Gravitational-Wave Implications for the Parity Symmetry of Gravity at GeV Scale

Yifan Wang
Max Planck Institute for Gravitationalphysics https://orcid.org/0000-0002-2928-2916
Rui Niu
University of Science and Technology of China
Wen Zhao (wzhao7@ustc.edu.cn)
University of Science and Technology of China
Tao Zhu
Zhejiang University of Technology https://orcid.org/0000-0003-2286-9009

Article

Keywords: gravitational-wave astronomy, parity symmetry, GeV Scale

Posted Date: August 27th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-57578/v1

Gravitational-Wave Implications for the Parity Symmetry of Gravity at GeV Scale

Yi-Fan Wang[1,2],Rui Niu[3,4], Tao Zhu[5,6], Wen Zhao[3,4,*]

[1]Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-30167 Hannover, Germany [2]Leibniz Universität Hannover, D-30167 Hannover, Germany [3]CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, China [4]School of Astronomy and Space Sciences, University of Science and Technology of China, Hefei, 230026, China [5]Institute for theoretical physics and Cosmology, Zhejiang University of Technology, Hangzhou, 310032, China [6]United center for gravitational wave physics (UCGWP), Zhejiang University of Technology, Hangzhou, 310032, China
*wzhao7@ustc.edu.cn

Einstein's general relativity, as the most successful theory of gravity, is one of the cornerstones of modern physics. However, the experimental tests for gravity in the high energy region are limited. The emerging gravitational-wave astronomy has opened an avenue for probing the fundamental properties of gravity in strong and dynamical field, and in particular, high energy regime. In this work, we focus on the parity symmetry of gravity. For broken parity, the left- and right-handed modes of gravitational waves would follow different equations of motion, dubbed as birefringence. We perform the first full Bayesian inference of the parity conservation of gravity by comparing the state-of-the-art waveform with the compact binary coalescence data released by LIGO and Virgo collaboration. We do not find any violations of general relativity, thus obtain the lower bound of the parity-violating energy scale to be 0.09 GeV through the velocity birefringence of gravitational waves. This provides the most stringent experimental test of gravitational parity symmetry up to date, and for the first time, in the high energy region, which ushers in a new era of using gravitational waves to test the ultraviolet behavior of gravity. We also find third-generation gravitational-wave detectors can enhance this bound to $\mathcal{O}(10^2)$ GeV if there is still no violation, comparable to the current Large Hadron Collider (LHC) energy scale in particle physics.

Symmetry is an essential characteristic of the fundamental theories of modern physics and thus must be tested experimentally. In this work, we focus on testing the parity symmetry which indicates the invariance of physical laws under reversed spatial coordinates. It is well-known that parity is conserved for strong and electromagnetic interactions but is broken in the weak interaction as firstly confirmed by the beta-decay experiment in cobalt-60 [1,2]. Gravitational parity is conserved in Einstein's general relativity (GR). Nevertheless, various parity-violating gravity models, including Chern-Simons gravity [3], ghost-free scalar-tensor gravity [4], the symmetric teleparallel equivalence of GR theory [5] and Hořava-Lifshitz gravity [6,7] have been proposed for different motivations such as gravity quantization. In particular, in some fundamental theories of gravity, such as string theory and loop quantum gravity, the parity violation in the high energy regime is inevitable [3]. However, the observational evidence for gravity in the *high energy* scale is limited, which leaves the gravitational wave (GW) observations as a last resort [8–10]. In contrast to the tests of the Solar system or binary pulsars, GW reflects the wave behavior of the gravitational field. Therefore, the tiny deviation from GR, if exists, could be accumulated and magnified during propagation of GWs. In this work, we report the first full Bayesian analysis for gravitational parity conservation at sub-GeV scale from the GW observation, which demonstrates the feasibility of probing the *high energy* behavior of gravity through GWs.

We first construct the generalized GW waveform generated by compact binary coalescence (CBC) with parity violation within the effective field theory (EFT) formalism. EFT provides a systematic framework to encode all kinds of modifications to an existing theory that could arise given certain new physics, thus simultaneously testing a range of modified gravity theories at once. To investigate the possible propagation effect due to parity violation, we consider the perturbation theory of gravitational field. EFT suggests that the leading-order modification to the GR linearized action comes from two terms with three derivatives, i.e., $\epsilon^{ijk}\dot{h}_{il}\partial_j\dot{h}_{kl}$ and $\epsilon^{ijk}\partial^2 h_{il}\partial_j h_{kl}$ with ϵ^{ijk} the antisymmetric symbol and h_{ij} the tensor perturbation of metric, ∂_j and a *dot* denote the derivatives with respect to spatial coordinates and time, respectively [11], ∂^2 is the Laplacian, $i, j... = 1, 2$ or 3 refer to spatial coordinate. Both terms are parity-violating. Dimensional analysis dictates that these new terms are each suppressed by an energy scale. We expect the two energy scales are of the same order, and denote collectively by $M_{\rm PV}$. Otherwise, if the two energy scales differ by orders of magnitude, only the term with lower energy scale dominates, thus we can neglect another term and our result for $M_{\rm PV}$ will not change (see *Methods*). This EFT with leading-order extensions to GR can be mapped to all the existing specific parity-violating modified gravity models in the market [12]. Also note that since parity violation emerges at the leading order modification, we expect the most stringent test on gravity from the propagation of GW, at least from the viewpoint of EFT, is on the gravitational parity symmetry.

As demonstrated by Ref. [13], the modifications to GR-based GW waveform only arise from the propagation effect given the leading order parity violation modification discussed above, because the generation effect occurs on a radiation-reaction timescale much smaller than the GW time of flight and its impact on the evolution of the GW waveform is negligible. Given the parity-violating terms, the equation of motion for the GW circular polarization mode h_A in a Friedmann-Robertson-Walker (FRW) universe is

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

where $A = L$ or R stands for the left- and right-hand modes, $\mathcal{H}$ is the conformal Hubble parameter, k is the wave-number, a *prime* denotes the derivative with respect to the conformal cosmic time. Note that $\mu_A = \nu_A = 0$ would reduce Eq. (1) to GR. Dimensional analysis indicates that both terms relate to the energy scale $M_{\rm PV}$ by $\mu_A \propto \rho_A k/M_{\rm PV}$ and $\nu_A \propto \rho_A k/M_{\rm PV}$ with $\rho_R = 1$ and $\rho_L = -1$. The broken parity leads to asymmetry between the left- and right-hand circular polarization modes of GW during propagation. In particular, the opposite sign of μ_A (as well as ν_A) for different modes leads to the birefringence effect of GWs, which is a characterized phenomenon for GW propagation in the parity-violating gravity. We find that the propagation of GWs can be affected in two ways. The term μ_A modifies the conventional dispersion relation of GWs. As a result, the velocities of left- and right-hand circular polarization of GWs are different, dubbed as the *velocity birefringence* of GW [14]. On the other hand, the term ν_A induces the different damping rates for two polarization modes when they propagate in the expanding Universe, which is called the *amplitude birefringence* of GWs [13]. In the general parity-violating gravity

theories, both effects exist. For each circular polarization mode, the former effect exactly induces the phase modifications of the GW waveform, and the latter one induces the amplitude modifications. Constraints on modification of equation of motion with form Eq. (1) are also obtained by LIGO and Virgo collaboration in Ref. [15], but only parity conserving terms are considered. In contrast, our work focus on the parity-violating effect. Note that, in EFT, the next-to-leading order modification terms in the action, which are leading-order parity-conserving terms , also follow the Eq.(1) with $\nu_A \propto (k/M_{\rm PV})^2$ and $\mu_A \propto (k/M_{\rm PV})^2$ [11,12,14]. Therefore, their effects on the GW waveform are much smaller than the parity-violating effects.

From the equation of motion, one can derive the parity-violating GW waveform in the frequency domain, which is

$$h_A^{\rm PV}(f) = h_A^{\rm GR}(f)\,(1+\rho_A\delta h)\,e^{i\rho_A\delta\Psi}\,, \qquad (2)$$

where f is the frequency, and the amplitude modification δh and the phase modification $\delta\Psi$ are induced by ν_A and μ_A, respectively. It should also be noted that since $\delta\Psi$ is larger than δh by about 20 order of magnitude (see Methods), it is safe to only take into account the contribution of $\delta\Psi$. But we also consider a special scenario where the velocity birefringence is forbidden, i.e., $\delta\Psi = 0$ as is the case for, e.g., Chern-Simons gravity.

With the waveform in Eq. (2), we can perform a direct comparison with the GW data using Bayesian inference to test the parity violation. Up to date, LIGO and Virgo collaborations have released the data of confident CBC events from the first and second observation run. The catalog GWTC-1 include ten binary black hole (BBH) events and a binary neutron star (BNS) event GW170817 [16]. Recently, a second BNS event, GW190425, has been released [17]. We analyze the open data [18] of the twelve events with the inference module of the open-source software `PyCBC` [19] developed for GW astronomy, which in turn has dependency on `LALSuite` [20].

For all the GW events, we do not find any signatures of parity violation. We thus put the lower limit of $M_{\rm PV}$ to be 0.09 GeV in the general parity-violating gravity. This is tighter than the Solar system tests and the binary pulsar observation by 17 orders of magnitude. The reason for this dramatic improvement is that the velocity birefringence effect in the modification of GW waveform is accumulated during the propagation of GW signals, and can be greatly amplified for distant GW events. We note that this result has direct application on constraining a range of specific parity-violating gravity models with velocity birefringence, including the ghost-free scalar-tensor gravity [4], the symmetric teleparallel equivalence of GR theory [5] and Hořava-Lifshitz gravity [6,7]. The detailed correspondence between the above modified gravity models and the EFT formalism can be found in Ref. [12]. We have made our inference results open to facilitate mapping the constraint to any specific parity-violating gravity theories that one is interested in.

By similar analysis, the constraint by only considering the amplitude birefringence modification is $M_{\rm PV} > 1\times10^{-22}$ GeV. This result can be directly compared to and is consistent with Refs. [13,21,22] which focuses on testing Chern-Simons gravity with GW. Compared to the constraint from velocity birefringence, the loose result for amplitude birefringence is because δh is negligibly small compared to $\delta\Psi$ and the GW detection is less sensitive to amplitude modification than phase.

Our results of the constraint on $M_{\rm PV}$ are shown in Fig. 1, where we have combined the results from the twelve CBC events to give an overall constraint. Other existing constraints including the Solar system tests and the binary pulsar observation are also plotted for comparison.

With the continuing sensitivity upgrade during the advanced LIGO and Virgo runs, the future GW astronomy is even more powerful to test the parity symmetry of gravity. The KAGRA detector has joined the global network very recently. The advanced LIGO and Virgo detectors are expected to achieve the design sensitivity in a few years [26].

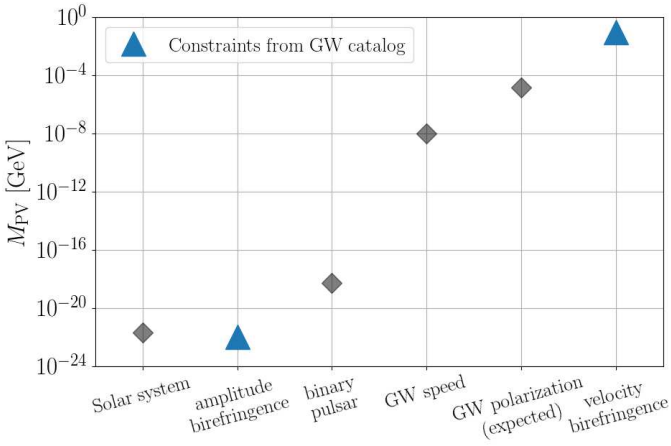

Figure 1 | Current constraints on the lower limits of parity-violating energy scales in gravity from various observations. The triangle markers denote the constraints from the GW catalog for the general parity-violating gravity with velocity birefringence and the special case with only amplitude birefringence, respectively. For comparison, the figure also includes the results from the LAGEOS satellite in the Solar system [23], that from the double pulsar system PSR J0737-3039 A/B [24], that from the arrival time difference between GW170817 and GRB170817A, and the potential result by considering the waveform-independent method developed in Ref. [25].

The third generation ground-based GW detectors, including the Einstein Telescope and the Cosmic Explorer, are under projection currently [27]. We investigate the ability of future GW astronomy to constrain the lower limit of $M_{\rm PV}$ by simulations. With one-year observation time, $M_{\rm PV}$ is expected to be constrained to be no less than $\mathcal{O}(1)$ GeV with the second generation detectors with designed sensitivity and $\mathcal{O}(10^2)$ GeV with the projected third generation detectors. This is comparable with the existing *high energy* experiments in particle physics from LHC. These results indicate that, through GW observations, for the first time it becomes feasible to test the ultraviolet behavior of gravity in the *high energy* region experimentally.

We note that other constraints on the violation of parity symmetry of gravity have also been derived in various analysis using GW or non-GW observations. In the following, we briefly summarize these results to describe the status-of-the-art of the constraint on $M_{\rm PV}$. The results are also presented in Fig. 1 as a comparison of this work. Compared to the following constraints which also use GW, one major difference is that our work makes use of the inspiral-merger-ringdown parity-violating GW waveform (Eq. (2)) which represents the maximum information that can be extracted from the signal. In addition, the Bayesian nature of our method allows for combining the results from a catalog of events.

Waveform-independent constraint from GWs: Our previous work Ref. [25] develops a waveform-independent way to decompose the left- and right-hand polarization modes from the observed GW data if the sky position of the event can be fixed by the observation of its electromagnetic counterparts. From the frequency-time representations we can read out the arrival times of GW in each frequency band. According to the velocity birefringence effect, for a specific frequency f, the arrival time difference between the two modes is $|t_{R-L}| = (2\pi f/M_{\rm PV})^2\int_{t_e}^{t_0} a^{-2}dt$ [25], where a is the scale factor of the Universe, t_0 and t_e are the cosmic time of the arrival and the emission of the GW event respectively. This formula gives a direct relation between the arrival time difference and the energy scale of parity violation $M_{\rm PV}$. Applying to the mock data, we find that if a nearly edge-on BNS at 40 Mpc is detected by the second-generation detector network consisting of advanced LIGO, advanced Virgo, KAGRA, and LIGO-India, one could

derive the waveform-independent bound $M_{\rm PV} > 1.4 \times 10^4$ eV. At this writing, the BNS signal GW170817 is the unique GW event with observed electromagnetic counterparts. However, this event is nearly face-on with the inclination angle $\iota \geq 152^\circ$ [28], thus the right-hand mode of this event is completely dominant. Therefore, the difference of the arrival time between the two modes cannot be determined from GW170817.

Constraint from GW speed: The velocity birefringence effect of GW can be constrained from the speed of GW, which in turn can be obtained by comparing the arrival time of GW signal and that of the electromagnetic signal. For the event GW170817/GRB170817A, the arrival time difference between GW and gamma-ray burst is 1.7 seconds. Assuming the difference of their emission time is less than 10 seconds, the speed of the right-hand circular mode of GW is in the range $-7 \times 10^{-16} < 1 - v_R < 3 \times 10^{-15}$ [29]. According to the relation $|v_R - 1| = \pi f / M_{\rm PV}$ [12], one obtains the constraint $M_{\rm PV} \gtrsim 10$ eV. This is consistent with the result in Ref.[30], where the authors focus on the ghost-free scalar-tensor gravity models with parity violation. Bounds on GW birefringence were also obtained in Ref. [14] with GW150914 for testing local Lorentz invariance by identifying the speed difference between two polarization modes. We note that our EFT formulation can be mapped to the formulation proposed in Ref. [14,31], more detailed analysis is beyond the scope of this work and thus leave as a future work.

Constraint from Solar system tests: In the parity-violating gravity, an important feature is that it leads to a change of frame-dragging effects around rotating objects, which can be used to test the theory. Focusing on the Chern-Simons gravity, Ref. [23] calculates the linearized metric of the spacetime around a non-relativistic, constant-density spinning body. It is found that the gravitomagnetic field in the parity-violating gravity differs from that in GR, which induces the modifications in the precession of orbits of gyroscopes moving in this spacetime. Using the measurement of Lense-Thirring drag around the Earth by the LAGEOS satellites, Ref. [23] sets the constraint on the characteristic Chern-Simons length scale, $k_{\rm CS}^{-1} \lesssim 1000$ km, which corresponds to $M_{\rm PV} \gtrsim 2 \times 10^{-13}$ eV.

Constraint from binary pulsar: In the parity-violating gravity, the theory selects a preferred direction in spacetime that corrects the precession of the orbital plane. Thus, observations of gravitomagnetic precession can be used to test the validity of the theory. In Refs.[24,32], the authors focus on the Chern-Simons modified gravity with a time-like Chern-Simons coupling scalar field, and calculate the leading-order correction to the post-Keplerian parameters of binary systems. They find that the precession of the periastron is corrected by the parity-violating term. Using the measurements of the rate of periastron precession in the double pulsar system PSR J0737-3039 A/B, they obtain a constraint of $k_{\rm CS}^{-1} \lesssim 0.4$ km, which corresponds to $M_{\rm PV} \gtrsim 5 \times 10^{-10}$ eV. Note that the constraints of $M_{\rm PV}$ from the measurements of the Solar system and binary pulsar are based on the effect of frame-dragging modifications in the theory, which is the local effect rather than the propagation effect. Since the frame-dragging modification around rotating objects is a common feature for all parity-violating gravity models, although these constraints are derived for a specific parity-violating theory, i.e. Chern-Simons gravity, we expect that the conclusions are applicable for other theories of parity-violating gravity.

Y.-F.W. thanks Badri Krishnan and Collin Capano for the fruitful discussion and acknowledges the Max Planck Gesellschaft for support and the Atlas cluster computing team at AEI Hannover. W.Z. and R.N. appreciate the helpful discussion with Linqing Wen, Xing Zhang, Qian Hu, Mingzheng Li and Anzhong Wang. W.Z. is supported by NSFC Grants No. 11773028, No. 11633001, No. 11653002, No. 11421303, No. 11903030, and the Strategic Priority Research Program of the Chinese Academy of Sciences Grant No. XDB23010200. T.Z. is supported in part by NSFC Grants No. 11675143, the Zhejiang Provincial NSFC Grant No. LY20A050002, and the Fundamental Research Funds for the Provincial Universities of Zhejiang in China Grants No. RF-A2019015. This research has made use of data, software and/or web tools obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO is funded by the U.S. National Science Foundation. Virgo is funded by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale della Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by Polish and Hungarian institutes.

Methods

In what follows we present our methods for inferring the constraints on parity violation in gravity from GW measurements. We first introduce the construction of the parity-violating GW waveform in the EFT framework, then discuss the Bayesian inference for obtaining the constraints and forecast the constraints with future GW astronomy.

GW waveform with parity violation In this part we follow Refs. [11,12,25] to briefly review the derivation of the GW waveform with parity-violation in the EFT framework. In the FRW universe, choosing the unitary gauge, the equation of motion of GW is determined by the following quadratic action [11]

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

where the last two terms with three derivatives correspond to the contribution from parity violation. c_1 and c_2 are dimensionless coefficients, which are functions respective to cosmic time in general. Note that, in EFT, the leading-order modifications from parity-conserving terms in action are suppressed by $M_{\rm PV}^0$ or $M_{\rm PV}^{-2}$, which indications the much looser constraint (or no constraint) of $M_{\rm PV}$ by GW observing these terms [11,12,14]. From the action, we can derive the equation of motion of GW in the vacuum as shown in Eq. (1). The exact forms for μ_A and ν_A are [12]

$$\begin{aligned} \nu_A &= [\rho_A \alpha_\nu(\tau)(k/aM_{\rm PV})]'/\mathcal{H}, \\ \mu_A &= \rho_A \alpha_\mu(\tau)(k/a\, M_{\rm PV}), \end{aligned} \tag{4}$$

where τ is the cosmic conformal time. The functions $\alpha_\nu \equiv -c_1$ and $\alpha_\mu \equiv c_1 - c_2$ are two arbitrary functions of time which can only be determined given a specific model of modified gravity. For the GW events at the local Universe, these two functions can be approximately treated as constant, i.e. ignoring their time-dependence. Note that we consider α_μ and α_ν to be $\sim \mathcal{O}(1)$ by absorbing the order of magnitude into $M_{\rm PV}$. But a special case when $\alpha_\mu = 0$ (i.e., $c_1 = c_2 = 0$) for Chern-Simons gravity is also considered, the corresponding result is plotted in Fig. 1 as amplitude birefringence.

The explicit parity-violating GW waveform can be derived from solving the equation of motion, as schematically shown by Eq. (2). The amplitude and phase modifications to the GR-based waveform due to birefringence take the following parametrized form

$$\delta h(f) = -A_\nu \pi f, \;\; \delta\Psi(f) = A_\mu (\pi f)^2 / H_0, \tag{5}$$

where H_0 is the Hubble constant. The coefficients A_ν and A_μ are given by

$$\begin{aligned} A_\nu &= M_{\rm PV}^{-1}\left(\alpha_\nu(z=0) - \alpha_\nu(z)(1+z)\right), \\ A_\mu &= M_{\rm PV}^{-1}\int_0^z \frac{\alpha_\mu(z')(1+z')dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_\Lambda}}, \end{aligned} \tag{6}$$

where z is the redshift of the GW event. In analysis we adopt a Planck cosmology ($\Omega_M = 0.315$, $\Omega_\Lambda = 0.685$, $H_0 = 67.4\,\mathrm{km/s/Mpc}$) [33].

We also convert the left- and right-hand GW polarization modes into the *plus* and *cross* modes which are used more often in GW data analysis. The relation between the parity-violating modes and the GR modes is

$$\begin{aligned} h_+^{\rm PV}(f) &= h_+^{\rm GR}(f) - h_\times^{\rm GR}(f)(i\delta h - \delta\Psi), \\ h_\times^{\rm PV}(f) &= h_\times^{\rm GR}(f) + h_+^{\rm GR}(f)(i\delta h - \delta\Psi). \end{aligned} \tag{7}$$

The above expression represents the waveform we employ to compare with the GW data. Let us assume the GW is emitted at the redshift $z \sim O(0.1)$, and α_ν and α_μ are expected to be the same order constant, we find the ratio $\delta\Psi/\delta h \sim \pi f/H_0 \gtrsim 10^{20}$, where $f \sim 100$ Hz for the ground-based GW detectors. Therefore, in the general parity-violating gravity, except for the case with only amplitude birefringence (e.g. Chern-Simons modified gravity), the corrections of GW waveform $h^{\rm PV}(f)$ mainly come from the contribution of velocity birefringence rather than that of amplitude birefringence.

Bayesian inference for GW events Bayesian inference framework is broadly employed in GW astronomy for estimating the source parameters and selecting the preferred model from observation. Given the data d of GW signal and a waveform model H, Bayes theorem claims

$$P(\vec{\theta}|d,H,I) = \frac{P(d|\vec{\theta},H,I)P(\vec{\theta}|H,I)}{P(d|H,I)}, \tag{8}$$

where $\vec{\theta}$ are the parameters characterizing H, I is any other background information. $P(\vec{\theta}|H,I)$ is the prior distribution for $\vec{\theta}$ and $P(d|\vec{\theta},H,I)$ is the likelihood for obtaining the data given a specific set of model parameters. The posterior $P(\vec{\theta}|d,H,I)$ contains all the information about the results of parameter estimation.

For the Gaussian and stationary noise from GW detectors, the likelihood function is

$$P(d|\vec{\theta},H,I) \propto \exp\left[-\frac{1}{2}\sum_i \langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right], \tag{9}$$

where $h(\vec{\theta})$ is the GW waveform template in model H, and i represents the i-th GW detector. The inner product $\langle a|b\rangle$ is defined to be

$$\langle a|b\rangle = 4\mathfrak{R}\int \frac{a(f)b^*(f)}{S_h(f)}df, \tag{10}$$

where $S_h(f)$ is the one-side noise power spectral density (PSD) of the GW detector.

To select the model favored by observation, normalizing both sides of Eq. (8) and we can obtain the Bayes evidence

$$P(d|H,I) = \int d\vec{\theta}P(d|\vec{\theta},H,I)P(\vec{\theta}|H,I). \tag{11}$$

Bayesian ratio is defined as the ratio of evidence between two competitive models H_1 and H_2 which are GR and parity-violating gravity within this work,

$$\mathcal{B}_2^1 = \frac{P(d|H_1,I)}{P(d|H_2,I)}. \tag{12}$$

The odds ratio between model H_1 and model H_2 can be expressed by

$$\mathcal{O}_2^1 = \frac{P(H_1|d,I)}{P(H_2|d,I)} = \frac{P(d|H_1,I)}{P(d|H_2,I)}\frac{P(H_1|I)}{P(H_2|I)} = \mathcal{B}_2^1\frac{P(H_1|I)}{P(H_2|I)}. \tag{13}$$

If the competitive models are assumed to be equally likely before any measurement, then odds ratio is equal to Bayesian ratio. Odds ratio quantitatively reflects the preference of data for competitive models.

We employ the open-source software `PyCBC` with the open data from [18] to perform the Bayesian inference. For the GR waveform $h^{\rm GR}(f)$, we use the spin precessing waveform `IMRPhenomPv2` [34,35] when analyzing BBH events and spin aligned waveform with tidal deformability added `IMRPhenomD_NRTidal` [36] for BNS events. The parity-violating waveform is constructed based on the above template through Eq.(7). We perform parameter estimation by selecting 16s data for BBH and 200s data for BNS events to account for the relatively long signal. The data is sampled at 2048 Hz and the likelihood is evaluated between 20 Hz and 1024 Hz. The PSD is generated from 1000s data using the median estimation with 8s Hann-windowed segments and overlapped by 4s [19]. The prior is chosen to be consistent with that of Ref. [16] and uniformly distributed for A_μ and A_ν. The posterior distribution are sampled by the nest sampling algorithm `dynesty` [37] over the fiducial BBH and BNS source parameters plus the parity-violating parameters A_μ for velocity birefringence or A_ν for amplitude birefringence. Also note that, since we do not find any violation of GR and aim for putting a lower limit to $M_{\rm PV}$, we ignore the calibration error from GW detectors, thus our lower limit should be interpreted as a conservative result for constraining $M_{\rm PV}$. All the settings and parameter estimation results can be found in our released posterior files.

Fig. 2 shows the marginalized posterior distribution for A_μ for velocity birefringence. From the figure, we can observe that the GR value $A_\mu = 0$ is within the 90% confidence level for every event. We also report that the natural logarithm of the Bayes ratio between GR and the parity-violating gravity is distributed in the range $[1.6, 5.8]$ for all the events, confirming no parity violation for gravity.

The relatively low-mass BBH events, such as GW151226, GW170608, and the two BNS events give tighter constraints on A_μ. This is because the velocity birefringence contribution corresponds to a 5.5 post-Newtonian (PN) order modification to the GR waveform which has larger impact on higher frequency, in line with the expectation that the low-mass events with higher cut-off frequency and longer signal yield better constraints.

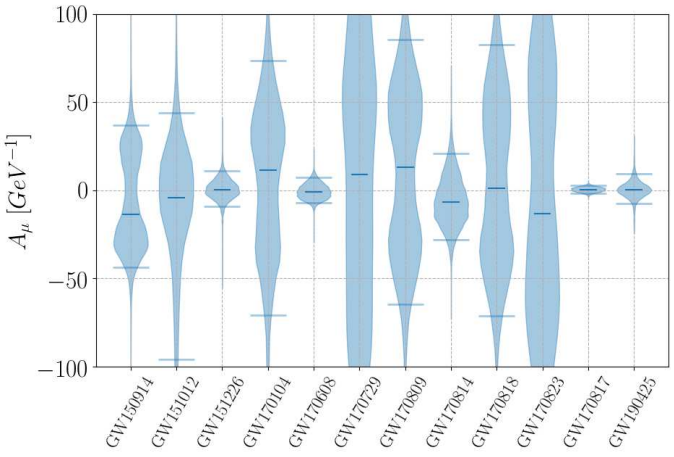

Figure 2 | Violin plots of the posteriors of the parameter A_μ The results are obtained by analyzing the twelve GW events. The region in the posterior between the upper and lower bar denote the 90% credible interval, and the bar at the middle denotes the median value. The GR value $A_\mu = 0$ is within the 90% confidence interval for each event. We notice that the two relative low-mass events GW151226 and GW170608 and the two BNS events yield the best constraint on A_μ.

For converting A_μ into $M_{\rm PV}$, we absorb the absolute value of α_μ into the definition of $M_{\rm PV}$, which is equivalent to set $|\alpha_\mu| = 1$ in the calculation, then the parameter $M_{\rm PV}$ can be obtained from A_μ and redshift z by Eq. (6). The marginalized posterior distributions of $M_{\rm PV}$ are shown in Fig. 3. It is straightforward to combine the posterior on $M_{\rm PV}$ from each event to give an overall constraint with all GW events

by

$$p(M_{\rm PV}|\{d_i\},H,I) \propto \prod_{i=1}^{N} p(M_{\rm PV}|d_i,H,I), \tag{14}$$

where d_i denotes the i-th GW event. The combined result show that the 90% lower limit for $M_{\rm PV}$ is 0.09 GeV. This is the first observational evidence of gravitational parity conservation from dynamical and strong-field observation and the tightest constraint on $M_{\rm PV}$ up to date.

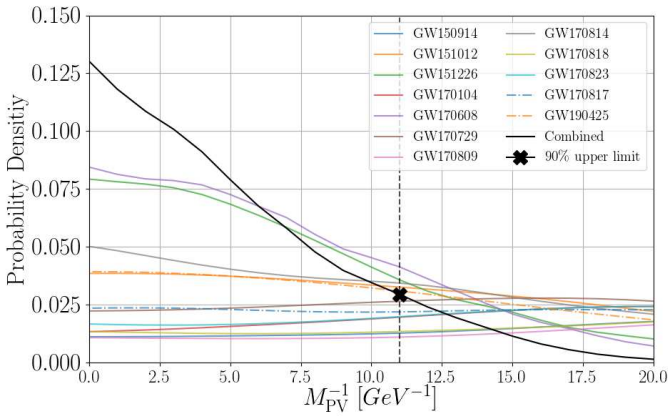

Figure 3 | The posterior distributions for $M_{\rm PV}^{-1}$. The inference results for the parity-violating energy scale for velocity birefringence are plotted. The results from individual GW event and the combination of all the events are considered. The abscissa value of the "x" marker represents the 90% upper limit for $M_{\rm PV}^{-1}$, or equivalently, the 90% lower limit for $M_{\rm PV}$, which is 0.09 GeV.

Testing parity of gravity in the high energy region with future GW detectors We have shown that the current GW detection is capable of probing the sub GeV parity-violating energy scale. With the continuing upgrade for GW detectors, we also forecast the ability of GW astronomy to constrain $M_{\rm PV}$. We consider four sets of detector configurations based on technologies currently available or under investigation, and simulate 200 BBH events from GR for each set. For the first set, we choose the advanced LIGO, advanced Virgo and KAGRA network, all running with designed sensitivity. The second and third sets substitute the two LIGO detectors with the 2.5 generation detector A+ [38] and the Voyager [39] configuration, respectively. The last set uses the third generation detectors including the Einstein Telescope [27,40] and two Cosmic Explorer [27,41] detectors located at the LIGO sites.

The simulated BBH events are uniformly located in the space and have mass uniformly distributed in the range $[5,50]M_\odot$. For the first three sets, the upper cutoff for luminosity distance is chosen to be 2000 Mpc, while for the third generation detectors the distance cutoff is 5000 Mpc. We do not consider more distant sources to give a conservative estimation of the constraining ability of the future GW detector configurations. We employ Bayesian inference to perform parameter estimation on the simulated events and choose the signal-to-noise ratio (SNR) > 8 as the criterion for detection.

In Fig. 4, we show the results of the combined constraints on $M_{\rm PV}$ with respect to the number of detections. We first notice that, out of the 200 sources, 40% of the sources can be detected by the advanced LIGO, advanced Virgo and KAGRA global network with design sensitivity, and $M_{\rm PV}$ can be constrained to 0.2 GeV, while the 2.5 generation detectors A+ and Voyager can resolve 65% and 90% of sources, respectively, and constrain $M_{\rm PV}$ to be not less than 0.6 GeV and 1 GeV.

For the last set of simulations, all the BBH sources can be detected by the third generation detectors, and the constraint with 200 events is 10 GeV. Given the local merger rate estimation 53.2 $\rm yr^{-1}$ $\rm Gpc^{-3}$ from LIGO and Virgo [42], it is expected that there are $\mathcal{O}(10^4)$ BBH coalescence events within 5000 Mpc in one year. Therefore, assuming the constraint on $M_{\rm PV}$ is inversely proportional to the square root of event number, the resultant constraint can reach $\mathcal{O}(10^2)$ GeV with a one-year observation with the third generation detectors. This demonstrates the promising future of GW astronomy to probe the ultraviolet property of gravity in the high energy region, which could shed light on deviations from GR, if exists, arising from the 100 GeV region.

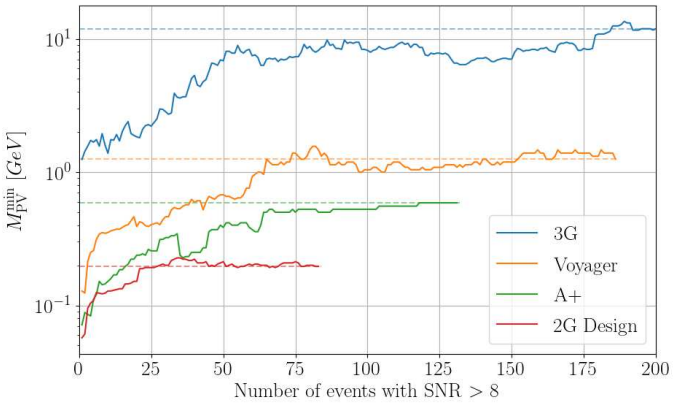

Figure 4 | The projected constraints for $M_{\rm PV}$ for future GW detectors. Using 200 BBH signals from GR, the constraints for the lower limit of the parity-violating energy scale for velocity birefringence are plotted. We consider four sets of global GW detectors network which are (1) the second generation detectors including advanced LIGO, advanced Virgo, and KAGRA with design sensitivity (2) the 2.5 generation detector A+ (3) the 2.5 generation detector Voyager (4) the third generation detector with the Einstein Telescope and Cosmic Explorer. As the number of detections increasing, the constraints for the lower limit of $M_{\rm PV}$ becomes tighter. In particular, the third generation detector can detect all the BBH coalescence signals within 5000 Mpc and can constrain $M_{\rm PV} > \mathcal{O}(10)$ GeV with 200 events. With a one-year observation run, the third generation detectors are expected to improve the constraint to $\mathcal{O}(10^2)$ GeV.

Data availability The posterior files for velocity and amplitude birefringence of the twelve GW events are released in https://yi-fan-wang.github.io/ParitywithGW/

Code availability This work used the open-source software `PyCBC` which is available from https://github.com/gwastro/pycbc.

1. Lee, T. D. & Yang, C. N. Question of parity conservation in weak interactions. *Phys. Rev.* **104**, 254–258 (1956). URL https://link.aps.org/doi/10.1103/PhysRev.104.254.
2. Wu, C. S., Ambler, E., Hayward, R. W., Hoppes, D. D. & Hudson, R. P. Experimental test of parity conservation in beta decay. *Phys. Rev.* **105**, 1413–1415 (1957). URL https://link.aps.org/doi/10.1103/PhysRev.105.1413.
3. Alexander, S. & Yunes, N. Chern–simons modified general relativity. *Physics Reports* **480**, 1 – 55 (2009). URL http://www.sciencedirect.com/science/article/pii/S037015730900177X.
4. Crisostomi, M., Noui, K., Charmousis, C. & Langlois, D. Beyond lovelock gravity: Higher derivative metric theories. *Phys. Rev. D* **97**, 044034 (2018). URL https://link.aps.org/doi/10.1103/PhysRevD.97.044034.
5. Conroy, A. & Koivisto, T. Parity-violating gravity and GW170817 in non-riemannian cosmology. *Journal of Cosmology and Astroparticle Physics* **2019**, 016–016 (2019). URL https://doi.org/10.1088%2F1475-7516%2F2019%2F12%2F016.
6. Hořava, P. Quantum gravity at a lifshitz point. *Phys. Rev. D* **79**, 084008 (2009). URL https://link.aps.org/doi/10.1103/PhysRevD.79.084008.

7. Wang, A., Wu, Q., Zhao, W. & Zhu, T. Polarizing primordial gravitational waves by parity violation. *Phys. Rev. D* **87**, 103512 (2013). URL https://link.aps.org/doi/10.1103/PhysRevD.87.103512.
8. Miller, M. C. & Yunes, N. The new frontier of gravitational waves. *Nature* **568**, 469–476 (2019). URL http://dx.doi.org/10.1038/s41586-019-1129-z.
9. Yunes, N. & Siemens, X. Gravitational-wave tests of general relativity with ground-based detectors and pulsar-timing arrays. *Living Reviews in Relativity* **16** (2013). URL http://dx.doi.org/10.12942/lrr-2013-9.
10. Berti, E. *et al.* Testing general relativity with present and future astrophysical observations. *Classical and Quantum Gravity* **32**, 243001 (2015). URL https://doi.org/10.1088%2F0264-9381%2F32%2F24%2F243001.
11. Creminelli, P., Gleyzes, J., Noreña, J. & Vernizzi, F. Resilience of the standard predictions for primordial tensor modes. *Phys. Rev. Lett.* **113**, 231301 (2014). URL https://link.aps.org/doi/10.1103/PhysRevLett.113.231301.
12. Zhao, W., Zhu, T., Qiao, J. & Wang, A. Waveform of gravitational waves in the general parity-violating gravities. *Phys. Rev. D* **101**, 024002 (2020). URL https://link.aps.org/doi/10.1103/PhysRevD.101.024002.
13. Alexander, S. H. & Yunes, N. Gravitational wave probes of parity violation in compact binary coalescences. *Phys. Rev. D* **97**, 064033 (2018). URL https://link.aps.org/doi/10.1103/PhysRevD.97.064033.
14. Kostelecký, V. A. & Mewes, M. Testing local lorentz invariance with gravitational waves. *Physics Letters B* **757**, 510 – 514 (2016). URL http://www.sciencedirect.com/science/article/pii/S0370269316301137.
15. Abbott, B. P. *et al.* Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1 (2019). 1903.04467.
16. Abbott, B. P. *et al.* GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs (2018). 1811.12907.
17. Abbott, B. P. *et al.* GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_{\odot}$ (2020). 2001.01761.
18. Vallisneri, M., Kanner, J., Williams, R., Weinstein, A. & Stephens, B. The LIGO Open Science Center. *J. Phys. Conf. Ser.* **610**, 012021 (2015). 1410.4839.
19. Biwer, C. M. *et al.* PyCBC inference: A python-based parameter estimation toolkit for compact binary coalescence signals. *Publications of the Astronomical Society of the Pacific* **131**, 024503 (2019). URL https://doi.org/10.1088%2F1538-3873%2Faaef0b.
20. LIGO Scientific Collaboration. LIGO Algorithm Library - LALSuite. free software (GPL) (2018).
21. Yagi, K. & Yang, H. Probing gravitational parity violation with gravitational waves from stellar-mass black hole binaries. *Phys. Rev. D* **97**, 104018 (2018). URL https://link.aps.org/doi/10.1103/PhysRevD.97.104018.
22. Nair, R., Perkins, S., Silva, H. O. & Yunes, N. Fundamental Physics Implications for Higher-Curvature Theories from Binary Black Hole Signals in the LIGO-Virgo Catalog GWTC-1. *Phys. Rev. Lett.* **123**, 191101 (2019). 1905.00870.
23. Smith, T. L., Erickcek, A. L., Caldwell, R. R. & Kamionkowski, M. Effects of chern-simons gravity on bodies orbiting the earth. *Phys. Rev. D* **77**, 024015 (2008). URL https://link.aps.org/doi/10.1103/PhysRevD.77.024015.
24. Ali-Haïmoud, Y. Revisiting the double-binary-pulsar probe of nondynamical chern-simons gravity. *Phys. Rev. D* **83**, 124050 (2011). URL https://link.aps.org/doi/10.1103/PhysRevD.83.124050.
25. Zhao, W. *et al.* Model-independent test of the parity symmetry of gravity with gravitational waves. *Eur. Phys. J. C* **80**, 630 (2020). 1909.13007.
26. Abbott, B. P. *et al.* Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA. *Living Rev. Rel.* **21**, 3 (2018). 1304.0670.
27. Abbott, B. P. *et al.* Exploring the sensitivity of next generation gravitational wave detectors. *Classical and Quantum Gravity* **34**, 044001 (2017). URL https://doi.org/10.1088%2F1361-6382%2Faa51f4.
28. Abbott, B. *et al.* GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **119**, 161101 (2017). 1710.05832.
29. Abbott, B. P. *et al.* Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817a. *The Astrophysical Journal* **848**, L13 (2017). URL https://doi.org/10.3847%2F2041-8213%2Faa920c.
30. Nishizawa, A. & Kobayashi, T. Parity-violating gravity and gw170817. *Phys. Rev. D* **98**, 124018 (2018). URL https://link.aps.org/doi/10.1103/PhysRevD.98.124018.
31. Kostelecky, V. & Russell, N. Data Tables for Lorentz and CPT Violation. *Rev. Mod. Phys.* **83**, 11–31 (2011). 0801.0287.
32. Yunes, N. & Spergel, D. N. Double-binary-pulsar test of chern-simons modified gravity. *Phys. Rev. D* **80**, 042004 (2009). URL https://link.aps.org/doi/10.1103/PhysRevD.80.042004.
33. Aghanim, N. *et al.* Planck 2018 results. VI. Cosmological parameters (2018). 1807.06209.
34. Schmidt, P., Ohme, F. & Hannam, M. Towards models of gravitational waveforms from generic binaries: Ii. modelling precession effects with a single effective precession parameter. *Phys. Rev. D* **91**, 024043 (2015). URL https://link.aps.org/doi/10.1103/PhysRevD.91.024043.
35. Hannam, M. *et al.* Simple model of complete precessing black-hole-binary gravitational waveforms. *Phys. Rev. Lett.* **113**, 151101 (2014). URL https://link.aps.org/doi/10.1103/PhysRevLett.113.151101.
36. Dietrich, T., Bernuzzi, S. & Tichy, W. Closed-form tidal approximants for binary neutron star gravitational waveforms constructed from high-resolution numerical relativity simulations. *Phys. Rev. D* **96**, 121501 (2017). URL https://link.aps.org/doi/10.1103/PhysRevD.96.121501.
37. Speagle, J. S. dynesty: A dynamic nested sampling package for estimating bayesian posteriors and evidences. *Monthly Notices of the Royal Astronomical Society* (2020). URL http://dx.doi.org/10.1093/mnras/staa278.
38. https://dcc.ligo.org/LIGO-T1800042/public.
39. https://dcc.ligo.org/LIGO-T1500293-v11/public.
40. Punturo, M. *et al.* The einstein telescope: a third-generation gravitational wave observatory. *Classical and Quantum Gravity* **27**, 194002 (2010). URL https://doi.org/10.1088%2F0264-9381%2F27%2F19%2F194002.
41. Reitze, D. *et al.* Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. *Bull. Am. Astron. Soc.* **51**, 035 (2019). 1907.04833.
42. Abbott, B. P. *et al.* Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo (2018). 1811.12940.

Figures

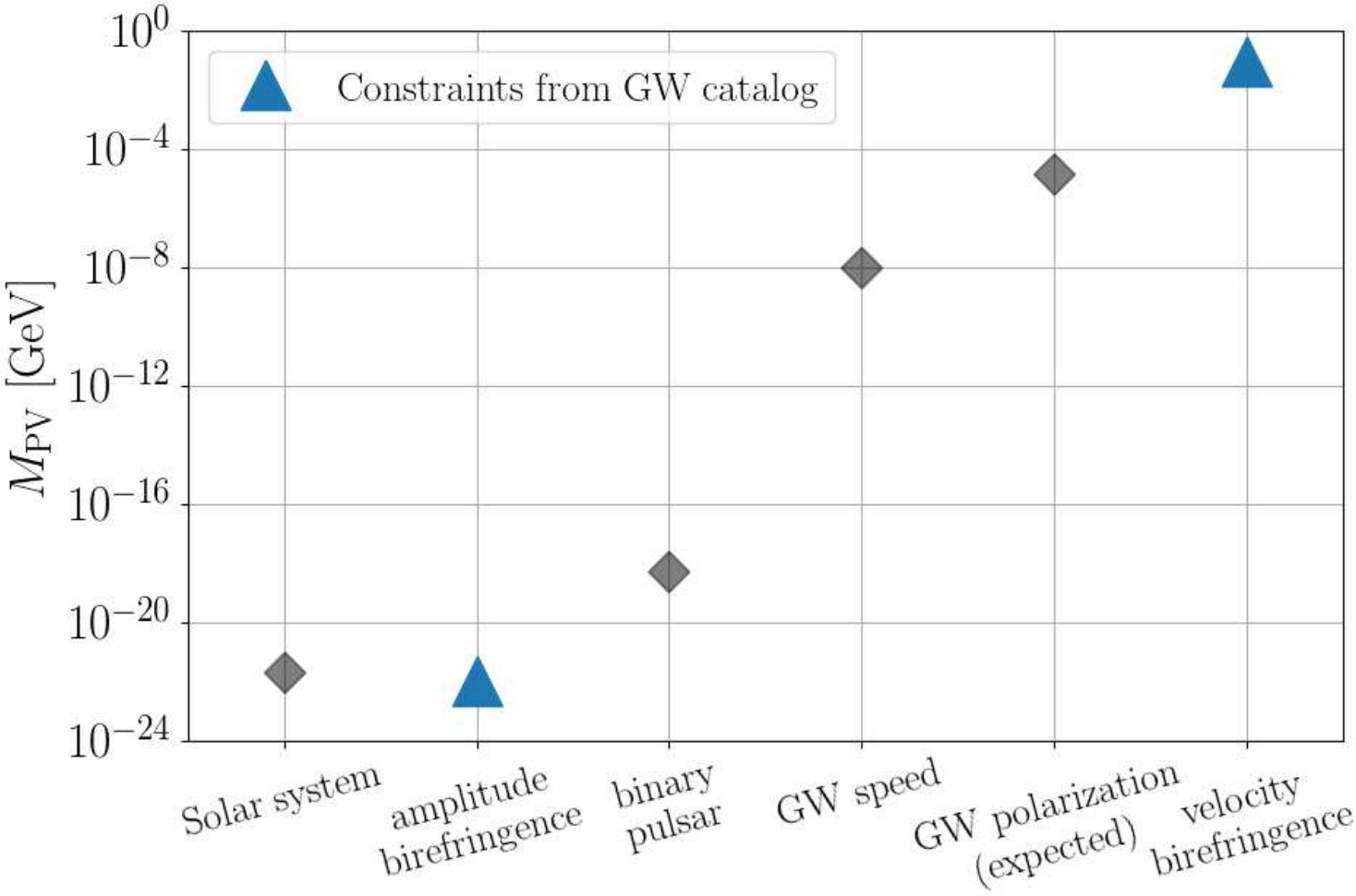

Figure 1

Current constraints on the lower limits of parity-violating energy scales in gravity from various observations. The triangle markers denote the constraints from the GW catalog for the general parity-violating gravity with velocity birefringence and the special case with only amplitude birefringence, respectively. For comparison, the figure also includes the results from the LAGEOS satellite in the Solar system 23, that from the double pulsar system PSR J0737-3039 A/B 24, that from the arrival time difference between GW170817 and GRB170817A, and the potential result by considering the waveform-independent method developed in Ref. 25.

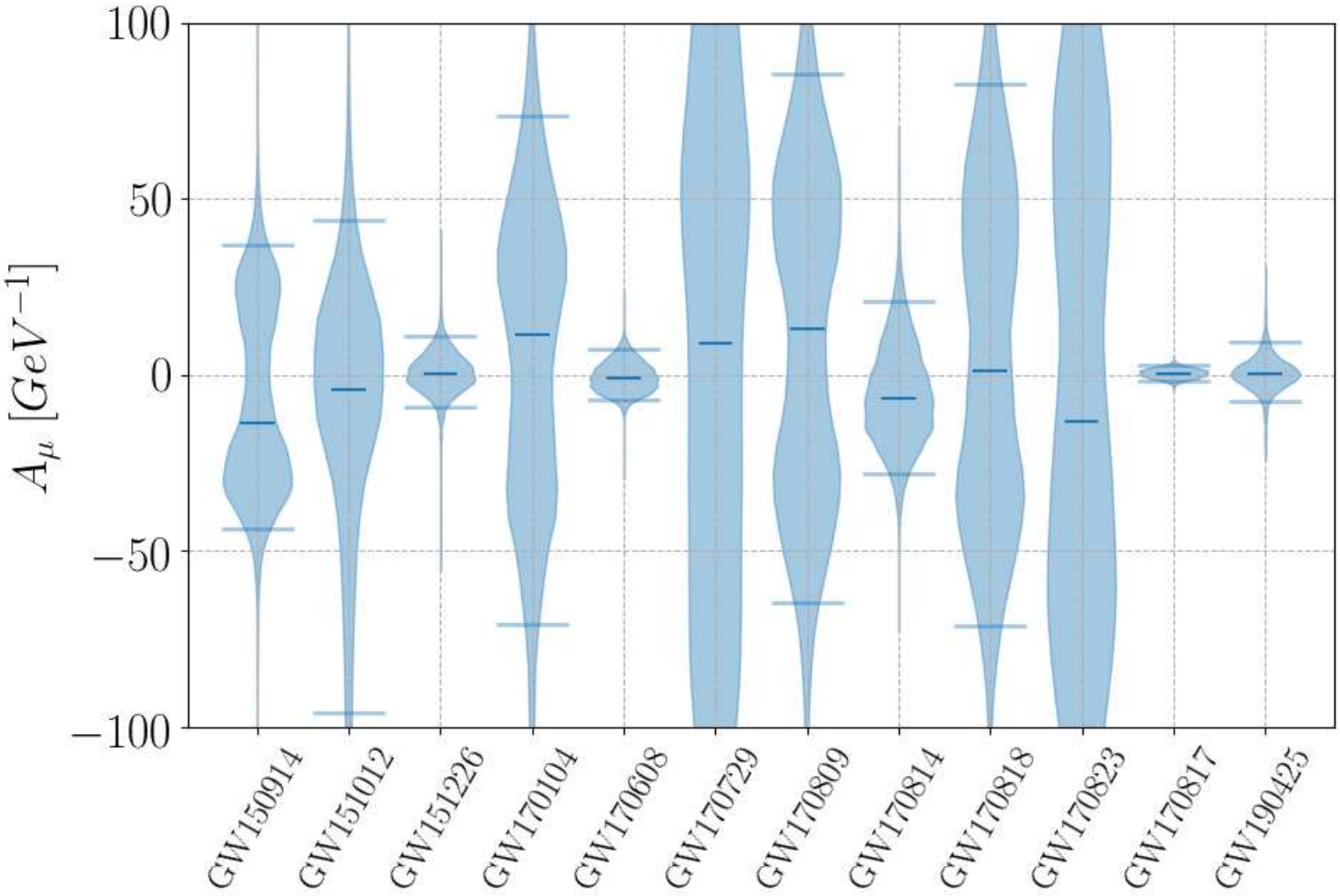

Figure 2

Violin plots of the posteriors of the parameter Aμ. The results are obtained by analyzing the twelve GW events. The region in the posterior between the upper and lower bar denote the 90% credible interval, and the bar at the middle denotes the median value. The GR value Aμ = 0 is within the 90% confidence interval for each event. We notice that the two relative low-mass events GW151226 and GW170608 and the two BNS events yield the best constraint on Aμ.

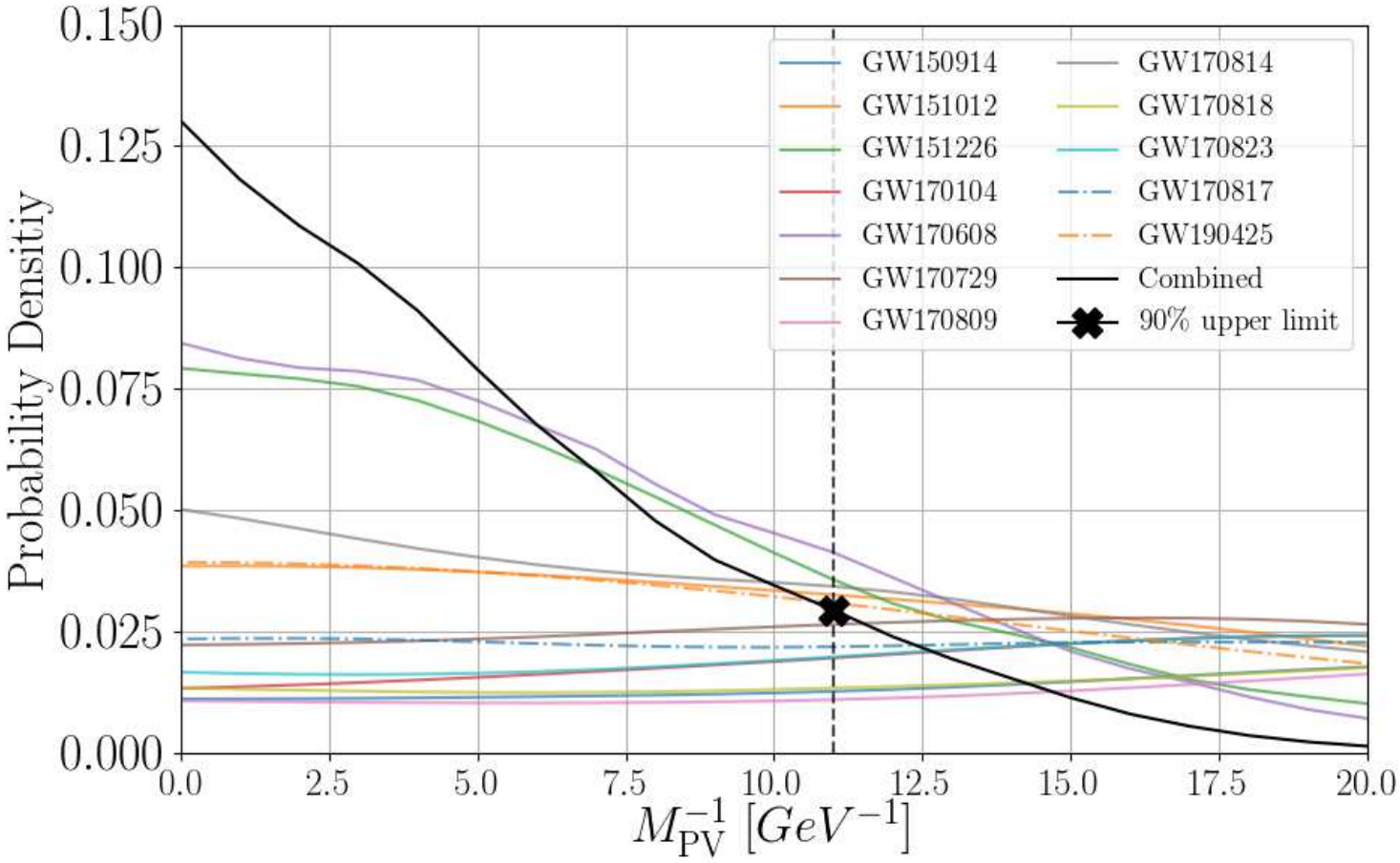

Figure 3

The posterior distributions for M-1_PV. The inference results for the parity-violating energy scale for velocity birefringence are plotted. The results from individual GW event and the combination of all the events are considered. The abscissa value of the “x” marker represents the 90% upper limit for M-1_PV, or equivalently, the 90% lower limit forMPV, which is 0:09 GeV.

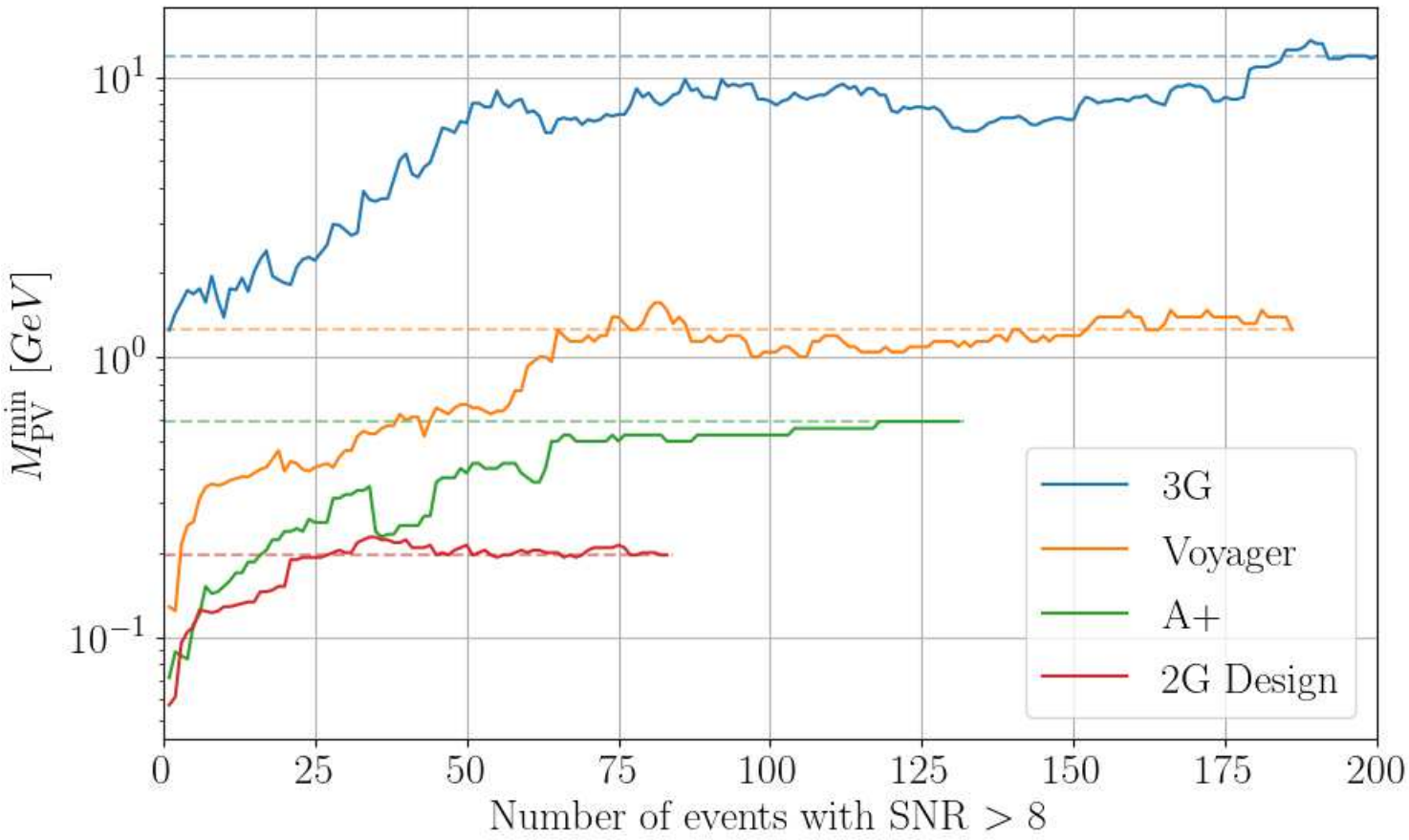

Figure 4

The projected constraints for MPV for future GW detectors. Using 200 BBH signals from GR, the constraints for the lower limit of the parityviolating energy scale for velocity birefringence are plotted. We consider four sets of global GW detectors network which are (1) the second generation detectors including advanced LIGO, advanced Virgo, and KAGRA with design sensitivity (2) the 2.5 generation detector A+ (3) the 2.5 generation detector Voyager (4) the third generation detector with the Einstein Telescope and Cosmic Explorer. As the number of detections increasing, the constraints for the lower limit of MPV becomes tighter. In particular, the third generation detector can detect all the BBH coalescence signals within 5000 Mpc and can constrain MPV > O(10) GeV with 200 events. With a one-year observation run, the third generation detectors are expected to improve the constraint to O(102) GeV.