

Erratum: Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog **[Phys. Rev. D 103, 122002 (2021)]**

R. Abbott *et al.*

(LIGO Scientific and Virgo Collaborations)*



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A reanalysis of O3a data produced a discrepancy between the value of the graviton-mass upper limit produced in the paper and that in the reanalysis. Furthermore, the bound in the paper is inconsistent with the paper's A_0 posterior. The discrepancy was traced to an error in the kernel density estimation code in connection to the resampling procedure. This error affects only the value of the graviton-mass upper limit. As a result, the correct upper limit for the graviton mass should be $m_g \leq 3.09 \times 10^{-23} \text{ eV}/c^2$, instead of $1.76 \times 10^{-23} \text{ eV}/c^2$. This represents an improvement over [1] by a factor of 1.5, instead of 2.7. This measurement is comparable to the Solar System bound of $3.16 \times 10^{-23} \text{ eV}/c^2$ [2], instead of 1.8 times more stringent as stated in the paper. We thank Tomasz Baka for noticing the bug in our calculation of the bound on the graviton mass and suggesting a correction to the code.

An error has been discovered in the results of the parametrized test of gravitational-wave generation with the SEOBNRv4_ROM waveform model. For this waveform model, a flexible theory-independent method [3] is used, including the spin dependence in the normalization of the post-Newtonian (PN) deviation parameters

$$\{\delta\hat{\varphi}_3, \delta\hat{\varphi}_4, \delta\hat{\varphi}_{5l}, \delta\hat{\varphi}_6, \delta\hat{\varphi}_7\}. \quad (1)$$

The posteriors of these deviation parameters for SEOBNRv4_ROM are reweighted to the normalization to the spin-independent part of the PN coefficients used in the article, where the convention $\varphi_i \rightarrow (1 + \delta\hat{\varphi}_i)\varphi_i^{\text{NS}} + \varphi_i^{\text{S}}$ is used. This erratum corrects an error in the implementation of the reweighting and presents results following reanalysis. The parameters $\{\delta\hat{\varphi}_{-2}, \delta\hat{\varphi}_0, \delta\hat{\varphi}_1, \delta\hat{\varphi}_2, \delta\hat{\varphi}_{6l}\}$ are not affected, but slight statistical fluctuations are present in the reanalysis of their population-marginalized posteriors. As a result, Figs. 5–8 and 19 replace Figs. 5–8 and 19 in the original article, respectively. Moreover, Table VI in this erratum replaces Table VI in the original article.

Additionally, due to an oversight, there is an error in Sec. VA and Appendix C in the description of analyses performed in order to mitigate waveform systematics. It is stated that GW190814 was analyzed with IMRPhenomPv3HM and SEOBNRv4HM_ROM waveform models, and that GW190412 was analyzed with IMRPhenomPv3HM. However, both GW190412 and GW190814 were analyzed with IMRPhenomPv3HM and SEOBNRv4HM_ROM, and the reported results use both waveform models.

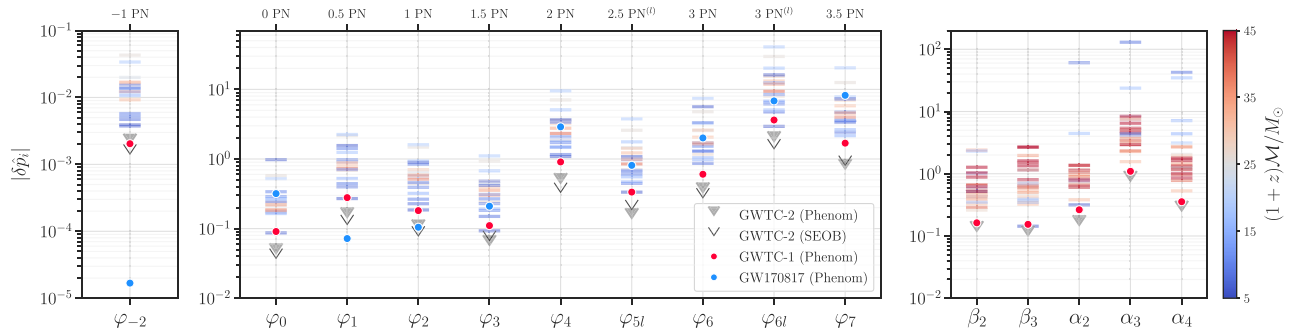


FIG. 5. Update Fig. 5 in the original article.

*Full author list is given at the end of the original article.

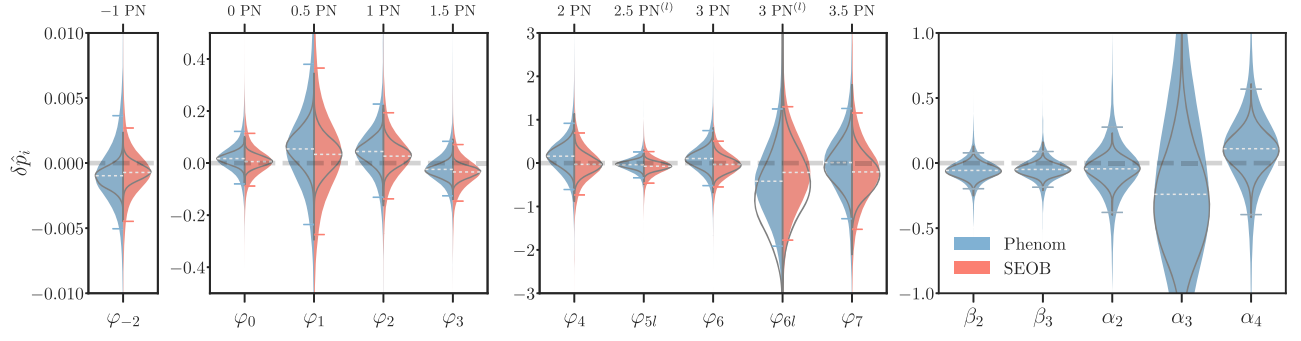


FIG. 6. Update Fig. 6 in the original article.

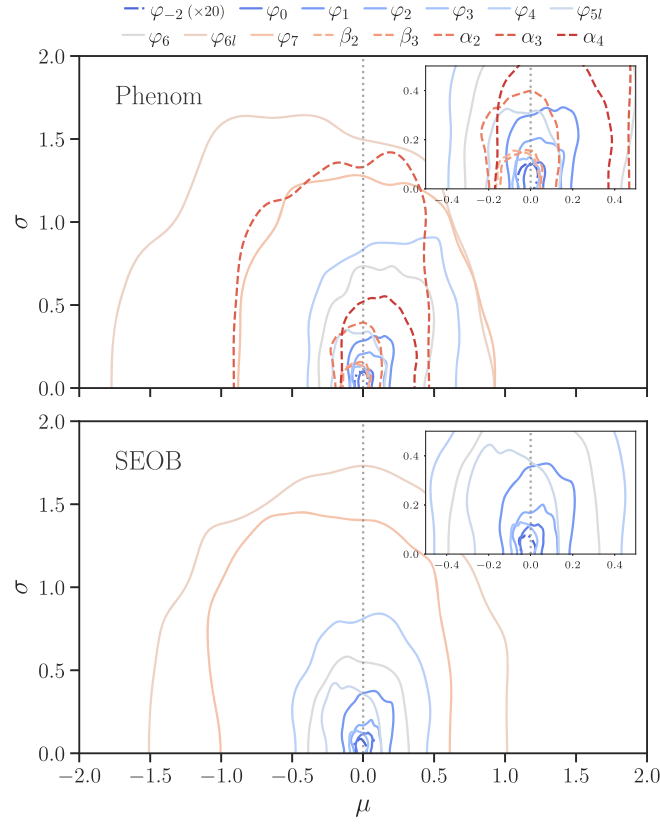


FIG. 7. Update Fig. 7 in the original article.

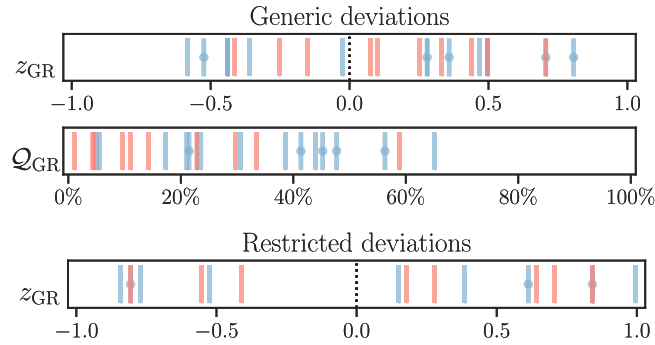


FIG. 8. Update Fig. 8 in the original article.

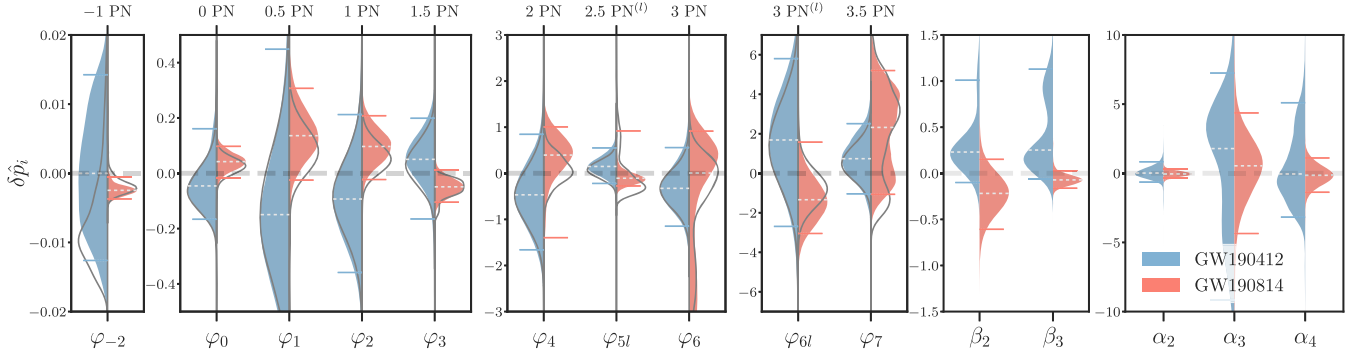


FIG. 19. Update Fig. 19 in the original article.

Two implementation oversights were discovered in the `pyRing` analysis presented in the original article. The first one concerns analyses using the Kerr_{HM} waveform model, where the start time of the analysis t_{start} was mistakenly used as the reference time for the waveforms, instead of the peak time t_0 of the strain ($h_+^2 + h_\times^2$), as described in the original article. The second one concerns all `pyRing` analyses where there could be an erroneous shift in the time axis of the strain data during the construction of the likelihood. The impacts due to these are fortunately minimal. As a result, the fractional deviation away from the Kerr frequency for the 221 mode is constrained to $\delta\hat{f}_{221} = 0.02^{+0.29}_{-0.33}$, instead of $\delta\hat{f}_{221} = 0.04^{+0.27}_{-0.32}$. The catalog-combined log odds ratio should be -0.61 , instead of -0.70 as stated in the original article. Fits with Kerr_{HM} templates start at $15GM_{\text{f}}(1+z)/c^3$ after t_0 , and not $10GM_{\text{f}}(1+z)/c^3$. For GW150914, the

TABLE VI. Updated Table VI in the original article.

$\hat{p}_i$	WF	General				Restricted	
		μ	σ	$\delta\hat{p}_i$	Q_{GR} (%)	$\delta\hat{p}_i$	Q_{GR} (%)
φ_{-2} [$\times 20$]	P	$-0.02^{+0.04}_{-0.03}$	< 0.08	$-0.02^{+0.09}_{-0.08}$	68	$-0.02^{+0.02}_{-0.02}$	93
	S	$-0.01^{+0.03}_{-0.03}$	< 0.07	$-0.01^{+0.07}_{-0.08}$	69	$-0.01^{+0.02}_{-0.02}$	86
φ_0	P	$0.02^{+0.05}_{-0.04}$	< 0.09	$0.02^{+0.10}_{-0.10}$	33	$0.02^{+0.04}_{-0.03}$	20
	S	$0.01^{+0.05}_{-0.04}$	< 0.10	$0.01^{+0.11}_{-0.09}$	44	$0.01^{+0.03}_{-0.04}$	34
φ_1	P	$0.06^{+0.14}_{-0.13}$	< 0.27	$0.05^{+0.32}_{-0.29}$	33	$0.07^{+0.10}_{-0.11}$	15
	S	$0.03^{+0.14}_{-0.14}$	< 0.29	$0.03^{+0.33}_{-0.31}$	40	$0.03^{+0.11}_{-0.10}$	29
φ_2	P	$0.05^{+0.09}_{-0.09}$	< 0.17	$0.04^{+0.18}_{-0.18}$	28	$0.04^{+0.07}_{-0.07}$	14
	S	$0.03^{+0.08}_{-0.08}$	< 0.15	$0.03^{+0.17}_{-0.16}$	34	$0.03^{+0.06}_{-0.06}$	21
φ_3	P	$-0.02^{+0.05}_{-0.05}$	< 0.10	$-0.02^{+0.11}_{-0.10}$	69	$-0.03^{+0.04}_{-0.04}$	90
	S	$-0.03^{+0.05}_{-0.05}$	< 0.10	$-0.03^{+0.11}_{-0.11}$	76	$-0.03^{+0.02}_{-0.04}$	96
φ_4	P	$0.14^{+0.44}_{-0.41}$	< 0.72	$0.16^{+0.76}_{-0.77}$	33	$0.17^{+0.36}_{-0.36}$	22
	S	$-0.01^{+0.40}_{-0.36}$	< 0.65	$-0.03^{+0.72}_{-0.70}$	53	$-0.05^{+0.33}_{-0.30}$	57
φ_{5l}	P	$-0.03^{+0.15}_{-0.15}$	< 0.27	$-0.04^{+0.29}_{-0.30}$	61	$-0.02^{+0.12}_{-0.15}$	65
	S	$-0.08^{+0.16}_{-0.17}$	< 0.33	$-0.07^{+0.34}_{-0.39}$	67	$-0.08^{+0.15}_{-0.15}$	80
φ_6	P	$0.10^{+0.32}_{-0.32}$	< 0.56	$0.10^{+0.64}_{-0.62}$	36	$0.08^{+0.30}_{-0.27}$	30
	S	$-0.04^{+0.30}_{-0.27}$	< 0.47	$-0.03^{+0.54}_{-0.52}$	54	$-0.05^{+0.27}_{-0.27}$	61
φ_{6l}	P	$-0.41^{+1.07}_{-1.01}$	< 1.27	$-0.42^{+1.67}_{-1.50}$	69	$-0.80^{+1.32}_{-1.29}$	84
	S	$-0.22^{+0.96}_{-1.01}$	< 1.31	$-0.22^{+1.52}_{-1.56}$	60	$-0.47^{+1.17}_{-1.17}$	74
φ_7	P	$0.02^{+0.70}_{-0.75}$	< 1.09	$0.01^{+1.25}_{-1.29}$	49	$-0.08^{+0.75}_{-0.66}$	56
	S	$-0.23^{+0.70}_{-0.68}$	< 1.16	$-0.20^{+1.36}_{-1.32}$	63	$-0.29^{+0.63}_{-0.66}$	76
β_2	P	$-0.06^{+0.07}_{-0.08}$	< 0.12	$-0.06^{+0.14}_{-0.14}$	79	$-0.07^{+0.08}_{-0.07}$	90
β_3	P	$-0.05^{+0.08}_{-0.08}$	< 0.12	$-0.05^{+0.14}_{-0.14}$	76	$-0.05^{+0.07}_{-0.06}$	90
α_2	P	$-0.04^{+0.13}_{-0.15}$	< 0.30	$-0.04^{+0.32}_{-0.33}$	61	$-0.04^{+0.11}_{-0.13}$	73
α_3	P	$-0.23^{+0.65}_{-0.56}$	< 1.10	$-0.24^{+1.36}_{-1.19}$	64	$-0.32^{+0.62}_{-0.55}$	80
α_4	P	$0.11^{+0.22}_{-0.23}$	< 0.44	$0.11^{+0.46}_{-0.51}$	30	$0.10^{+0.19}_{-0.22}$	21

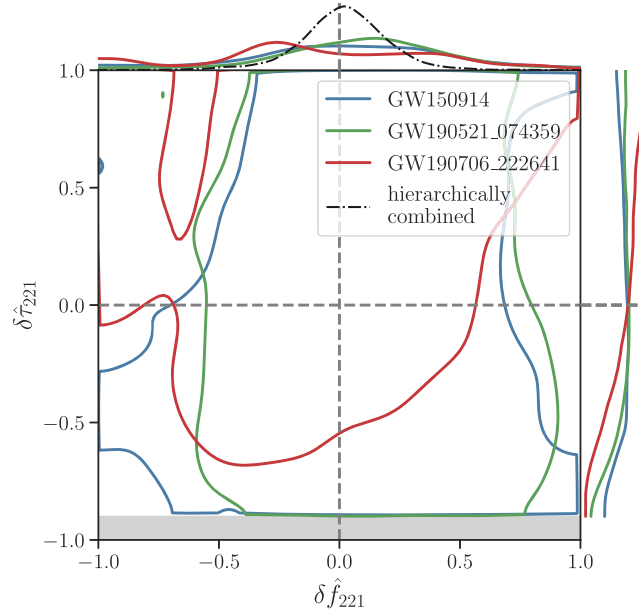


FIG. 13. Update Fig. 13 in the original article.

TABLE VIII. The median, and symmetric 90%-credible intervals, of the redshifted final mass and final spin, inferred from the full IMR analysis (IMR) and the pyRing analysis with three different waveform models (Kerr₂₂₀, Kerr₂₂₁, and Kerr_{HM}). We quantify the contribution of the HMs using log Bayes factors $\log_{10} \mathcal{B}_{220}^{\text{HM}}$, where a positive value reflects the presence of HMs in the data. Similarly, we quantify the contribution of the first overtone using log Bayes factors $\log_{10} \mathcal{B}_{220}^{221}$, where a positive value reflects the presence of the first overtone in the data. We also quantify the level of agreement with GR for each event using log odds ratios $\log_{10} \mathcal{O}_{\text{GR}}^{\text{modGR}}$ comparing the generic modified-GR hypothesis with GR. The catalog-combined log odds ratio is slightly negative (-0.61), and the log odds ratios for individual events are also inconclusive, showing no evidence that the Kerr metric is insufficient.

Event	Redshifted final mass				Final spin				Higher modes		Overtones	
	$(1+z)M_{\text{f}}[M_{\odot}]$				χ_{f}				$\log_{10} \mathcal{B}_{220}^{\text{HM}}$		$\log_{10} \mathcal{B}_{220}^{221}$	
	IMR	Kerr ₂₂₀	Kerr ₂₂₁	Kerr _{HM}	IMR	Kerr ₂₂₀	Kerr ₂₂₁	Kerr _{HM}	$\log_{10} \mathcal{B}_{220}^{\text{HM}}$	$\log_{10} \mathcal{B}_{220}^{221}$	$\log_{10} \mathcal{O}_{\text{GR}}^{\text{modGR}}$	
GW150914	68.8 ^{+3.6} _{-3.1}	59.5 ^{+19.7} _{-10.6}	67.3 ^{+15.8} _{-13.3}	220.2 ^{+180.4} _{-144.5}	0.69 ^{+0.05} _{-0.04}	0.44 ^{+0.39} _{-0.39}	0.61 ^{+0.24} _{-0.43}	0.60 ^{+0.23} _{-0.47}	0.01	0.15	-0.22	
GW170104	58.5 ^{+4.6} _{-4.1}	61.8 ^{+20.8} _{-14.1}	61.5 ^{+20.0} _{-12.8}	214.1 ^{+179.9} _{-126.7}	0.66 ^{+0.08} _{-0.11}	0.27 ^{+0.42} _{-0.24}	0.47 ^{+0.41} _{-0.41}	0.58 ^{+0.25} _{-0.48}	0.05	-0.66	-0.11	
GW170814	59.7 ^{+3.0} _{-2.3}	74.1 ^{+326.9} _{-58.1}	56.2 ^{+41.2} _{-13.2}	188.6 ^{+126.5} _{-120.9}	0.72 ^{+0.07} _{-0.05}	0.52 ^{+0.42} _{-0.47}	0.54 ^{+0.37} _{-0.47}	0.61 ^{+0.23} _{-0.53}	0.01	-0.69	-0.05	
GW170823	88.8 ^{+11.2} _{-10.2}	73.5 ^{+29.1} _{-16.5}	83.6 ^{+40.6} _{-16.1}	136.5 ^{+137.9} _{-69.7}	0.72 ^{+0.09} _{-0.12}	0.47 ^{+0.39} _{-0.41}	0.45 ^{+0.45} _{-0.40}	0.65 ^{+0.21} _{-0.54}	0.04	-1.17	0.07	
GW190408_181802	53.0 ^{+3.2} _{-3.4}	201.7 ^{+280.5} _{-188.4}	51.0 ^{+26.0} _{-14.6}	122.0 ^{+164.2} _{-76.1}	0.67 ^{+0.06} _{-0.07}	0.42 ^{+0.49} _{-0.38}	0.51 ^{+0.39} _{-0.45}	0.55 ^{+0.29} _{-0.56}	0.02	-1.66	0.00	
GW190512_180714	43.5 ^{+4.0} _{-2.8}	72.5 ^{+58.4} _{-44.5}	41.3 ^{+60.9} _{-13.4}	108.1 ^{+107.2} _{-35.0}	0.65 ^{+0.07} _{-0.07}	0.53 ^{+0.40} _{-0.48}	0.46 ^{+0.39} _{-0.41}	0.70 ^{+0.16} _{-0.51}	0.01	-1.00	-0.10	
GW190513_205428	70.6 ^{+11.5} _{-6.7}	62.7 ^{+364.0} _{-36.3}	71.4 ^{+23.5} _{-12.5}	129.3 ^{+159.1} _{-75.2}	0.68 ^{+0.14} _{-0.12}	0.41 ^{+0.46} _{-0.37}	0.34 ^{+0.44} _{-0.31}	0.57 ^{+0.27} _{-0.55}	0.05	-0.89	-0.10	
GW190519_153544	146.8 ^{+14.7} _{-15.4}	124.9 ^{+37.9} _{-26.1}	128.4 ^{+31.9} _{-25.5}	181.8 ^{+59.2} _{-49.0}	0.79 ^{+0.07} _{-0.13}	0.52 ^{+0.33} _{-0.45}	0.56 ^{+0.26} _{-0.42}	0.72 ^{+0.14} _{-0.31}	0.11	-0.03	-0.27	
GW190521	256.6 ^{+36.6} _{-30.4}	292.5 ^{+50.4} _{-58.9}	296.9 ^{+41.4} _{-40.2}	303.4 ^{+29.9} _{-41.6}	0.71 ^{+0.12} _{-0.16}	0.79 ^{+0.12} _{-0.31}	0.82 ^{+0.09} _{-0.16}	0.81 ^{+0.07} _{-0.17}	0.28	-0.06	-0.37	
GW190521_074359	88.0 ^{+4.3} _{-4.8}	87.7 ^{+24.4} _{-20.5}	90.4 ^{+16.8} _{-16.6}	101.8 ^{+147.9} _{-29.2}	0.72 ^{+0.05} _{-0.07}	0.66 ^{+0.25} _{-0.53}	0.72 ^{+0.16} _{-0.33}	0.77 ^{+0.11} _{-0.54}	0.04	0.04	-0.35	
GW190602_175927	163.8 ^{+20.7} _{-18.3}	151.2 ^{+67.9} _{-29.0}	173.2 ^{+50.1} _{-37.6}	258.7 ^{+53.9} _{-70.7}	0.70 ^{+0.10} _{-0.14}	0.33 ^{+0.41} _{-0.30}	0.58 ^{+0.25} _{-0.42}	0.74 ^{+0.12} _{-0.28}	0.03	-0.87	-0.13	
GW190706_222641	171.1 ^{+20.0} _{-23.7}	142.3 ^{+53.6} _{-29.9}	153.1 ^{+34.2} _{-28.6}	209.9 ^{+151.1} _{-129.0}	0.78 ^{+0.09} _{-0.07}	0.46 ^{+0.40} _{-0.41}	0.58 ^{+0.26} _{-0.43}	0.63 ^{+0.22} _{-0.49}	0.03	0.04	-0.36	
GW190708_232457	34.4 ^{+2.7} _{-2.7}	387.3 ^{+104.4} _{-370.2}	35.1 ^{+30.9} _{-21.3}	105.8 ^{+166.6} _{-61.0}	0.69 ^{+0.04} _{-0.04}	0.32 ^{+0.54} _{-0.29}	0.37 ^{+0.47} _{-0.34}	0.59 ^{+0.25} _{-0.58}	0.01	-1.25	0.07	
GW190727_060333	99.2 ^{+10.7} _{-9.8}	84.8 ^{+47.8} _{-72.2}	98.6 ^{+34.7} _{-22.2}	108.9 ^{+120.0} _{-65.6}	0.73 ^{+0.10} _{-0.10}	0.59 ^{+0.34} _{-0.52}	0.63 ^{+0.30} _{-0.54}	0.60 ^{+0.24} _{-0.54}	0.02	-2.08	-0.20	
GW190828_063405	75.7 ^{+6.0} _{-5.2}	82.6 ^{+39.0} _{-32.4}	82.3 ^{+24.3} _{-24.6}	102.5 ^{+150.3} _{-45.9}	0.75 ^{+0.06} _{-0.07}	0.85 ^{+0.13} _{-0.67}	0.84 ^{+0.13} _{-0.62}	0.69 ^{+0.17} _{-0.60}	0.05	-1.51	-0.24	
GW190910_112807	97.0 ^{+9.3} _{-7.1}	118.3 ^{+28.6} _{-32.2}	107.4 ^{+31.9} _{-27.0}	154.0 ^{+98.9} _{-43.2}	0.70 ^{+0.08} _{-0.07}	0.80 ^{+0.15} _{-0.53}	0.75 ^{+0.18} _{-0.48}	0.79 ^{+0.09} _{-0.32}	0.19	-1.18	-0.05	
GW190915_235702	74.8 ^{+7.9} _{-7.4}	270.6 ^{+197.4} _{-257.2}	72.0 ^{+246.4} _{-16.2}	246.1 ^{+153.7} _{-122.6}	0.70 ^{+0.09} _{-0.11}	0.50 ^{+0.41} _{-0.45}	0.42 ^{+0.46} _{-0.38}	0.60 ^{+0.23} _{-0.42}	0.10	-1.43	0.03	

TABLE IX. Updated Table IX in the original article.

Event	Redshifted frequency [Hz]			Redshifted damping time [ms]		
	IMR	DS	pSEOBS	IMR	DS	pSEOBS
GW150914	248^{+8}_{-7}	247^{+15}_{-16}	...	$4.2^{+0.3}_{-0.2}$	$4.3^{+4.0}_{-1.9}$	...
GW170104	287^{+15}_{-25}	220^{+78}_{-93}	...	$3.5^{+0.4}_{-0.3}$	$2.4^{+15.7}_{-1.5}$	...
GW170814	293^{+11}_{-14}	525^{+332}_{-331}	...	$3.7^{+0.3}_{-0.2}$	$24.7^{+22.5}_{-19.3}$	...
GW170823	197^{+17}_{-17}	216^{+558}_{-53}	...	$5.5^{+1.0}_{-0.8}$	$8.4^{+34.1}_{-5.6}$	...
GW190408_181802	319^{+11}_{-20}	464^{+503}_{-418}	...	$3.2^{+0.3}_{-0.3}$	$10.3^{+32.4}_{-9.1}$	...
GW190421_213856	162^{+14}_{-14}	...	171^{+50}_{-16}	$6.3^{+1.2}_{-0.8}$	...	$8.5^{+5.3}_{-4.2}$
GW190503_185404	191^{+17}_{-15}	...	265^{+501}_{-79}	$5.3^{+0.8}_{-0.8}$	...	$3.5^{+3.4}_{-1.8}$
GW190512_180714	381^{+33}_{-42}	214^{+525}_{-34}	...	$2.6^{+0.2}_{-0.2}$	$22.9^{+23.7}_{-18.6}$	...
GW190513_205428	241^{+26}_{-28}	277^{+480}_{-108}	...	$4.3^{+1.1}_{-0.4}$	$6.1^{+22.7}_{-4.7}$	...
GW190519_153544	127^{+9}_{-9}	126^{+11}_{-17}	124^{+12}_{-13}	$9.5^{+1.7}_{-1.5}$	$9.7^{+9.2}_{-4.1}$	$10.3^{+3.6}_{-3.1}$
GW190521	68^{+4}_{-4}	65^{+3}_{-3}	67^{+2}_{-2}	$15.8^{+3.9}_{-2.5}$	$22.3^{+12.6}_{-7.5}$	$30.7^{+7.7}_{-7.4}$
GW190521_074359	198^{+7}_{-7}	195^{+15}_{-17}	205^{+15}_{-12}	$5.4^{+0.4}_{-0.4}$	$7.8^{+7.3}_{-3.5}$	$5.3^{+1.5}_{-1.2}$
GW190602_175927	105^{+10}_{-9}	97^{+12}_{-23}	99^{+15}_{-15}	$10.0^{+2.0}_{-1.4}$	$8.8^{+12.6}_{-3.9}$	$8.8^{+5.4}_{-3.6}$
GW190706_222641	108^{+11}_{-10}	109^{+7}_{-12}	112^{+7}_{-8}	$10.9^{+2.4}_{-2.2}$	$19.6^{+25.5}_{-12.5}$	$19.4^{+7.2}_{-8.9}$
GW190708_232457	497^{+10}_{-46}	768^{+152}_{-717}	...	$2.1^{+0.2}_{-0.1}$	$26.5^{+21.3}_{-24.4}$	...
GW190727_060333	178^{+18}_{-16}	351^{+587}_{-276}	201^{+11}_{-21}	$6.1^{+1.1}_{-0.8}$	$20.5^{+26.0}_{-17.5}$	$15.4^{+5.3}_{-6.1}$
GW190828_063405	239^{+10}_{-11}	248^{+294}_{-14}	...	$4.8^{+0.6}_{-0.5}$	$16.3^{+25.5}_{-9.7}$	...
GW190910_112807	177^{+8}_{-8}	165^{+9}_{-11}	174^{+12}_{-8}	$5.9^{+0.8}_{-0.5}$	$12.8^{+16.2}_{-6.0}$	$9.5^{+3.1}_{-2.7}$
GW190915_235702	232^{+14}_{-18}	512^{+445}_{-473}	...	$4.6^{+0.8}_{-0.6}$	$15.7^{+30.3}_{-14.3}$	...

truncation time chosen is at $t_0 = 1126259462.42322$ GPS in Hanford, instead of $t_0 = 1126259462.42335$ as stated in the original article. In addition, Tables VIII and IX in this erratum replace Tables VIII (including the caption) and IX, respectively, in the original article. Figure 13 in this erratum replaces Fig. 13 in the original article. The list of events for which the posterior distributions are shown in the figure has also been changed accordingly.

We have updated the data release at [4] with the corrected graviton mass samples, results from the pyRing analysis, and results from the parametrized test with the SEOBNRv4_ROM waveform model.

While preparing this erratum, we noticed that some errors had been introduced during the typesetting of Table I of the original paper. These are as follows:

- (i) For GW190421_213856, the lower bound on the final mass (M_f) should be -11.3 (not -11.13).
- (ii) For GW190602_175927, the upper bound on the final spin (χ_f) should be $+0.10$ (not $+0.18$).
- (iii) For GW190708_232457, the value for M_f is reprinted in the χ_f column, the value for χ_f is printed in the SNR column, and the SNR value ($13.1^{+0.2}_{-0.3}$) has been omitted.

The table appears correctly in [5].

- [1] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1, *Phys. Rev. D* **100**, 104036 (2019).
- [2] L. Bernus, O. Minazzoli, A. Fienga, M. Gastineau, J. Laskar, P. Deram, and A. Di Ruscio, Constraint on the Yukawa suppression of the Newtonian potential from the planetary ephemeris INPOP19a, *Phys. Rev. D* **102**, 021501 (2020).
- [3] A. K. Mehta, A. Buonanno, R. Cotesta, A. Ghosh, N. Sennett, and J. Steinhoff, Tests of general relativity with gravitational-wave observations using a flexible theory-independent method, *Phys. Rev. D* **107**, 044020 (2023).
- [4] <https://dcc.ligo.org/P2000438/public>
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