26], and universal statistical properties [27–29]. This work concentrates on the GWs related to Q-ball decay in the context of AD baryogenesis, whose frequency band

can be covered by a wide range of GW detectors. Since Q-balls redshift as matter, their energy density can exceed radiation's, leading to an early matter-dominated (eMD) era. When Q-balls decay into SM particles, with a typical timescale much shorter than the Hubble time, the Universe transition into a radiation-dominated (RD) era. As the transition is sudden, Q-ball density perturbations reentering the horizon during the eMD era have no time to sufficiently dissipate. They evolve into relativistic sound waves in the RD era and resonantly induce GWs [30], acting as detectable signals for AD baryogenesis. Existing studies focus on the spectrum of these GWs [23– 26]. However, the GW spectrum solely provides limited information about the dynamics of AD field. Besides, other cosmological scenarios involving PBHs [31–37], oscillons [38, 39], curvatons [40], or axions [41], etc., can also produce similar GW spectra.

In this Letter, we propose the anisotropies in the gravitational wave background (GWB) as a new essential observable for AD baryogenesis. In AD baryogenesis, the quantum fluctuations of AD field during inflation can cause non-Gaussian baryonic isocurvature perturbations through CP-violating interactions [42]. The spatial distribution of resulting Q-balls can be affected by this non-Gaussianity, leading to non-linear couplings between the large- and small-scale Q-ball density perturbations. We will demonstrate that the GWs induced by small-scale Q-ball density perturbations would experience modulation on superhorizon scales due to the presence of large-scale perturbations, resulting in observable anisotropies in the GWB. These anisotropies are revealed to exhibit close connections to the CP-violating dynamics of AD field.

Furthermore, we will present that the anisotropies in the GWB from AD baryogenesis can be remarkably large, with a reduced angular power spectrum  $\sim 10^{-2}$ . Considering the anisotropies in the GWB originated from most

cosmological scenarios are challenging to observe, this highly anisotropic GWB is of particular observational interests, potentially detected by future GW experiments, e.g., Laser Interferometer Space Antenna (LISA) [43–45], Einstein Telescope (ET) [46], Cosmic Explorer (CE) [47], Deci-hertz Interferometer Gravitational wave Observatory (DECIGO) [48, 49], Big Bang Observer (BBO) [50, 51], etc. The large anisotropies in the GWB, accompanied with the GW spectrum, provide distinctive signals for AD baryogenesis and valuable insights into the longstanding question of baryon asymmetry.

Affleck-Dine baryogenesis.— The AD field for baryogenesis could naturally be many potential-vanishing directions carrying baryon number in supersymmetric theories, parameterized as  $\phi = |\phi| e^{i\theta}/\sqrt{2}$ . During inflation,  $\phi$  forms a scalar condensate with a large vacuum expectation value with CP violation as an initial condition. After inflation, as the direction is lifted by some non-renormalizable term (i.e.,  $\phi^n$  with  $n \geq 4$ ) in superpotential, the condensate relaxes from its initial position and follows a rotating trajectory in field space. The baryon asymmetry can be effectively created by the angular motion of  $\phi$ , with the resulting baryon density  $n_b \propto \sin n\theta_i$ , where  $\theta_i$  denotes its initial value set in inflation. Here, the phase component  $\theta_i$ , manifesting as the CP phase for baryogenesis, is a crucial parameter in this mechanism.

In AD baryogenesis, quantum fluctuations of  $\theta_i$  during inflation lead to baryonic isocurvature perturbations  $S_b \simeq \delta n_b/n_b$  [42, 52–55]. Given the Gaussian fluctuations  $\delta \theta_i$ ,  $S_b$  can be non-Gaussian due to the non-linear dynamics, i.e.,  $S_b = (n \cot n\theta_i) \delta \theta_i - (n^2/2) (\delta \theta_i)^2$  [42]. It can also be recast as  $S_b = S_{bg} + F_{nl,b} S_{bg}^2$ , where  $S_{bg} = (n \cot n\theta_i) \delta \theta_i$  denotes the Gaussian component of S, and  $F_{nl,b} = -(1/2) \tan^2 n\theta_i$  is the non-linearity parameter. The non-Gaussianity of  $S_b$  is directly related the the CP phase of  $\phi$ , and can be significant if  $|\tan n\theta_i| \gg 1$ .

Q-ball density perturbations.— Following baryogenesis, the AD field condensates generally form Q-balls, with almost all the baryon number being absorbed into these Q-balls [11, 56]. Therefore, the initial  $\mathcal{S}_b$  from AD baryogenesis are inherited by the resulting Q-ball density perturbations  $\mathcal{S} \simeq \delta_Q$ , where  $\delta_Q$  is the density contrast of Q-balls. Considering thin-wall Q-balls with the linear mass-charge relation [7], the total energy of Q-balls within a Hubble patch is approximately proportional to their baryon number. In this case,  $\mathcal{S}$  at a coarse-grained position follow the same statistics as the initial  $\mathcal{S}_b$ , i.e.,

$$S \simeq S_g + F_{\rm nl} S_g^2 ,$$
 (1)

with  $S_g \simeq S_{bg}$  and  $F_{nl} \simeq F_{nl,b}$ . The non-linear term in Eq. (1) could introduce the coupling between the large- and small-scale modes in Fourier space through the term  $F_{nl} S_{qL} S_{qS}$ . Here, the subscript "L" (or "S") repre-

sents large (or small) scales, and  $F_{\rm nl}$  reflects the coupling strength. It indicates that due to the non-Gaussianity, the spatial distribution of Q-balls at small scales can be modulated across large scales. Moreover, the statistics of  $\mathcal S$  also contains clues of CP-violating dynamics of  $\phi$  during AD baryogenesis.

The dimensionless power spectrum of  $S_g$  is defined as  $\langle S_{g,\mathbf{k}}S_{g,\mathbf{k}'}\rangle = \delta(\mathbf{k} + \mathbf{k}')(2\pi^2/k^3)\mathcal{P}_{S_g}(k)$ , where  $\langle ... \rangle$  represents ensemble average,  $\mathbf{k}$  is the Fourier mode of perturbations and  $k = |\mathbf{k}|$ . At Q-ball formation,  $\mathcal{P}_{S_g}$  can be modeled as

$$\mathcal{P}_{\mathcal{S}_g}(k) = \mathcal{A}_{L} + \mathcal{A}_{S} \left(\frac{k}{k_{\text{max}}}\right)^{n_S} \Theta(k_{\text{max}} - k) . \tag{2}$$

On large scales,  $\mathcal{P}_{\mathcal{S}_g}$  has a nearly scale-invariant amplitude  $\mathcal{A}_{\mathrm{L}} \simeq (n \cot n\theta_{\mathrm{i}})^2 \mathcal{P}_{\delta\theta_{\mathrm{i}}}$ , where  $\mathcal{P}_{\delta\theta_{\mathrm{i}}} \simeq [H_{\mathrm{i}}/(2\pi|\phi_{\mathrm{i}}|)]^2$  is given by fluctuations of the light field  $\theta$  during inflation, with  $|\phi_{\mathrm{i}}|$  and the Hubble scale  $H_{\mathrm{i}}$  being valued at the horizon exit. As isocurvature modes, the large-scale amplitude is constrained by the cosmic microwave background (CMB) observations as  $\mathcal{A}_{\mathrm{L}} \lesssim 10^{-11}$  [57]. On much smaller scales, the statistical characteristics of Q-balls give rise to a blue-tiled spectrum, where  $\mathcal{A}_{\mathrm{S}}$  is the spectral amplitude at a cutoff scale  $k_{\mathrm{max}}$ , and  $n_{\mathrm{S}}$  is the small-scale spectral index. For example, the statistically independent Q-ball formation at small scales gives  $n_{\mathrm{S}} = 3$ , while additional gravitational clustering effects can modify the index to  $2 \lesssim n_{\mathrm{S}} \lesssim 3$  [27, 58].

After formation, Q-balls can dominate the early Universe until they decay. We assume that the eMD era begins at  $\eta_{\rm m}$  and ends at  $\eta_{\rm d}$  with  $\eta$  the conformal time, and focus on the mode of  $\mathcal{S}$  reentering the horizon during this era, i.e.,  $k_{\rm d} \lesssim k \lesssim k_{\rm m}$ , where  $k_{\rm d}\eta_{\rm d} = k_{\rm m}\eta_{\rm m} = 1$ . These small-scale  $\mathcal{S}$  evolve into curvature perturbations  $\zeta \simeq \mathcal{S}/3$  and keep constant in the eMD era. Once Q-balls decay into SM particles, their density perturbations transform into relativistic sound waves and act as sources of GWs in the RD era, as will be discussed below.

Gravitational waves.— Due to the non-linear effect of gravity, the evolution of  $\zeta$  inside the horizon inevitably induces GWs at the second order [59–65]. Taking into account the leading source term, the GW strain is given by  $h \sim \eta^2 \zeta' \zeta'$ , where a prime denotes the derivation with respect to  $\eta$ . For the mode  $k \gg k_{\rm d}$ ,  $\zeta$  oscillates in the RD era at a frequency much larger than the cosmic expansion rate. Besides, since the eMD-to-RD transition is rapid, the amplitude of  $\zeta$  has no time to decay sufficiently during these oscillations. These two factors result in amplified GWs [30], i.e.,  $h \sim (k\eta_{\rm d})^2 \zeta^2 \gg \zeta^2$ , as a typical observable for Q-balls in AD baryogenesis [23–26].

The energy-density fraction spectrum of GWs at emission is given by  $\Omega_{\rm gw}(\mathbf{x}, \nu) = [\mathrm{d} \ln \rho_{\rm gw}(\mathbf{x})/\mathrm{d} \ln \nu]/\rho_c$ , where  $\nu = k/(2\pi)$  is the GW frequency,  $\rho_c$  is the critical energy density of the Universe, and  $\rho_{\rm gw}(\mathbf{x}) \sim \langle \partial h \partial h \rangle_{\mathbf{x}}$  is

the GW energy density at a coarse-grained spatial position  $\mathbf{x}$  at emission. The homogeneous and isotropic component of the GWB is described by the background level of  $\Omega_{\rm gw}(\mathbf{x},\nu)$ , namely,  $\bar{\Omega}_{\rm gw}(\nu) = \langle \Omega_{\rm gw}(\mathbf{x},\nu) \rangle$ . In our model,  $\bar{\Omega}_{\rm gw}$  is proportional to the four-point correlation of the small-scale non-Gaussian  $\mathcal{S}$  (or, equivalently,  $\zeta$ ), i.e.,  $\mathcal{S}_{\rm S} = \mathcal{S}_{g\rm S} + F_{\rm nl} \mathcal{S}_{g\rm S}^2$  [66–79], and is significantly amplified due to the rapid Q-ball decay, parameterized as

$$\bar{\Omega}_{\rm gw}(\nu_{\rm S}) = \mathcal{N}(\nu_{\rm S}) \langle \zeta_{\rm S}^4 \rangle \simeq (1/3)^4 \mathcal{N}(\nu_{\rm S}) \langle \mathcal{S}_{\rm S}^4 \rangle .$$
 (3)

Here,  $\mathcal{N}$  is an amplification factor, numerically given by  $\mathcal{N} \sim \text{few} \times 10^{-7} (\eta_{\rm d}/\eta_{\rm m})^7$  at  $\sim \nu_{\rm m}$  [30]. In FIG. 1, we plot the unscaled results of  $\bar{\Omega}_{\rm gw}^{(m)}$  (m=0,1,2), where  $\bar{\Omega}_{\rm gw}^{(m)}$  denotes the  $\mathcal{O}(\mathcal{A}_{\rm S}^{m+2}F_{\rm nl}^{2m})$  components of  $\bar{\Omega}_{\rm gw}$ . We also plot the present-day energy-density fraction spectrum  $\bar{\Omega}_{\rm gw,0}(\nu_{\rm S}) \simeq \Omega_{\rm rad,0} \bar{\Omega}_{\rm gw}(\nu_{\rm S})$ , where  $\Omega_{\rm rad,0} = 4.2 \times 10^{-5}/h_0^2$  is the current energy-density fraction of radiation, with  $h_0 = 0.674$  the dimensionless Hubble constant [80]. The spectrum typically exhibits a sharp peak at  $\sim \nu_{\rm m}$  and can be detected by future GW detectors. Besides, primordial curvature perturbations, with a nearly scale-invarant spectral amplitude  $\sim 10^{-9}$  [80], could also be the source of GWs, but their contribution should be subdominated at  $\sim \nu_{\rm m}$  for  $\mathcal{A}_{\rm S} \gg 10^{-9}$ .

Anisotropies in the gravitational wave background.—Let us now focus on the GW anisotropies in our model, which arise from the large-scale inhomogeneities in the GWB, i.e.,  $\delta\Omega_{\rm gw}(\mathbf{x},\nu)=\Omega_{\rm gw}(\mathbf{x},\nu)-\bar{\Omega}_{\rm gw}(\nu)$ . In contrast, we should note that  $\delta\Omega_{\rm gw}$  on subhorizon scales make no contribution to observed anisotropies. Since the horizon at GW emission is extremely small compared to the angular resolution of detectors, the GW signal along the line of sight is actually an average over a large number of such horizons. Therefore, the small-scale  $\delta\Omega_{\rm gw}$  would vanish after being averaged.

In AD baryogenesis, the large-scale  $\delta\Omega_{\rm gw}$  result from the large-scale Q-ball density perturbations. As aforementioned, the non-Gaussianity of  $\mathcal{S}$  couples large- and small-scale modes, the latter of which are sources of enhanced GWs. Due to the presence of  $\mathcal{S}_{\rm gL}$ , the GW energy density  $\sim \langle \mathcal{S}_{\rm S}^4 \rangle_{\mathbf{x}}$  would be redistributed on large scales [76, 77, 81–88]. The resulting large-scale  $\delta\Omega_{\rm gw}$  is proportional to  $\mathcal{S}_{\rm gL}$  at the leading order, and can be heuristically expressed as

$$\delta\Omega_{\rm gw}(\mathbf{x}, \nu_{\rm S}) \simeq (1/3)^4 \mathcal{N}(\nu_{\rm S}) F_{\rm nl} \mathcal{S}_{aL} \langle \mathcal{S}_{aS} \mathcal{S}_{\rm S}^3 \rangle_{\mathbf{x}} ,$$
 (4)

where one  $S_{\rm S}$  in the four-point correlation is replaced by the non-linear term  $F_{\rm nl} S_{g\rm L} S_{g\rm S}$ , compared to Eq. (3). Here, the effects of higher order of  $S_{g\rm L}$  is negligible since  $S_{g\rm L} \ll 1$ . Though  $S_{g\rm S}$  remains uncorrelated for two distant spatial positions,  $S_{g\rm L}$  acts as a bridge to correlate large-scale  $\delta\Omega_{\rm gw}$ , leading to  $\langle\delta\Omega_{\rm gw}^2\rangle\propto\langle S_{g\rm L}^2\rangle\sim A_{\rm L}$ .

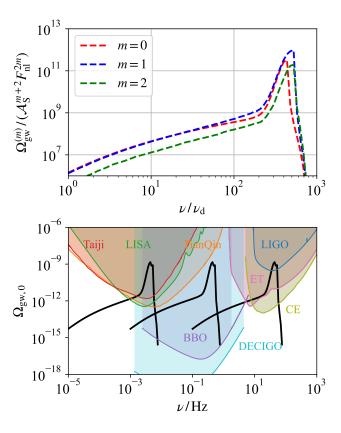


FIG. 1. Upper panel: Unscaled components of energy-density fraction spectrum  $\Omega_{\rm gw}^{(m)}/(\mathcal{A}_{\rm S}^{m+2}F_{\rm nl}^{2m})$  versus the GW frequency  $\nu/\nu_{\rm d}$ . Lower panel: Present-day energy-density fraction spectra  $\bar{\Omega}_{\rm gw,0}(\nu)$  with  $\nu_{\rm d}/{\rm Hz}=10^{-5},10^{-3},$  and  $10^{-1}$  from left to right. Other parameters are set as  $\mathcal{A}_{\rm S}=5\times10^{-8}$  and  $F_{\rm nl}=-2500.$  We compare the spectra to the sensitivities of LISA (green), Taiji (red), TianQin (orange), BBO (purple), DECIGO (cyan), LIGO (blue), ET (pink), and CE (yellow). In both panels, we assume an instantaneous eMD-to-RD transition and set  $\eta_{\rm d}/\eta_{\rm m}=400,\ k_{\rm max}=k_{\rm m},$  and  $n_{\rm S}=3.$ 

Similar to the CMB, the anisotropies in the GWB are characterized by the reduced angular power spectrum  $\widetilde{C}_{\ell}$ , which is given by the following two-point correlation

$$\ell(\ell+1)\,\widetilde{C}_{\ell}(\nu) = \frac{\pi}{2} \left\langle \frac{\delta\Omega_{\rm gw}(\mathbf{x},\nu)}{\bar{\Omega}_{\rm gw}(\nu)} \, \frac{\delta\Omega_{\rm gw}(\mathbf{x}',\nu)}{\bar{\Omega}_{\rm gw}(\nu)} \right\rangle \,, \quad (5)$$

where  $\ell$  is the multipole corresponding to the angular subtended by two distant positions  $\mathbf{x}$  and  $\mathbf{x}'$ . Here we omit propagation effects after GW emission [84, 89–91]. For large anisotropies of our interest,  $\widetilde{C}_{\ell}$  should be mainly determined by large inhomogeneities at GW emission, and propagation effects are negligible in this case.

Based on Eqs. (3-5), the reduced angular power spectrum of the GWB from AD baryogenesis is obtained as

$$\ell(\ell+1)\,\widetilde{C}_{\ell}(\nu_{\rm S}) \simeq 128\,\pi\mathcal{A}_{\rm L}\,F_{\rm nl}^2\,\epsilon^2\,,$$
 (6)

where  $\epsilon = [\bar{\Omega}_{\rm gw}^{(0)} + \bar{\Omega}_{\rm gw}^{(1)}/2]/\bar{\Omega}_{\rm gw}$  [76, 77], measuring the fraction of the GW energy density modulated by  $\mathcal{S}_{qL}$  to

the total. In FIG. 2, we plot  $\ell(\ell+1)$   $\widetilde{C}_{\ell}$  in the parameter space of  $\{\mathcal{A}_{\rm S}, |F_{\rm nl}|\}$ , and limit our calculation in perturbative regimes (i.e.,  $\mathcal{A}_{\rm S}F_{\rm nl}^2\ll 1$ ) to guarantee its validity. Since  $\epsilon\sim 1$  is insensitive to  $\mathcal{A}_{\rm S}$  and  $F_{\rm nl}$ , the result of  $\widetilde{C}_{\ell}$  is almost determined by  $F_{\rm nl}$ , i.e.,  $\widetilde{C}_{\ell}\propto F_{\rm nl}^2$ . Therefore, these anisotropies provide a universal probe to the non-Gaussianity, regardless of details in small-scale  $\mathcal{P}_{\mathcal{S}_{g}}$ .

To compare with angular sensitivities of GW detectors, we define the angular power spectrum of the GWB as  $C_{\ell} = [\bar{\Omega}_{\mathrm{gw},0}/4\pi]^2 \tilde{C}_{\ell}$ . Specially, we show in the upper panel of FIG. 2 the region in the parameter space  $\{\mathcal{A}_{\mathrm{S}}, |F_{\mathrm{nl}}|\}$  leading to observable anisotropies for LISA, say,  $\ell(\ell+1) C_{\ell} \gtrsim 10^{-23}$ . For larger  $\mathcal{N}$  (i.e., larger  $\eta_{\mathrm{d}}/\eta_{\mathrm{m}}$ ), the region of smaller  $\mathcal{A}_{\mathrm{S}}$  can be covered by detectors.

AD baryogenesis can generate large anisotropies in the GWB, which are also observable for future GW detectors. In this mechanism, Q-balls serve as highly non-Gaussian sources of GWs and induce the rapid eMD-to-RD transition, leading to large  $|F_{\rm nl}|$  and large  $\mathcal N$  meanwhile. As discussed above, these two factors are both important for the observation of large anisotropies. As a specific realization, we choose the related parameters as  $\eta_{\rm d}/\eta_{\rm m}=400,~\mathcal A_{\rm L}=10^{-11},~\mathcal A_{\rm S}=5\times10^{-8},$  and  $F_{\rm nl}=-2500,$  which do not violate the perturbative condition or observational constraints from the CMB. Under these choices, the reduced angular power spectrum at  $\sim \nu_{\rm m}$  is estimated as

$$\ell(\ell+1) \, \widetilde{C}_{\ell}(\nu_{\rm m}) \simeq 0.016 \; .$$
 (7)

In the lower panel of FIG. 2, we plot the corresponding angular power spectrum  $\ell(\ell+1)\,C_\ell(\nu_{\rm m})\simeq 8\times 10^{-23}$ , and compare it to the optimal sensitivities of several GW detectors. These anisotropies can be observed at low multipoles by LISA and ET-CE network, and at up to much larger multipoles by BBO and DECIGO.

The anisotropies in the GWB reveal the CP-violating dynamics in AD baryogenesis. In Eq. (6), given  $A_{\rm L} \propto$  $\cot^2 n\theta_i$ ,  $F_{\rm nl} \propto \tan^2 n\theta_i$ , and  $\epsilon \sim 1$ , the reduced angular power spectrum exhibits a basic relation to the CP phase of  $\phi$ , i.e.,  $\ell(\ell+1) \widetilde{C}_{\ell} \propto \tan^2 n\theta_i$ . The measurement of the GW anisotropies, along with the baryonic isocurvature perturbations on CMB scales, provides two independent probes to the parameter space of  $\{\theta_i, H_i/|\phi_i|\}$ . For instance, the results  $\ell(\ell+1) \tilde{C}_{\ell} \simeq 0.016$  and  $\mathcal{A}_{\rm L} \simeq 10^{-11}$ given in the last paragraph indicate  $\tan n\theta_{\rm i} \simeq 70.7$  and  $|\phi_i| \simeq 4.3 \times 10^3 H_i$  for n = 6 in our model. This CPviolation also closely relates the observed baryon asymmetry through  $n_b \propto \sin n\theta_i$ . The large anisotropies imply sizable CP violation, which is crucial for successful baryogenesis. We expect that future GW observations could detect these essential parameters for AD baryogenesis, and provide profound implications for the origin of baryon asymmetry.

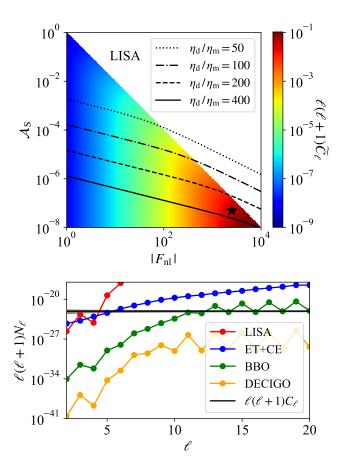


FIG. 2. Upper panel: Reduced angular power spectrum  $\ell(\ell+1) \widetilde{C}_{\ell}(\nu_{\rm m})$  in the parameter space of  $\{\mathcal{A}_{\rm S}, |F_{\rm nl}|\}$  with  $\mathcal{A}_{\rm L}=10^{-11}$ . Black lines are given by  $\ell(\ell+1)\,C_{\ell}=10^{-23}$  for  $\eta_{\rm d}/\eta_{\rm m}=50$  (dotted), 100 (dashdot), 200 (dashed), and 400 (solid). The regions above these lines are anticipated to be detectable by LISA. Lower panel: Angular power spectrum  $\ell(\ell+1)\,C_{\ell}(\nu_{\rm m})$  with  $\eta_{\rm d}/\eta_{\rm m}=400$ ,  $\mathcal{A}_{\rm L}=10^{-11}$ ,  $\mathcal{A}_{\rm S}=5\times10^{-8}$ , and  $F_{\rm nl}=-2500$  (the latter two are marked as a star in the upper panel). Shaded black region represents the uncertainties at 68% confidence level due to the cosmic variance. We compare  $\ell(\ell+1)\,C_{\ell}(\nu_{\rm m})$  to the noise angular power spectra  $\ell(\ell+1)\,N_{\ell}$  of LISA, ET-CE network, BBO, and DECIGO, assuming that  $\nu_{\rm m}$  aligns with the optimal sensitivity frequency of each detector. These noise angular power spectra are plotted in Fig. 7 in Ref. [92].

Conclusion and discussion.—In this work, we studied the anisotropies in the GWB related to AD baryogenesis as a novel observable for this high-energy mechanism. The non-Gaussianity in baryonic isocurvature perturbations from AD baryogenesis couples large- and small-scale Q-ball density perturbations, thus leading to large-scale anisotropies in the GWB sourced by Q-balls. Resulting from large  $|F_{\rm nl}|$  and large  $\mathcal N$  in this mechanism, the anisotropies in the GWB can be significant with  $\ell(\ell+1)$   $\widetilde C_\ell \sim \mathcal O(10^{-2})$ , and are potential to detected by future GW experiments like LISA. These anisotropies

serve as a powerful probe to detect AD baryogenesis and the CP-violating dynamics of AD field, with valuable physical insights into the problem of baryon asymmetry.

Compared with other sources, these GW anisotropies provide distinctive signals for AD baryogenesis. (a) Multipole dependence: The angular power spectrum scales as  $C_{\ell} \sim \ell^{-2}$  in our model, contrasting with the  $C_{\ell} \sim$  $\ell^{-1}$  scaling for astrophysical sources (see Ref. [81] for a review). (b) Cross-correlation with the CMB: These anisotropies showcase minimal cross-correlation with the CMB due to the isocurvature nature of the GW sources, distinguishing them from anisotropies produced by adiabatic sources [29]. (c) Large anisotropies: The observation of the anisotropies  $\ell(\ell+1) \widetilde{C}_{\ell} \sim 10^{-2}$  requires not only highly non-Gaussian sources but also a rapid eMDto-RD transition (for comparison, see the results from scenarios without such transition in Refs. [76, 77, 83–87]). These features narrow down the GW origins to limited scenarios, particularly Q-balls in AD baryogenesis, offering crucial clues to validate this mechanism.

We demonstrated that large anisotropies can be generated in AD baryogenesis even in the linear regime. If the eMD era lasts sufficiently long,  $\delta_{\rm Q}$  would exceed the unit and lead to more violent GW production, suggested by numerical studies [25, 93–96]. The study of the GW anisotropies beyond the linear regime may provide insights into AD baryogenesis in more general cases, and we leave it for future investigation.

Recent studies indicate that some details in Q-ball models (e.g., the speed of decay [30, 97–100] and the mass distribution [31, 99]) can significantly affect  $\bar{\Omega}_{\rm gw}$ . In contrast, we emphasize that  $\tilde{C}_\ell$  is insensitive to these details since they meanwhile affect the numerator and denominator of  $\epsilon$  in Eq. (6). This insensitivity can be understood as  $\tilde{C}_\ell$  only cares about the physics related to large scales, which usually originates from the initial conditions of  $\phi$  during inflation. Therefore, the relation between the CP violation in AD baryogenesis and the GW anisotropies remains robust.

Our work established a framework to probe the CP violation through GW anisotropies. Future works could include more scenarios, e.g., Q-balls with non-linear mass-charge relation [5, 11, 101], the presence of anti-Q-balls [102], or Q-ball modulated reheating [103], etc. These effects may generate additional perturbations and non-Gaussianity, making the comprehensive analysis of S more complicated. However, for the calculation of GW anisotropies, we only need to modify the specific expression of  $F_{\rm nl}$ , without altering the framework of this paper. Besides, this work can be extended to other baryogenesis mechanisms with non-Gaussian baryonic perturbations and Q-balls, e.g., spontaneous baryogenesis [104–106].

In light of the recent observation of the CP violation

in baryon decays at the LHCb [107], we are entering a new era for searching additional CP violation sources beyond the SM and determining the nature of baryon asymmetry. In the future, GW anisotropies are expected to detect the CP violation at energy scales far beyond the reach of traditional particle physics experiments, opening a new road to address these essential problems.

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