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Fundamental Physics Implications on Higher-Curvature Theories from the Binary Black Hole Signals in the LIGO-Virgo Catalog GWTC-1

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Gravitational-wave astronomy offers not only new vistas into the realm of astrophysics, but also opens an avenue for probing, for the first time, general relativity in its strong-field, nonlinear and dynamical regime, where the theory's predictions manifest themselves in their full glory. We present a study of whether the gravitational-wave events detected so far by the LIGO-Virgo scientific collaborations can be used to probe higher-curvature corrections to general relativity. In particular, we focus on two examples, Einstein-dilaton-Gauss-Bonnet and dynamical Chern-Simons gravity. We find that the two events with a low-mass $m \approx 7M_\odot$ BH (GW151226 and GW170608) place stringent constraints on Einstein-dilaton-Gauss-Bonnet gravity, $\alpha_{\rm EdGB}^{1/2} \lesssim 5.6$ km, whereas dynamical Chern-Simons gravity remains unconstrained by the gravitational-wave observations analyzed.

Introduction. General relativity (GR) remains our most accurate theory for the gravitational interaction [1]. The centennial theory has passed a plethora of tests ranging from those carried out in the weak-gravitational field and low-velocity regime of our Solar System, to those performed in the extreme, nonlinear and highly-dynamical regime of plunging and merging compact objects, such as neutron stars (NSs) and black holes (BHs) [2, 3]. The agreement between the observations and predictions is dazzling. In turn, any new observation that may hint toward a failure of GR will require us to revisit its foundations. Experimental tests of GR not only allow us to place its foundational principles on solid ground, but they also allow us to constrain (or even rule out) contending theories that violate one or more of its pillars. Such contending theories have been developed to address certain outstanding mysteries in recent observations [4, 5], such as the enigmatic late-time acceleration of the Universe [6, 7], the matter-antimatter asymmetry in our Universe [8, 9] and the rotation curve of galaxies [10, 11].

One broad class of modifications to GR that arise naturally in attempts to unify gravity with quantum mechanics are quadratic gravity theories [12]. This class of theories is characterized by the presence of an additional scalar degree of freedom (violating the GR pillar that gravity is mediated by a single metric tensor) coupled to a higher-order curvature scalar. Two preeminent examples of such theories are Einstein-dilaton-Gauss-Bonnet (EdGB) and dynamical Chern-Simons (dCS) gravity [13]. Both of these emerge naturally in the context of grand unified theories (string theory in particular) in the low-energy limit upon dimensional reduction. Phenomenologically, they predict BHs that carry a nontrivial scalar field, resulting in a violation of the strong equivalence principle.

Aside from these theoretical motivations, are EdGB and dCS gravity consistent with experimental tests? Within the confines of our Solar System, the parameterized-post-Newtonian parameters of EdGB gravity are identical to those of GR [14], and therefore the theory survives all experimental tests in this regime. In contrast, dCS gravity contains a nonzero (different from GR) parameter that leads to modifications in the Lense-Thirring precession of spinning bodies [15, 16]. Solar System experiments such as LAGEOS [17] and Gravity Probe B [18] can place constraints on the dCS coupling parameter, but due to the weak curvatures in the Solar System, these constraints are extremely weak [19]. Exquisitely accurate binary-pulsar observations suffer the same fate. The post-Keplerian motion of NS binaries in EdGB and dCS gravity is very similar to that in GR, because the scalar field sourced by such stars is suppressed relative to that created by BHs, which means that constraints with present day binary pulsar observations are not possible [12, 20].

This leaves us with gravitational wave (GW) observations as a last resort. In recent years, considerable effort has been made in modeling the inspiral [21–23], merger [24–27] and ringdown [28, 29] phases of compact binaries in these two theories. One could then imagine comparing such waveform models against the GW data to determine how small the EdGB and dCS coupling parameters must be in order to be consistent with statistical noise. We build on these efforts and use the constraints on GR deviations obtained by the LIGO-Virgo collaboration (LVC) [30] to analyze whether these two theories can be constrained with the binary BH events detected during the first two observation runs of the LVC. More specifically, we will consider the binary BH events in the LIGO-Virgo Catalog GWTC-1 GW150914 [31, 32], GW151226 [33], GW170104 [34], GW170608 [35] and GW170814 [36] for which the posteriors on theory-independent GR modifications, obtained through a Markov-Chain-Monte-Carlo (MCMC) exploration of the parameter space, have been made public [3, 37].

Quadratic gravity. dCS and (decoupled) EdGB theories are

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defined in vacuum by the Lagrangian density [12]

$$\mathscr{L}_{\rm dCS} = \kappa R - \frac{1}{2}\nabla_\mu\vartheta_{\rm dCS}\nabla^\mu\vartheta_{\rm dCS} + \frac{\alpha_{\rm dCS}}{4}\,\vartheta_{\rm dCS}\,{}^*RR, \tag{1}$$

$$\mathscr{L}_{\rm EdGB} = \kappa R - \frac{1}{2}\nabla_\mu\vartheta_{\rm EdGB}\nabla^\mu\vartheta_{\rm EdGB} + \alpha_{\rm EdGB}\,\vartheta_{\rm EdGB}\,\mathscr{G}, \tag{2}$$

where $\kappa \equiv (16\pi)^{-1}$, g is the determinant of the metric $g_{\mu\nu}$, ${}^*RR = R_{\nu\mu\rho\sigma}{}^*R^{\mu\nu\rho\sigma}$ is the Pontryagin density (constructed in terms of the Riemann tensor and its dual), $\mathscr{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$ is the Gauss-Bonnet density (where R and $R_{\mu\nu}$ are the Ricci scalar and tensor), and we have used geometric units, in which $c = 1 = G$. These quadratic-in-curvature scalars are coupled[1] to a massless scalar (pseudo-scalar) field $\vartheta_{\rm EdGB}$ ($\vartheta_{\rm dCS}$) through the coupling constants $\alpha_{\rm EdGB}$ ($\alpha_{\rm dCS}$), with units of (length)^2.

To ensure the perturbative well-posedness of these theories, we work in the small-coupling approximation, in which modifications to GR are *small deformations*. This is a justified assumption given the agreement of GR with various observations, GW events included. It is convenient to define the dimensionless parameter $\zeta_{\rm dCS,EdGB} \equiv \alpha^2_{\rm dCS,EdGB}/(\kappa\,\ell^4)$, where ℓ is the typical mass scale of a system. For the small-coupling approximation to be valid we must have $\zeta_{\rm dCS,EdGB} < 1$ or $\alpha^{1/2}_{\rm dCS,EdGB}/m_s \lesssim 0.5$ where m_s is the smallest mass scale involved in the problem. Note that 0.5 is a rough threshold which we use as a proxy for the validity of the approximation.

Consistency with Solar System experiments (in dCS) and with low-mass x-ray binary observations (in EdGB) impose the upper bounds $\alpha^{1/2}_{\rm dCS} \leq O(10^8\ \text{km})$ [13, 19] and $\alpha^{1/2}_{\rm EdGB} \leq O(2\ \text{km})$ [38].

How can the GWs emitted by BH binaries in these theories be different from GR's predictions? In both theories, BHs support a nontrivial scalar field – dipolar in dCS [39] and monopolar in EdGB [40] – which results in the emission of scalar quadrupole (in dCS) and scalar dipole (in EdGB) radiation during the inspiral. This additional channel for binding energy loss results in modification to the GW phase, which appear at 2PN[2] (for dCS) and -1PN (for EdGB) order. In dCS gravity, the scalar field also introduces a quadrupolar correction to the binary BH spacetime, introducing 2PN corrections to the binding energy, which in turn affect the GW phase evolution at the same PN order. Hereafter, we use these facts, together with the estimates of the GW model parameters and the posterior distributions released in [3, 30], to investigate how well (if at all) the observed GW events in the LVC catalog can be used to constrain these theories.

Order of magnitude constraints. It is illuminating to start with a simple order-of-magnitude calculation to assess if the binary BH events detected by LIGO-Virgo can place any constraints on dCS and EdGB gravity. Consider the Fourier domain gravitational waveform $\tilde{h} = A(f)\exp[i\Psi(f)]$, and for simplicity we assume that the spins of the compact objects are (anti)aligned to the orbital angular momentum. Under these assumptions, the leading-order modification to the Fourier phase $\Psi(f)$ takes on the parameterized post-Einsteinian (ppE) form [2] $\Psi = \Psi_{\rm GR} + \beta\,(\pi\mathcal{M}f)^b$, where $b_{\rm dCS} = -1/3$ in dCS gravity (a 2PN correction) and $b_{\rm EdGB} = -7/3$ in EdGB gravity (a -1PN correction). The amplitude coefficient β is

$$\beta_{\rm dCS} = -\frac{5}{8192}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\frac{(m_1\,s_2^{\rm dCS} - m_2\,s_1^{\rm dCS})^2}{m^2} + \frac{15075}{114688}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\frac{1}{m^2}\left(m_2^2\chi_1^2 - \frac{305}{201}m_1\,m_2\,\chi_1\chi_2 + m_1^2\chi_2^2\right) \tag{3}$$

in dCS gravity[3] [45] and

$$\beta_{\rm EdGB} = -\frac{5}{7168}\frac{\zeta_{\rm EdGB}}{\eta^{18/5}}\frac{\left(m_1^2\,s_2^{\rm EdGB} - m_2^2\,s_1^{\rm EdGB}\right)^2}{m^4}, \tag{4}$$

in EdGB gravity [21], where $\mathcal{M} = (m_1\,m_2)^{3/5}/(m_1+m_2)^{1/5}$ is the chirp mass, $\eta = m_1 m_2/m^2$ (with $m = m_1 + m_2$) is the symmetric mass ratio, $\chi_{s,a} = (\chi_1 \pm \chi_2)/2$ are the symmetric and antisymmetric dimensionless spin combinations with $\chi_i = \vec{S}_i\cdot\hat{L}/m_i^2$ the projections of dimensional spin angular momenta $\vec{S}_i$ in the direction of the orbital angular momentum $\hat{L}$ and

$$s_i^{\rm dCS} = \frac{2 + 2\chi_i^4 - 2(1-\chi_i^2)^{1/2} - \chi_i^2[3 - 2(1-\chi_i^2)^{1/2}]}{2\chi_i^3}, \tag{5}$$

$$s_i^{\rm EdGB} = \frac{2\,[(1-\chi_i^2)^{1/2} - 1 + \chi_i^2]}{\chi_i^2}, \tag{6}$$

are the dimensionless spin and mass-dependent BH scalar charges, to all orders in spin, in both theories [43, 45, 46]. Although $\beta_{\rm dCS}$ has uncontrolled remainders of $O(\chi^4)$, $\beta_{\rm EdGB}$ is valid to all orders in the spin. We can obtain an order-of-magnitude bound on $\zeta_{\rm dCS,EdGB}$ using the best-fit parameters from GW170608 and doing a crude Fisher matrix analysis[4]. Given that the event is consistent with GR, we can ask how large

[1] In EdGB, the coupling to the Gauss-Bonnet density is usually of exponential form. We here work in the decoupling (effective field theory) limit, in which the exponential is expanded to linear order [12].

[2] In the PN formalism, quantities of interest such as the conserved energy, flux etc. can be written as expansions in (v/c), where v is the characteristic speed of the binary system and c is the speed of light. $O((v/c)^n)$ corrections counting from the Newtonian (leading order GR) term are referred to as $(n/2)$PN-order terms [41, 42].

[3] Our expression for $\beta_{\rm dCS}$ is different from that presented, e.g. in [43, 44]. First, we corrected an error in the rate of scalar radiation emission $d\delta E^{(\vartheta)}/dt$, which propagates to the final expression for $\beta_{\rm dCS}$ [20]. Second, we do not expand the charge $s_i^{\rm dCS}$ to leading order in χ_i as has been done in the past. The reason is the following: the binding energy contribution to $\beta_{\rm dCS}$ in Eq. (3) only contains the quadrupole moment to $O(\chi_i^2)$. In principle, there will be a $O(\chi_i^4)$ correction to it, which will also enter at 2PN order and has not been calculated yet. Thus, unlike in the EdGB case, we cannot calculate the dCS correction at 2PN order to also all orders in the spins. To estimate how robust our bounds are to the absence of this quadrupolar contribution, we include the full expression for $s_i^{\rm dCS}$, in the calculation of β, as a proxy for the missing $O(\chi_i^4)$ term. We checked that all our results are unaffected by using Eq. (6) or its leading order in spin expansion.

[4] We use this particular event as an example because it will allows us to compare our analytical estimate with more robust calculations later.

$\zeta_{\rm dCS,EdGB}$ can be and yet remain consistent with the event. For sufficiently high signal-to-noise ratio (SNR) ρ, the accuracy at which a parameter θ^a of the GW model can be estimated from the Cramer-Rao bound [47] $\Delta\theta^a = \sqrt{(\Gamma^{-1})^{aa}}$ where the Fisher matrix is

$$\Gamma_{ab} \equiv 4\,{\rm Re}\int_{f_{\rm min}}^{f_{\rm max}} \frac{\partial_a \tilde{h}(f)\,\partial_b \tilde{h}^*(f)}{S_n(f)}\,{\rm d}f\,, \tag{7}$$

and the asterisk stands for complex conjugation. The partial derivatives are taken with respect to the model parameters θ^i and $S_n(f)$ is the spectral noise density of the detector. The integration limits denote the lower and upper cut-off frequencies at which the detector operates. For a rough estimate, it suffices to neglect correlations between model parameters, and thus, Γ_{ab} is approximately diagonal. With this, one then finds that the variance satisfies $(\Delta\zeta)^2 = 1/\Gamma_{\zeta\zeta}$, which can be evaluated analytically assuming white noise. This matrix element is dominated by the lower limit of integration $f_{\rm min}$, and thus, one finds that

$$(\Delta\alpha_{\rm dCS,EdGB})^{1/2} \gtrsim \left(1 - \frac{3 b_{\rm dCS,EdGB}}{2}\right)^{1/8} \frac{(\pi\hat{\mathcal{M}} f_{\rm min})^{-b_{\rm dCS,EdGB}/4}}{(16\pi\hat{\rho})^{1/4}} \frac{\hat{m}}{\hat{\beta}^{1/4}_{\rm dCS,EdGB}}. \tag{8}$$

where the overhead hat stands for the best-fit values, with $\zeta_{\rm dCS,EdGB}$ set to unity in $\hat{\beta}_{\rm dCS,EdGB}$. As the individual spins χ_i could not be resolved for the events we are considering, we assign $\chi_1 = \chi_{\rm eff}(m/m_1)$ and $\chi_2 = 0$ to proceed. Using $f_{\rm min} = 10$ Hz and the SNR $\hat{\rho}$ and median values for m_1, m_2 and $\chi_{\rm eff}$, we obtain $(\Delta\alpha_{\rm dCS})^{1/2} \approx 1.1$ km and $(\Delta\alpha_{\rm EdGB})^{1/2} \approx 1.0$ km at 90% credibility. These bounds agrees well with the forecast made in [45] for dCS and in [48] for EdGB.

Fisher-estimated constraints on LIGO-Virgo data. We also perform a fully numerical calculation of the Fisher matrix, by modeling the binaries with the phenomenolgical waveform template IMRPhenomD [49, 50] We make similar assumptions for the fiducial parameters as we made to obtain the order of magnitude constraints and consider 5 GW events, GW150914, GW151226, GW170104, GW170608 and GW170814 (cf. Table III in [30]). The bounds obtained for the two most constraining events, GW151226 and GW170608. are shown in Table I and they are in good agreement with our order-of-magnitude calculation for both theories.. The Fisher-estimated constraints for dCS gravity are not shown because they violate the small coupling approximation, as we will discuss in more detail below.

Bayesian-estimated constraints on LIGO-Virgo data. The LVC recently released constraints on model-independent deviations from GR to check consistency of the GW events with GR predictions [3, 37]. The model used to capture these deviations is a variant of IMRPhenomPv2 [49, 51–53], where parameterized relative shifts in the PN coefficients of the Fourier phase of IMRPhenomPv2 are introduced, namely

$$\phi_i \to \phi_i\,(1 + \delta\phi_i)\,, \tag{9}$$

with $\delta\phi_i$ then treated as additional *free* parameters in the model. This modification is nothing but an implementation of

System	Method	$\alpha^{1/2}_{\rm EdGB}$ [km]	$\alpha^{1/2}_{\rm dCS}$ [km]
Current	Frequentist	2	10^8
GW151226	estimate	0.9	0.5
	Fisher	6.0	–
	Bayesian	5.7	–
GW170608	estimate	1.0	1.1
	Fisher	3.9	–
	Bayesian	5.6	–

TABLE I. Current constraints on EdGB and dCS gravity from low-mass x-ray binary and Solar System observations respectively, with the Fisher-estimated constraints, and Bayesian constraints using LVC (testing GR) posteriors for GW151226 and GW170608 [3, 37]

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the ppE framework [2, 54], as shown explicitly in [43], with the mapping

$$\beta_{\rm dCS} = \frac{3}{128}\,\phi_4\,\delta\phi_4\,\eta^{-4/5}\,, \tag{10a}$$

$$\beta_{\rm EdGB} = \frac{3}{128}\,\delta\phi_{-2}\,\eta^{2/5}\,, \tag{10b}$$

where ϕ_4 is the GR coefficient of the Fourier phase at 2PN order (cf. Appendix B in [50]). Since the predictions from both dCS and EdGB theories can be mapped to the ppE framework, one can propagate the LIGO-Virgo bounds on $\delta\phi_{-2}$ and $\delta\phi_4$ to constraints on the dCS and EdGB coupling constants. More specifically, we use the posteriors provided by the LVC on $\delta\phi_{-2}$ and $\delta\phi_4$ to first obtain constraints on $\beta_{\rm dCS}$ and $\beta_{\rm EdGB}$, which we then translate into constraints on $\alpha^{1/2}_{\rm dCS}$ and $\alpha^{1/2}_{\rm EdGB}$ using Eqs. (3)-(4).

The 90% constraints on $\alpha^{1/2}_{\rm dCS}$ and $\alpha^{1/2}_{\rm EdGB}$ are shown in Table I for the two most constraining events (GW151226 and GW170608) and the corresponding posterior distributions are shown in Fig. 1. The Fisher estimates, although quite close to the constraints using posteriors derived from GW data, are over-optimistic since they assume a Gaussian posterior around the peak, which we see in Fig. 1 is not correct. Moreover, since the Fisher analysis is a point estimate, it is difficult to gauge its robustness. On the other hand, a MCMC exploration of the posterior surface helps us evaluate *explicitly* how much support the posterior distributions have in the regions of validity set by the small-coupling approximation.

Constraints on quadratic gravity theories that employ the small-coupling approximation are robust only provided the former satisfy the requirements of the latter. For the systems considered, this translates to $\alpha^{1/2}_{\rm dCS,EdGB} \lesssim 5.6$ km, which is shown with vertical lines in Fig. 1. For dCS gravity (left panel of Fig. 1), more than 99% of the posterior distribution of $\alpha^{1/2}_{\rm dCS}$ lies *beyond* this region of validity for GW151226 and GW170608 and for all the other events we considered.

Consequently, *we cannot place constraints on dCS gravity with the events for which the posteriors samples obtained by LIGO-Virgo have been released.*

For EdGB, the situation is strikingly different. As one can observe in the right panel of Fig. 1, more than 90% of the posterior distribution falls *within* the requirements of the small-

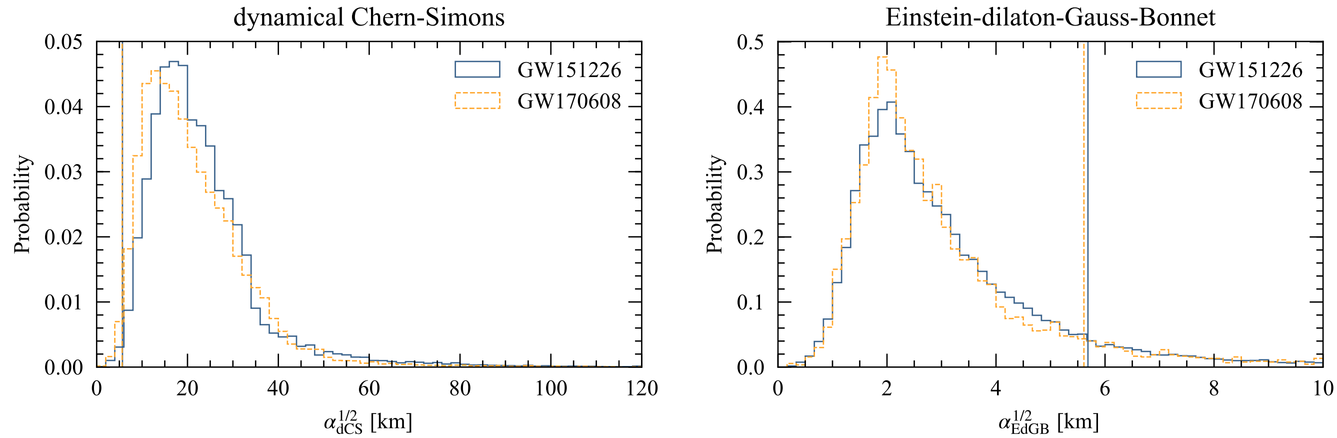

FIG. 1. Posterior distributions of $\alpha^{1/2}_{\rm dCS}$ (left panel) and $\alpha^{1/2}_{\rm EdGB}$ (right panel) obtained using GW151226 and GW170608. For the GW events shown in both panels, $m_2/M_\odot = 7.7^{+2.2}_{-2.6}$ (GW151226) and $m_2/M_\odot = 7.6^{+1.3}_{-2.1}$ (GW170104) at 90% credibility. This implies that the small-coupling approximation is valid only when $\alpha^{1/2}_{\rm dCS,EdGB} \lesssim 5.6$, shown as vertical lines in the plots. For dCS gravity (left-panel) we see that most of the support of the posterior distributions of these two events lays *passed* the bounds set by the small-coupling approximation. Consequently, one cannot place constraints on $\alpha^{1/2}_{\rm dCS}$ with these two events. For EdGB gravity (right-panel) most (> 90%) of the posteriors' support lays *within* the bound, therefore allowing us to constrain the theory with these two events. For the other three events, which contain a large m_2 ($\gtrsim 13\,M_\odot$) BH [30], the vertical lines are pushed towards the left, leaving most of the posterior's support outside the small-coupling approximation bound. We stress that the location of the peaks in the posteriors *are not an indication of a deviation from GR*. Instead, as detailed in the main text, the lack of support at zero is an artifact of the choice of the sampling variable $\delta\phi_i$.

coupling approximation for the GW151226 and GW170608 events. *This implies that a 90% bound of $\alpha^{1/2}_{EdGB} \lesssim 5.6$ km is statistically meaningful and can be placed on EdGB gravity using these two events.* This is not the case for the other events (GW150914, GW170104 and GW170814), for which constraints would violate the small coupling approximation.

We emphasize that the location of the peaks in the posteriors of Fig. 1 *do not indicate a deviation from GR*. Rather, the lack of support at zero is an artifact of the choice of the sampling variable $\delta\phi_i$ and its functional dependence on $\alpha^{1/2}_{\rm dCS,EdGB}$. A uniform prior in $\delta\phi_i$ translates to a non-uniform prior on $\alpha^{1/2}_{\rm dCS/EdGB}$ with almost no support near $\alpha^{1/2}_{\rm dCS,EdGB} = 0$. One can reweight the $\alpha^{1/2}_{\rm dCS/EdGB}$ posteriors with the priors to obtain better estimates, albeit at the cost of introducing binning errors close to $\alpha^{1/2}_{\rm dCS/EdGB} = 0$.

Alternatively, this issue could be avoided by sampling directly in $\alpha_{\rm dCS,EdGB}$ instead of in the generic parameter $\delta\phi_i$. We expect that this would shift our 90% bound to the left, thereby improving our bounds, and hence our constraints are *conservative and robust* to changes in the sampling variable.

The fact that GW151226 and GW170608 have more constraining power than their cousins is not surprising. These two events were produced by binaries in which the secondary BH had the lowest mass ($m_2 \approx 7M_\odot$) of all events in the catalog. Quadratic gravity theories introduce new length scales, and deviations from GR are thus proportional to the curvature scale, which for BH binaries scales inversely with the square of the lowest mass, m_2^{-2}. Hence one can expect the largest deviations for GW151226 and GW170608 and thus, the strongest constraints. In dCS gravity, the modifications enter at 2PN order, and thus, they are much more weakly constrained than the EdGB modifications, which enter at -1PN order. This deterioration in the constraint then implies that a large percentage of the posterior weight is outside the regime of validity of the small coupling approximation, rendering the constraint invalid.

Fundamental physics implications. Our results dramatically constrain EdGB gravity, essentially confining deviations from GR due to this theory down to the horizon scale of stellar mass BHs. These constraints are competitive with those obtained in [38] ($\alpha^{1/2}_{\rm EdGB} \lesssim 2$ km at 95% confidence level) from the orbital decay on the BH low-mass x-ray binary A0620-00, which probes the theory in a different energy scale. Our constraints, however, have the advantage of being robust to astrophysical systematics, unlike those placed in [38] which require assumptions about the mass transfer efficiency and the specific angular momentum carried by stellar winds.

The constraint we have placed on (decoupled) EdGB gravity is stringent, limiting this type of quantum-inspired violation of the strong equivalence principle, the strength of the scalar monopole charge carried by black holes, and the possibility of using EdGB gravity to explain the late-time acceleration of the universe. However, our constraints do not directly apply to other functional couplings between the Gauss-Bonnet density and a scalar field. For example, in models where BHs acquire charges through spontaneous scalarization [55–59], BHs are identical to GR unless they fall within certain mass intervals (at fixed coupling parameter of the theory) and thereby can (in principle) mimic binary BH mergers in GR.

Our results also have important implications for restricting parity-violation in the gravitational interaction. Recently, a broad class of ghost-free, parity-violating theories, which in four-dimensions requires the presence of a massless scalar field, was presented [60]. In [61–63], these theories were tested against the exquisite constraint obtained on the speed of GW propagation from the binary NS event GW170817/GRB 170817A, which estimated that $c_{\rm GW}$ is the same as the speed of light in vacuum to one part in 10^{15}. dCS gravity is the only ghost-free, parity-violating theory in four-dimensions that is consistent with this constraint [61, 64]. Therefore, our results combined with those by [61], leave dCS as the single subclass of the broad set of parity-violating theories of gravity which remains consistent with observations.

Future work could focus on constraints on other modified theories within the broad class of quadratic gravity models [12]. Alternatively, one could include GW amplitude corrections due to EdGB and dCS gravity to determine whether GW constraints become stronger [44]. Finally, one could study how well future ground-based and space-based detectors could constraint quadratic gravity theories, or the type of system that would be ideal to place constraints the hitherto evasive dCS gravity.

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