Tests of Gravitational-Wave Birefringence with the Gravitational-Wave Catalog

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The routine detection of gravitational-wave events from compact binary coalescence has allowed precise tests of gravity in strong field, dynamical field, and high energy regime. To date, a total of 57 gravitational-wave events have been reported by the third Open Gravitational-wave Catalog (3-OGC). In this work, we report the results of testing gravitational-wave birefringence using the events from 3-OGC. Birefringence, an effect where the left- and right-handed polarizations of gravitational waves follow different equations of motion, occurs when the parity symmetry of gravity is broken. This arises naturally in the effective field theory extension of general relativity. Using Bayesian inference with state-of-the-art waveform modeling, we use all events in 3-OGC to constrain the lower limit of energy scale at which parity violation effects emerge. Overall we do not find evidence for a violation of general relativity, and thus we constrain the parity-violating energy scale to $M_{\rm PV} > 0.14$ GeV at 90% confidence level, which is an improvement over previous results by one order of magnitude. Intriguingly, we find an outlier, GW190521, that supports the existence of birefringence over general relativity with a higher match-filtering signal-to-noise ratio and a natural log Bayes factor of 7.84. Because the inferred $M_{\rm PV}$ from GW190521 is in tension with the combined constraints, we hypothesize that this may be caused by the limitations of the existing waveform approximants, such as systematic errors during merger phase of the waveform, or by the existence of physical effects such as eccentricity which are not taken into account by the current waveform approximants.

I. INTRODUCTION

The advanced LIGO-Virgo [1, 2] detector network has completed three observation runs (O1-O3) and announced the detection of 50 significant gravitational wave (GW) events [3, 4] plus more subthreshold events [5]. These events are from the coalescence of binary black holes, binary neutron stars, or neutron star black hole systems, and are all included in the Gravitational-Wave Transient Catalog (GWTC)-1/2/2.1. Additional compact binary coalescence events were reported by independent analysis [6–8] of the publicly available data [9]. For instance, the third Open Gravitational-wave Catalog (3-OGC) used the PyCBC toolkit [10] to analyze the most recent LIGO-Virgo data release and detected 57 events [8] which are largely consistent with the GWTC. In this work, we focus on the events reported by 3-OGC.

The detection of gravitational waves has enabled numerous precise tests of general relativity (GR) in the strong field, dynamical field [11–13], and high energy (sub-GeV) regimes [14]. All the tests to date have confirmed that GW data is consistent with the predictions of general relativity.

In this paper, we test GW birefringence, extending our previous work [14] by including the recently published 3-OGC results. Birefringence of GWs emerges when the parity symmetry, which is the invariance of physical laws with regard to the inversion of spacial coordinates, is broken between the left- and right-handed GW polarizations. In general relativity, the parity symmetry is conserved. Nevertheless, parity-violating theories of gravity such as Chern–Simons gravity [15], Hořava–Lifshitz gravity [16, 17], and ghost-free scalar-tensor gravity [18] have been proposed to account for the existence of dark matter and dark energy. Furthermore, parity violation arises at high energy scales in quantum gravity theories such as loop quantum gravity and string theory [15].

We utilize a Lorentz-invariant effective field theory (EFT) extension of the linearized Einstein-Hilbert action to study possible deviations from general relativity in GWs. EFT is a flexible framework that includes all action terms that purposely preserve or violate certain symmetries. The leading order higher derivative modification of the linearized action comes from terms that violate parity. Parity violation leads to an asymmetry of the propagation speed and amplitude damping between left- and right-hand polarizations of a GW, which leads to the phase and amplitude birefringence, respectively. Compared to velocity birefringence, the effect from amplitude birefringence is negligibly small [14, 19]; therefore, we do not consider it in this analysis. Given the relation between parity violation and Lorentz violation [20], our tests also have implications for constraining standard

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model extension (SME) of gravity [21, 22], which is the most general EFT extension of linearized GR that violates Lorentz symmetry.

Tests of GW birefringence were first done in ref. [23], where they checked for waveform peak splitting in the first ever detected GW event, GW150914. Ref. [24] constrained birefringence using the GW propagation speed measured from the binary neutron star merger event GW170817 [25]. Further constraints on birefringence using GWTC-1/2 events were given in refs.[26–31]. Ref. [14] performed Bayesian parameter estimation on the advanced LIGO-Virgo O1 and O2 events with a waveform that explicitly included parity violation and constrained the parity violating energy scale in EFT. In this paper we improve on ref. [14] by including more GW events (from twelve events in O1/O2 to fifty-seven events in 3-OGC) and using the state-of-the-art waveform approximant IMRPhenomXPHM [32], which includes higher order harmonic modes and spin precession effects for quasi-circular binary black hole coalescences. The events previously analyzed in ref. [14] are reanalyzed with this more updated waveform. For binary neutron stars, the IMRPhenomD_NRTidal waveform [33], which includes tidal effects, is used.

Over all, we do not find evidence for GW birefringence and thereby place constraints on the cutoff energy scale $M_{\rm PV} > 0.14$ GeV, which is more stringent than ref. [14] by one order of magnitude. The result can be mapped to the SME coefficient $\left|\bar{\varsigma}^{(5)}\right| < 3.5 \times 10^{-16}$ m, which describes isotropic birefringence with mass dimension $d = 5$. Intriguingly, we find an outlier; the high-mass event GW190521 [34, 35] supports the birefringence waveform over the GR one with a natural log Bayes factor of 7.84. From this event, the inferred EFT energy scale at which parity symmetry violation becomes relevant is $M_{\rm PV} = 0.005$ GeV, which is in tension with the combined constraints from the rest of the 3-OGC events. The nonzero birefringence results may be caused by systematic errors in the existing waveform templates for binary black hole mergers or by physical effects not taken into account by the standard assumptions for quasi-circular binary black hole mergers i.e. the presence of orbital eccentricity [36, 37], hyperbolic encounter [38] or entirely new physics [39]. In addition to possible waveform systematics, we also examine the background noise quality around GW190521 and do not find evidence of significant deviations from the assumption that the noise is stationary and Gaussian.

In the following we first overview the construction of waveform templates for GW birefringence II and the Bayesian analysis framework III. Then we report the results of tests for all 3-OGC events IV, and discuss possible origins for the result of GW190521 IV A. We finish with concluding remarks and discussion V.

II. WAVEFORM TEMPLATES FOR GW BIREFRINGENCE

In this section, we briefly overview the construction of the waveform templates used to test GW birefringence, following the method developed in [19]. In Lorentz invariant EFT, the leading order modifications to the linearized Einstein-Hilbert action are terms with three derivatives: $\epsilon^{ijk}\dot{h}_{il}\partial_j\dot{h}_{kl}$ and $\epsilon^{ijk}\partial^2 h_{il}\partial_j h_{kl}$. Here $i, j ... = 1, 2, 3$ refer to spacial coordinates, ∂_j denotes spacial derivatives, dot denotes derivatives with respect to time, ∂^2 is the Laplacian, ϵ^{ijk} is the antisymmetric symbol, and h_{ij} is the tensor perturbation of metric. As terms that break rotation/boost symmetry lead to a great many complications, we do not consider them here, see e.g. refs. [23, 40] for the effects of these terms. Combining the higher derivative terms above with the linearized Einstein-Hilbert action gives

$$S = \frac{1}{16\pi G}\int dt d^3x a^3 \Bigg[\frac{1}{4}\dot{h}_{ij}^2 - \frac{1}{4a^2}(\partial_k h_{ij})^2 + \frac{1}{4}\left(\frac{c_1}{aM_{\rm PV}}\epsilon^{ijk}\dot{h}_{il}\partial_j\dot{h}_{kl} + \frac{c_2}{a^3 M_{\rm PV}}\epsilon^{ijk}\partial^2 h_{il}\partial_j h_{kl}\right)\Bigg], \tag{1}$$

where a is the cosmic scale factor, $M_{\rm PV}$ is the energy scale for EFT that the higher order modification starts to be relevant, c_1 and c_2 are two undetermined functions of cosmic time that can only be fixed given a specific modified gravity theory; the speed of light and reduced Planck's constant are set to $c = \hbar = 1$. Notably, both of the added terms violate parity. Thus, from the viewpoint of Lorentz invariant EFT, the leading order modification to GW propagation arises from parity-violation. Eq (1) is a generic form of the action and can be mapped to specific theories beyond general relativity, for a detailed mapping see ref. [19].

The equation of motion for the GW circular polarization modes h_A, where $A = R$ or $A = L$ for the right- and left-hand modes, can be derived from the action in Eq. (1) as

$$h_A'' + (2 + \nu_A)\mathcal{H}h_A' + (1 + \mu_A)k^2 h_A = 0 \ , \tag{2}$$

where $\mathcal{H}$ is the conformal Hubble parameter, k is the wavenumber, and a prime denotes the derivative with respect to the conformal cosmic time. The exact forms for μ_A and ν_A are

$$\begin{aligned} \nu_A &= [\rho_A \alpha_\nu(\tau)(k/aM_{\rm PV})]'/\mathcal{H}, \\ \mu_A &= \rho_A \alpha_\mu(\tau)(k/a\ M_{\rm PV}), \end{aligned} \tag{3}$$

where τ is the cosmic conformal time, $\alpha_\nu \equiv -c_1$ and $\alpha_\mu \equiv c_1 - c_2$ are two arbitrary functions of cosmic time that are free in general EFT but can be fixed by the choice of a specific theory of modified gravity. The fact that $\rho_R = 1$ and $\rho_L = -1$ represents broken parity and leads to an asymmetry between the left- and right-hand circular polarization modes of GWs during propagation.

In particular, ν_A and μ_A contribute to amplitude and phase birefringence, respectively. We ignore the contribution of ν_A because the modification to GW strain from amplitude birefringence is negligibly small compared to μ_A. Note that by setting $\mu_A = \nu_A = 0$ in Eq. (2) one retrieves the GR solution.

An explicit parity-violating GW waveform can be derived by solving Eq. (2). The right- and left-handed circular polarization modes are then transformed into the plus (h_+) and cross ($h_\times$) modes, which are typically used in GW data analysis. The parity-violating waveform in frequency domain is

$$\begin{aligned} h_+^{\rm PV}(f) &= h_+^{\rm GR}(f) + h_\times^{\rm GR}(f)\delta\Psi, \\ h_\times^{\rm PV}(f) &= h_\times^{\rm GR}(f) - h_+^{\rm GR}(f)\delta\Psi. \end{aligned} \tag{4}$$

The phase modification to the GR-based waveform $h^{\rm GR}(f)$ takes the following form

$$\delta\Psi(f) = \frac{(\pi f)^2}{M_{\rm PV}} \int_0^z \frac{\alpha_\mu(z')(1+z')dz'}{H_0\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}, \tag{5}$$

where H_0 is the Hubble constant, z is the cosmic redshift, the frequency term f^2 corresponds to a modification at 5.5 post-Newtonian order. We adopt a ΛCDM Cosmology with parameters $\Omega_M = 0.3075$, $\Omega_\Lambda = 0.691$, $H_0 = 67.8$ km s^{-1} Mpc^{-1} following ref. [41]. We make the simplifying assumption that $\alpha_\mu(z) \equiv c_1 - c_2$ is a constant of unity by attributing its order of magnitude to $M_{\rm PV}$ as most GW sources detected by the current LIGO-Virgo detectors are from local Universe (but see an exception from GW190521 reported in this work). Note that the sign of α_μ remains uncertain, we thus choose $\alpha_\mu = 1$ and -1, respectively, for the template; nevertheless both choices give similar results for constraining $M_{\rm PV}$. Also note that there is a special case that we do not consider in this work: $\alpha_\mu = 0$ (thus $c_1 = c_2$) which is the case for dynamical Chern-Simons gravity [42–44]. Constraints on the dynamical Chern-Simons theory and amplitude birefringence using GWTC can be found in Refs. [26, 30].

III. BAYESIAN INFERENCE

We use Bayesian parameter estimation and model selection to test gravitational parity violation with the 3-OGC events. Consider GW time series data $d(t)$ which is a sum of the detector noise $n(t)$ and a GW signal $h(t,\vec{\theta})$ with characterizing parameters $\vec{\theta}$, then Bayes theorem states that

$$P(\vec{\theta}|d,H) = \frac{P(d|\vec{\theta},H)P(\vec{\theta}|H)}{P(d|H)}, \tag{6}$$

where $P(\vec{\theta}|d,H)$ is the posterior probability distribution for parameters $\vec{\theta}$, $P(\vec{\theta}|H)$ is the prior distribution and contains any a priori information about the parameter distribution, $P(d|\vec{\theta},H)$ is the likelihood for obtaining the data given model parameters, $P(d|H,I)$ is a normalization factor called evidence. H is the underlying hypothesis modeling the data. In the context of this work we consider two competing hypotheses, H_1: $h(t,\vec{\theta})$ is described by Eq. (4) with birefringence and H_2: the GW waveform $h(t,\vec{\theta})$ is described by GR. The Bayes factor of the evidences of two hypotheses is

$$\mathcal{B}_2^1 = \frac{P(d|H_1)}{P(d|H_2)}, \tag{7}$$

which quantitatively measures the degree that data favor one hypothesis over another.

For GR waveform modeling, we use the state-of-the-art approximant IMRPhenomXPHM [32] which includes the subdominant harmonic modes of GW and accounts for spin-precession effects for a quasi-circular-orbit binary black hole coalescence. For the binary neutron star events, we use IMRPhenomD_NRTidal, a spin-aligned waveform template that takes the tidal deformability into account [33, 45–47]. The same GR waveform approximants were used in analyzing the events in 3-OGC [8]. We generate a parity-violating waveform with birefringence by applying Eq. (4) to the GR waveform used.

Using PyCBC inference [48], we perform parameter estimation over all GW intrinsic (mass $m_{1,2}$, spin $\vec{s}_{1,2}$, and, in the case of neutron stars, tidal deformability $\Lambda_{1,2}$) and extrinsic parameters (luminosity distance d_L, inclination angle ι, polarization angle Ψ, right ascension α, declination δ, coalescence time t_c and phase ϕ_c) as well as for the parity violation parameter $M_{\rm PV}^{-1}$. The priors for the standard GW intrinsic and extrinsic parameters as well as the sampler settings are broadly consistent with those used in the 3-OGC analysis [8]. The prior for $M_{\rm PV}^{-1}$ is chosen to be uniformly distributed. Assuming $M_{\rm PV}^{-1}$ is a universal quantity for all events (excluding GW190521), the $M_{\rm PV}^{-1}$ posteriors can be combined to obtain an overall constraint,

$$p(M_{\rm PV}^{-1}|\{d_i\},H) \propto \prod_{i=1}^{N} p(M_{\rm PV}^{-1}|d_i,H), \tag{8}$$

where d_i denotes data of the i-th GW event.

IV. RESULTS

In fifty-six out of fifty-seven events, we find that the zero value of $M_{\rm PV}^{-1}$ is within the range of $\mu \pm 2.3\sigma$, where μ and σ are the median and the standard variance of posterior distribution, respectively. Among these events, the value of $M_{\rm PV}^{-1}$ that deviates from zero the most comes from GW190814 with 2.3σ. Similar nonzero results of testing GR parameters were seen in ref. [11]. Given the Bayes factor of GW190814 supports the GR templates, we conclude we do not find significant evidence of violation of GR, thus place a lower limit of 0.14 GeV (90%

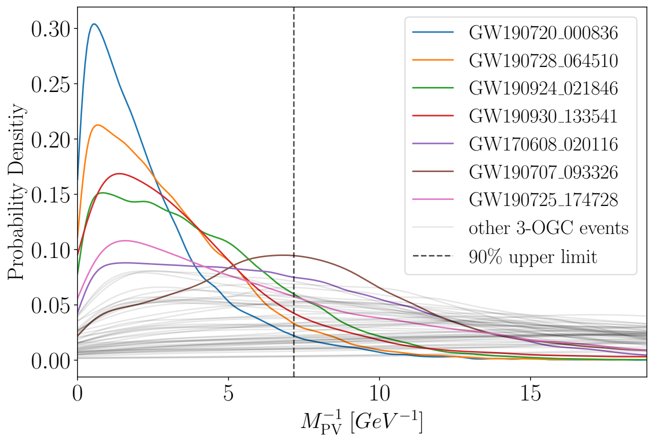

FIG. 1. The posterior distributions for $M_{\rm PV}^{-1}$ for all 3-OGC events except GW190521. The vertical dash line denotes the 90% upper limits for $M_{\rm PV}^{-1}$ from combined results.

confidence level) on the energy scale of GR violations arising from birefringence.

The $M_{\rm PV}^{-1}$ posteriors for these events are shown in Figure 1. The tightest constraint is from GW190720_000836, a $12.9M_\odot - 7.7M_\odot$ binary black hole merger event at a distance $\sim 10^3$ Mpc [8]. This is unsurprising because, as can be seen from Eq. (5), the birefringence modification to GW waveform is more significant in the higher frequency band and at larger distances. As expected, the most stringent constraints all come from events with component mass $\sim 10M_\odot$.

The overall constraint is obtained by multiplying the posterior distributions of all these events together. We find the 90% upper limit of $M_{\rm PV}^{-1}$ to be $7.2{\rm GeV}^{-1}$, which corresponds to $M_{\rm PV} > 0.14$ GeV. This result is more stringent by one order of magnitude than that from O1 and O2, where ref. [14] obtained lower energy cutoff 0.01 GeV (note that ref. [14] used $h = 1$ not $\hbar = 1$ and we have converted their results for proper comparison with this work). This improvement is due to an increased number of events and the use of higher harmonic mode GW waveforms [32] with longer duration.

The limit on $M_{\rm PV}$ can be straightforwardly mapped to bounds on the SME coefficients that describe isotropic birefringence of GWs at mass dimension $d = 5$, via $\left|\vec{\varsigma}^{(5)}\right| \sim \frac{1}{4}M_{\rm PV}^{-1}$ [23, 49]. For $M_{\rm PV} > 0.14\,{\rm GeV}$, one gets $\left|\vec{\varsigma}^{(5)}\right| < 3.5 \times 10^{-16}\,{\rm m}$. This is slightly tighter than but comparable to limits from the anisotropic birefringence of GWs [27, 31]. These results are within expectation because here we combine a catalog of GW events to constrain one particular parity-violating parameter, namely, the $M_{\rm PV}$. The work on anisotropic birefringence, on the other hand, simultaneously bound multiple CPT/Lorentz-violating coefficients [40]. Additionally, the methodology used in this work is statistically more advanced than the simple approach adopted in refs. [23, 27, 31].

A. GW190521

We find a clear non-zero result for the birefringence parameter ($M_{\rm PV}^{-1} = 198^{+100}_{-62}$ ${\rm GeV}^{-1}$) for the event GW190521. This corresponds to the EFT lower energy cutoff $M_{\rm PV} = 0.005^{+0.002}_{-0.002}$ GeV at 90% confidence level. The posterior on $M_{\rm PV}^{-1}$ as well as the posteriors for the source frame chirp mass $\mathcal{M}^{src}$, mass ratio q, and luminosity distance d_L (which all differ from the GR posteriors published in 3-OGC) can be seen in Fig. 2.

For comparison, we reanalyze GW190521 with the GR templates using IMRPhenomXPHM approximant and the same priors as the birefringence case for all GR parameters. The natural log Bayes factor is determined to be $\ln \mathcal{B}_{\rm GR}^{\rm PV} = 7.84$ in favor of the parity-violating case. For $\ln \mathcal{B} \geq 4.6$ (Bayes factor ≥ 100) the hypothesis H_1 is decisively favored over H_2 by the data [50]. Furthermore, the match-filtered signal-to-noise ratio (SNR) is higher for the birefringence waveform, with SNRs of 15.47 and 15.29 for parity-violating and GR waveforms, respectively. Therefore we find strong evidence with Bayesian analysis that the GW190521 data favor parity-violation hypothesis over that of GR.

As mentioned above, we find that the posteriors on mass and distance differ from their GR values. In the parity-violation case, the chirp mass and mass ratio, and thus the component masses, are found to be lower than the GR values. The luminosity distance is significantly higher than that inferred assuming GR, with median value 18 Gpc corresponding to redshift 2.20. It is possible that this larger distance may violate our simplifying assumption that $a_\mu(z)$ is a constant. In the $\mathcal{M}^{src}-q$ subplot of Fig. 2, the maximum likelihood sample inferred with GR templates are marked for comparison.

In Fig. 3, we plot the GW strain around GW190521 whitened by noise amplitude spectral density, together with the best fit whitened waveform templates from both GR and birefringence, for a visual inspection.

To further investigate possible waveform systematics, we perform another birefringence analysis on GW190521 with the same priors but a different frequency domain waveform approximant, IMRPhenomPv3HM [51], which also includes higher harmonic modes and spin-precession effects. The results are consistent with those from IMRPhenomXPHM and thus confirm the robustness of nonzero parity-violation parameter. We also check the data quality around GW190521 by examining the background noise power spectral density (PSD) variation as defined in ref. [52]. The PSD variation in a one hour time window centered at GW190521 shows no significant deviation from other ordinary times. For the GW190521 trigger, the PSD variation is 1.07 for LIGO Hanford and 0.95 for LIGO Livingston, also indicating no abnormal fluctuations for background. We thus conclude the background noise is consistent with the Gaussian and stationary assumption.

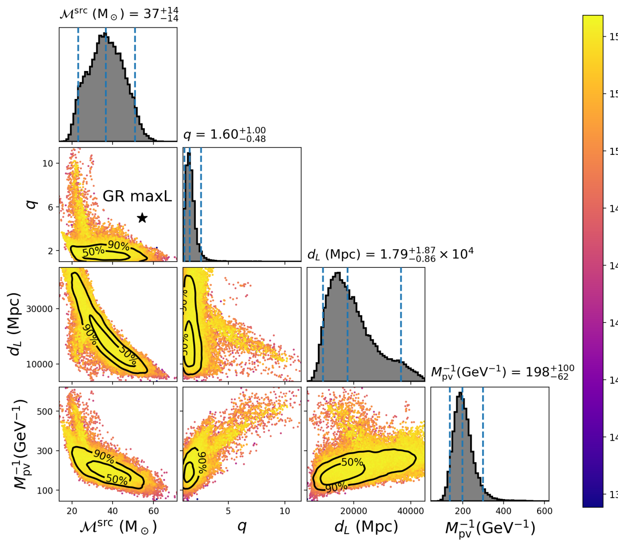

FIG. 2. The posterior distributions for chirp mass $\mathcal{M}^{src}$, mass ratio q, luminosity distance d_L, and inverse cutoff energy $M_{\rm PV}^{-1}$ for GW190521 and the birefringence waveform. The median values and 90% credible interval are both reported and denoted with dotted vertical lines. The vertical color bar shows the SNR of the scatter plot. A nonzero value of $M_{\rm PV}$ is clearly indicated. In the $\mathcal{M}^{src}-q$ subplot, the sample with maximum likelihood from the GR analysis is shown for comparison.

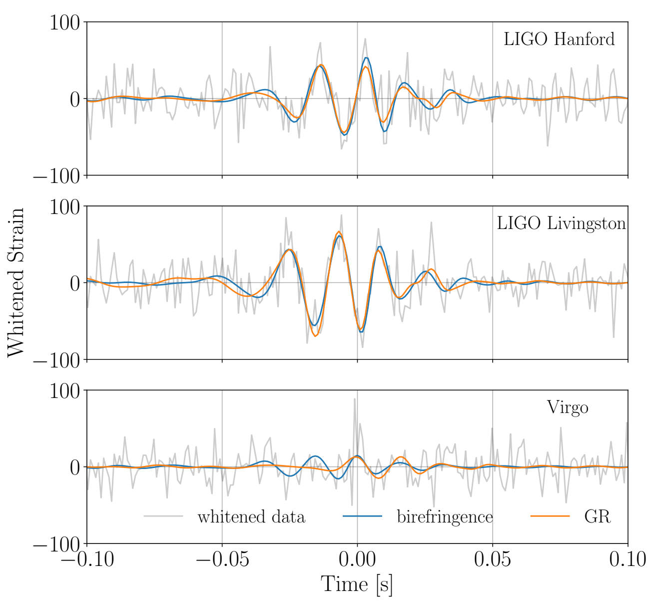

FIG. 3. Whitened strain data for GW190521 along with the best fit GR and birefringence whitened waveforms. The whitened data for GW190521 recorded by LIGO Hanford, LIGO Livingston, and Virgo detectors are plotted in gray. The whitened waveform templates with the maximum likelihood parameters predicted by birefringence (blue) and GR (orange) are plotted. The SNR for these waveform templates are 15.47 and 15.29 for birefringence and GR, respectively.

V. CONCLUSION AND DISCUSSION

In this work we performed a test of GW propagation birefringence using the GW events reported by the recently published 3-OGC and state-of-the-art waveform templates. Combining the results of all 3-OGC events except GW190521, we constrain the lower energy scale cutoff to $M_{\rm PV} > 0.14$ GeV. This is an improvement over previous constraints on the energy scale by a factor of 10. It allows us to place a constraint on the SME isotropic birefringence parameter with mass dimension $d = 5$ of $\left|\vec{\varsigma}^{(5)}\right| < 3.5 \times 10^{-16}$ m. The constraints can only be expected to improve with further GW observations; this shows promising future for GW astronomy to probe the GeV energy scale of gravity.

For GW190521, we surprisingly find evidence in support of GW birefringence. We check for possible waveform systematics but find no disparity between two state-of-the-art frequency domain waveform approximants. Furthermore, we find no significant issue with the data quality. However, this event is clearly an outlier. It is well documented that GW190521 is an exceptional event that may not fit well into the simple quasi-circular binary black hole merger picture. For instance, refs. [36, 37] show that GW190521 is consistent with the merger of a binary black hole system with eccentric orbit, ref. [38] gives a high Bayes factor in favor of a hyperbolic encounter over a quasi-circular merger, and ref. [39] shows that there may be genuinely new physics such as a proca star collision. Another hypothesis is that there are limitations on the current GR waveform approximants at the merger stage of binary black hole coalescence. This is quite relevant as most of the data for GW190521 occurs in the merger band.

Our discovery provides further evidence for non-standard physical effects, which are not currently accounted for by the available GR waveform approximants. With the constant upgrading of the advanced LIGO and Virgo detectors, we expect more GW events, especially GW190521-like ones, will be detected in the future. With more data, the true origin of GW190521 with hopefully be revealed.

We release all posterior files and the scripts necessary to reproduce this work in `https://github.com/gwastro/3ogc_birefringence`.

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