Test of GR in O3

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Tests of General Relativity with GWTC-3

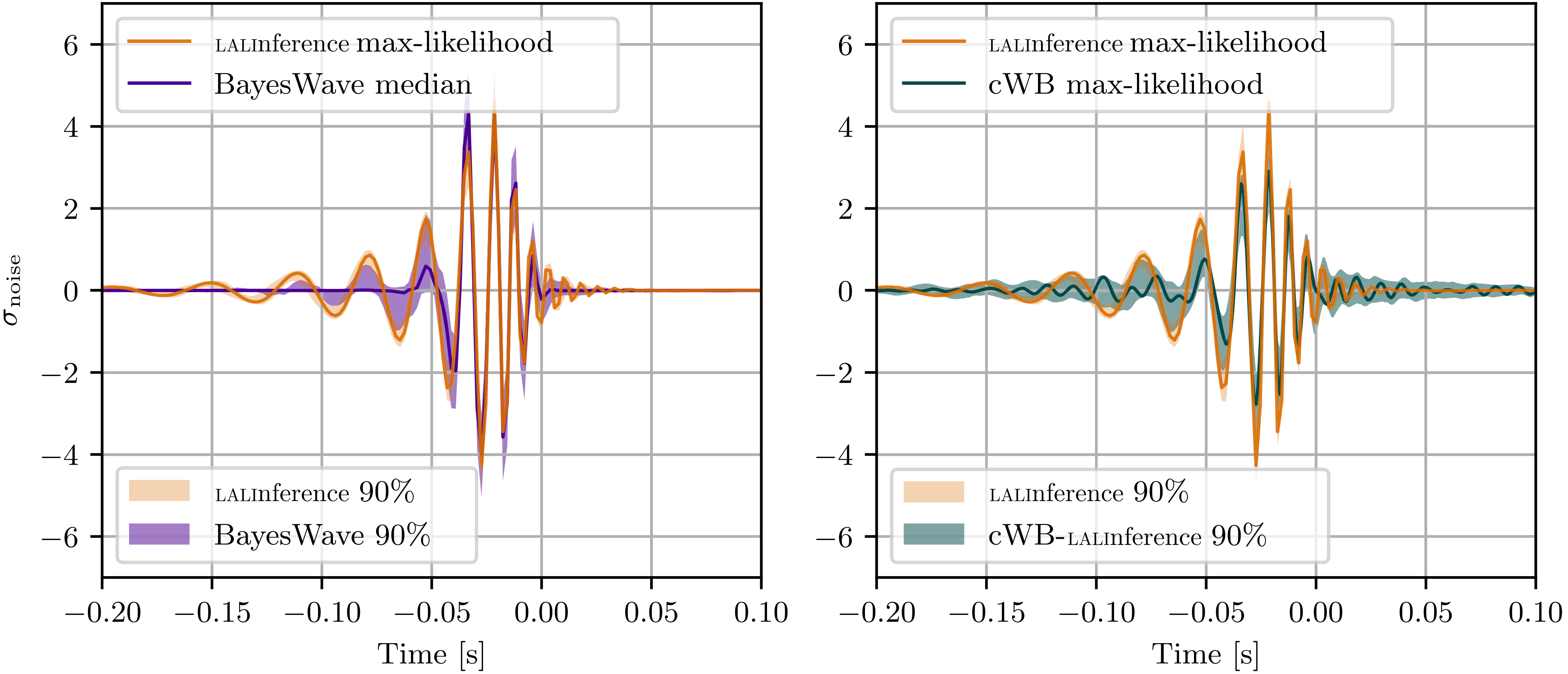
The ever-increasing number of detections of gravitational waves from compact binaries by the Advanced LIGO and Advanced Virgo detectors allows us to perform ever-more sensitive tests of general relativity (GR) in the dynamical and strong-field regime of gravity. We perform a suite of tests of GR using the compact binary signals observed during the second half of the third observing run of those detectors. We restrict our analysis to the 15 confident signals that have false alarm rates $\leq 10^{-3}\,\mathrm{yr}^{-1}$. In addition to signals consistent with binary black hole mergers, the new events include GW200115_042309, a signal consistent with a neutron star–black hole merger. We find the residual power, after subtracting the best fit waveform from the data for each event, to be consistent with the detector noise. Additionally, we find all the post-Newtonian deformation coefficients to be consistent with the predictions from GR, with an improvement by a factor of ~ 2 in the -1PN parameter. We also find that the spin-induced quadrupole moments of the binary black hole constituents are consistent with those of Kerr black holes in GR. We find no evidence for dispersion of gravitational waves, non-GR modes of polarization, or post-merger echoes in the events that were analyzed. We update the bound on the mass of the graviton, at 90% credibility, to $m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2$. The final mass and final spin as inferred from the pre-merger and post-merger parts of the waveform are consistent with each other. The studies of the properties of the remnant black holes, including deviations of the quasi-normal mode frequencies and damping times, show consistency with the predictions of GR. In addition to considering signals individually, we also combine results from the catalog of gravitational waves signals to calculate more precise population constraints. We find no evidence in support of physics beyond general relativity.

TABLE I. Summary of methods and results. This table summarizes the names of the tests performed, the corresponding sections, the parameters involved in the test, and the improvement with regard to our previous analysis. The analyses performed are: RT = residuals test; IMR = inspiral–merger–ringdown consistency test; PAR = parametrized tests of GW generation; SIM = spin-induced moments; MDR = modified GW dispersion relation; POL = polarization content; RD = ringdown; ECH = echoes searches. The last column provides the *approximate* improvement in the bounds over the previous analyses reported in [11]. This is defined as $X_{\text{GWTC-2}}/X_{\text{GWTC-3}}$, where X denotes the width of the 90% credible interval for the parameters for each test, using the combined results on all events considered. For the MDR test, some of the bounds have worsened in comparison to GWTC-2. See the corresponding section for details. Note that the high improvement factor for pSEOB is due to the larger number of events from GWTC-2 analysed here compared to [11].

Test	Section	Quantity	Parameter	Improvement w.r.t. GWTC-2
RT	IV A	p-value	p-value	Not applicable
IMR	IV B	Fractional deviation in remnant mass and spin	$\left\{\frac{\Delta M_f}{\bar{M}_f}, \frac{\Delta \chi_f}{\bar{\chi}_f}\right\}$	1.1–1.8
PAR	V A	PN deformation parameter	$\delta\hat{\phi}_k$	1.2–3.1
SIM	V B	Deformation in spin-induced multipole parameter	$\delta\kappa_s$	1.1–1.2
MDR	VI	Magnitude of dispersion	$\lvert A_\alpha \rvert$	0.8–2.1
POL	VII	Bayes Factors between different polarization hypotheses	$\log_{10} \mathcal{B}^{\text{X}}_{\text{T}}$	New Test
RD	VIII A 1	Fractional deviations in frequency (pyRing)	$\delta\hat{f}_{221}$	1.1
	VIII A 2	Fractional deviations in frequency and damping time (pSEOB)	$\{\delta\hat{\tau}_{220}, \delta\hat{f}_{220}\}$	1.7–5.5
ECH	VIII B	Signal-to-noise Bayes Factor	$\log_{10} \mathcal{B}_{\text{S/N}}$	New Test

TABLE II. List of O3b events considered in this paper. The first block of columns gives the names of the events and lists the instruments (LIGO **H**anford, LIGO **L**ivingston, **V**irgo) involved in each detection, as well as some relevant properties obtained assuming GR: luminosity distance $D_{\rm L}$, redshifted total mass $(1+z)M$, redshifted chirp mass $(1+z)\mathcal{M}$, redshifted final mass $(1+z)M_{\rm f}$, dimensionless final spin $\chi_{\rm f} = c|\vec{S}_{\rm f}|/(GM_{\rm f}^2)$, and network signal-to-noise ratio SNR. Reported quantities correspond to the median and 90% symmetric credible intervals, as computed in Table IV in GWTC-3 [81]. The final mass and final spin quantities are inferred from analysis of the entire signal and are for the remnant long after the coalescence and ringdown are complete, as described in [99]. The last block of columns indicates which analyses are performed on a given event according to the selection criteria in Sec. II: RT = residuals test (Sec. IV A); IMR = inspiral–merger–ringdown consistency test (Sec. IV B); PAR = parametrized tests of GW generation (Sec. V A); SIM = spin-induced moments (Sec. V B); MDR = modified GW dispersion relation (Sec. VI); POL = polarization content (Sec. VII); RD = ringdown (Sec. VIII A); ECH = echoes searches (Sec. VIII B).

Event	Inst.	Properties					SNR	Tests performed							
		$D_{\rm L}$ [Gpc]	$(1+z)M$ [$M_\odot$]	$(1+z)\mathcal{M}$ [$M_\odot$]	$(1+z)M_{\rm f}$ [$M_\odot$]	$\chi_{\rm f}$		RT	IMR	PAR	SIM	MDR	POL	RD	ECH
GW191109_010717	HL	$1.29^{+1.13}_{-0.65}$	140^{+21}_{-17}	$60.1^{+9.8}_{-9.3}$	135^{+19}_{-15}	$0.61^{+0.18}_{-0.19}$	$17.3^{+0.5}_{-0.5}$	✓	–	–	–	–	✓	✓	✓
GW191129_134029	HL	$0.79^{+0.26}_{-0.33}$	$20.10^{+2.94}_{-0.64}$	$8.49^{+0.06}_{-0.05}$	$19.19^{+3.07}_{-0.67}$	$0.69^{+0.03}_{-0.05}$	$13.1^{+0.2}_{-0.3}$	✓	–	✓	✓	✓	–	–	✓
GW191204_171526	HL	$0.65^{+0.19}_{-0.25}$	$22.74^{+1.94}_{-0.48}$	$9.70^{+0.05}_{-0.05}$	$21.60^{+2.05}_{-0.50}$	$0.73^{+0.03}_{-0.03}$	$17.5^{+0.2}_{-0.2}$	✓	–	✓	✓	✓	✓	–	✓
GW191215_223052	HLV	$1.93^{+0.89}_{-0.86}$	$58.4^{+4.8}_{-3.7}$	$24.9^{+1.5}_{-1.4}$	$55.8^{+4.8}_{-3.3}$	$0.68^{+0.07}_{-0.07}$	$11.2^{+0.3}_{-0.4}$	✓	–	–	–	✓	✓	–	✓
GW191216_213338	HV	$0.34^{+0.12}_{-0.13}$	$21.17^{+2.93}_{-0.66}$	$8.94^{+0.05}_{-0.05}$	$20.18^{+3.06}_{-0.70}$	$0.70^{+0.03}_{-0.04}$	$18.6^{+0.2}_{-0.2}$	✓	–	✓	✓	✓	✓	–	✓
GW191222_033537	HL	$3.0^{+1.7}_{-1.7}$	119^{+16}_{-13}	$51.0^{+7.2}_{-6.5}$	114^{+14}_{-12}	$0.67^{+0.08}_{-0.11}$	$12.5^{+0.2}_{-0.3}$	✓	–	–	–	✓	✓	✓	✓
GW200115_042309	HLV	$0.29^{+0.15}_{-0.10}$	$7.8^{+1.9}_{-1.8}$	$2.58^{+0.01}_{-0.01}$	$7.7^{+1.9}_{-1.8}$	$0.42^{+0.09}_{-0.05}$	$11.3^{+0.3}_{-0.5}$	✓	–	✓	–	–	–	–	✓
GW200129_065458	HLV	$0.90^{+0.29}_{-0.38}$	$74.6^{+4.5}_{-3.8}$	$32.1^{+1.8}_{-2.6}$	$70.9^{+4.2}_{-3.4}$	$0.73^{+0.06}_{-0.05}$	$26.8^{+0.2}_{-0.2}$	✓	✓	✓	✓	✓	✓	✓	✓
GW200202_154313	HLV	$0.41^{+0.15}_{-0.16}$	$19.01^{+1.99}_{-0.34}$	$8.15^{+0.05}_{-0.05}$	$18.12^{+2.09}_{-0.35}$	$0.69^{+0.03}_{-0.04}$	$10.8^{+0.2}_{-0.4}$	✓	–	✓	–	✓	–	–	✓
GW200208_130117	HLV	$2.23^{+1.00}_{-0.85}$	91^{+11}_{-10}	$38.8^{+5.2}_{-4.8}$	$87.5^{+10.3}_{-9.1}$	$0.66^{+0.09}_{-0.13}$	$10.8^{+0.3}_{-0.4}$	✓	✓	–	–	✓	✓	–	✓
GW200219_094415	HLV	$3.4^{+1.7}_{-1.5}$	103^{+14}_{-12}	$43.7^{+6.3}_{-6.2}$	98^{+13}_{-11}	$0.66^{+0.10}_{-0.13}$	$10.7^{+0.3}_{-0.5}$	✓	–	–	–	✓	✓	–	✓
GW200224_222234	HLV	$1.71^{+0.49}_{-0.64}$	$94.9^{+8.3}_{-7.2}$	$40.9^{+3.5}_{-3.8}$	$90.2^{+7.5}_{-6.4}$	$0.73^{+0.07}_{-0.07}$	$20.0^{+0.2}_{-0.2}$	✓	✓	–	–	✓	✓	✓	✓
GW200225_060421	HL	$1.15^{+0.51}_{-0.53}$	$41.2^{+3.0}_{-4.0}$	$17.65^{+0.98}_{-1.97}$	$39.4^{+2.9}_{-3.6}$	$0.66^{+0.07}_{-0.13}$	$12.5^{+0.3}_{-0.4}$	✓	✓	✓	✓	✓	✓	–	✓
GW200311_115853	HLV	$1.17^{+0.28}_{-0.40}$	$75.9^{+6.2}_{-5.7}$	$32.7^{+2.7}_{-2.8}$	$72.4^{+5.6}_{-5.1}$	$0.69^{+0.07}_{-0.08}$	$17.8^{+0.2}_{-0.2}$	✓	✓	✓	–	✓	✓	✓	✓
GW200316_215756	HLV	$1.12^{+0.47}_{-0.44}$	$25.5^{+8.7}_{-1.1}$	$10.68^{+0.12}_{-0.12}$	$24.3^{+9.0}_{-1.1}$	$0.70^{+0.04}_{-0.04}$	$10.3^{+0.4}_{-0.7}$	✓	–	✓	✓	–	–	–	✓



LALInference max-likelihood
BayesWave median
LALInference 90%
BayesWave 90%
σ_{noise}
Time [s]
LALInference max-likelihood
cWB max-likelihood
LALInference 90%
cWB-LALInference 90%
Time [s]