LIGO Scientific Collaboration
Virgo Collaboration

start time
15:00 UTC

Tests of General Relativity with Binary Black Holes from GWTC-2

testing GR paper

dcc.ligo.org/LIGO-P2000091/public
[arXiv:2010.14529]

data release
dcc.ligo.org/LIGO-P2000438/public

presentation slides
dcc.ligo.org/LIGO-G2002002/public

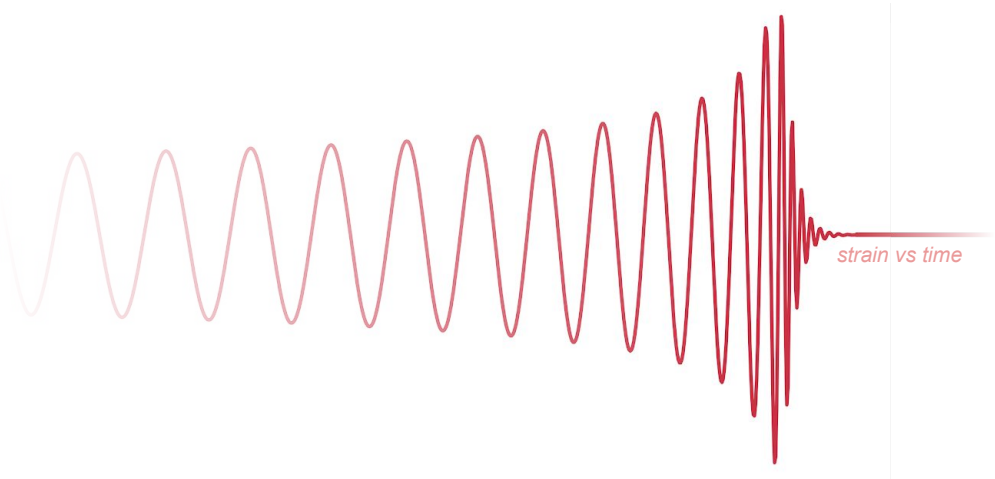
related papers

detection catalog
dcc.ligo.org/LIGO-P2000061/public
[arXiv:2010.14527]

astrophysical populations
dcc.ligo.org/LIGO-P2000077/public
[arXiv:2010.14533]

tests of GR with BBHs from GWTC-2

- ➔ 8 tests of general relativity, or modeling systematics
- ➔ 24 binary-black-hole events (FAR < 1 per 1000 yrs)
- ➔ event-by-event and collective results from sets of events



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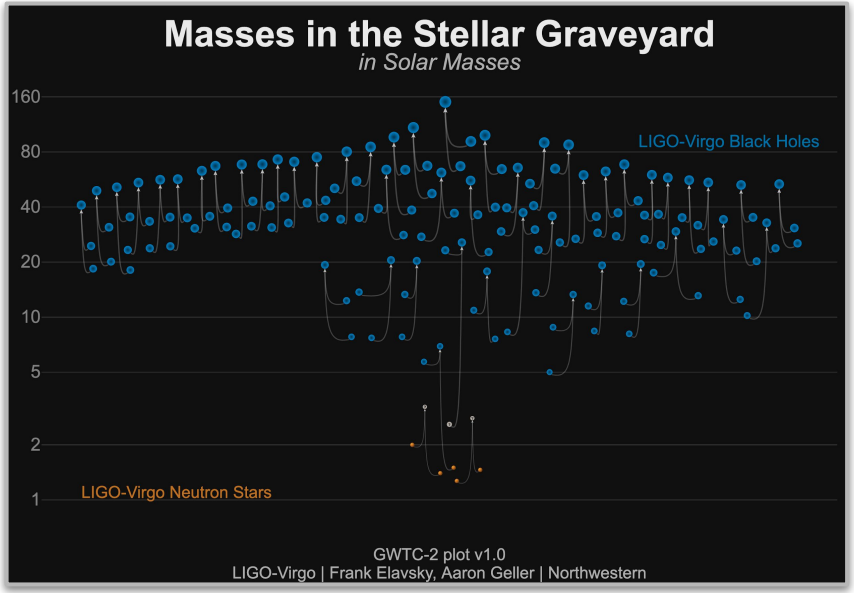


panelists

Sergei Ossokine
Albert Einstein Institute Potsdam
consistency tests

Geraint Pratten
University of Birmingham
source dynamics

Rico Lo
California Institute of Technology
remnant properties

Anuradha Gupta
The University of Mississippi
dispersion & polarization

Maximiliano Isi
Massachusetts Institute of Technology
moderator

consistency tests

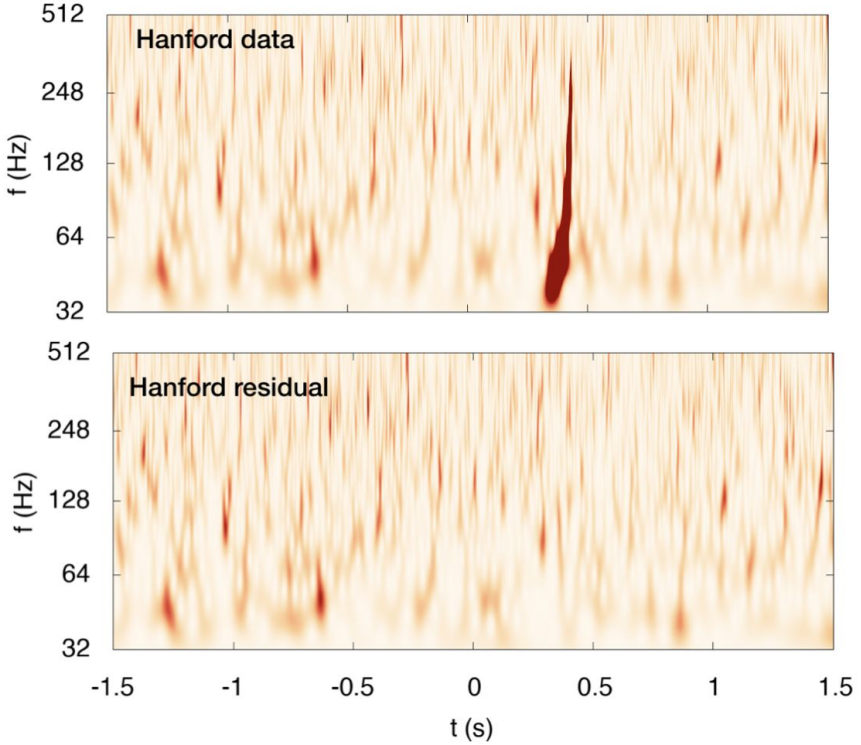
Sergei Ossokine

residuals test

- Subtract the best fit template for the event from the strain data and compute the 90% upper limit on residual SNR.
- Check whether the residual SNR is consistent with SNR from noise: measure SNR from noise-only times around the event times, yielding a p-value

$$p = P(\mathrm{SNR}_n \geq \mathrm{SNR}_{\mathrm{residual}} \mid \mathrm{noise})$$

- If GR model is good fit to the data we expect:
  - No correlation between the SNR of the event and residual SNR
  - p-values indicating consistency with noise.



[arXiv:1908.11170]

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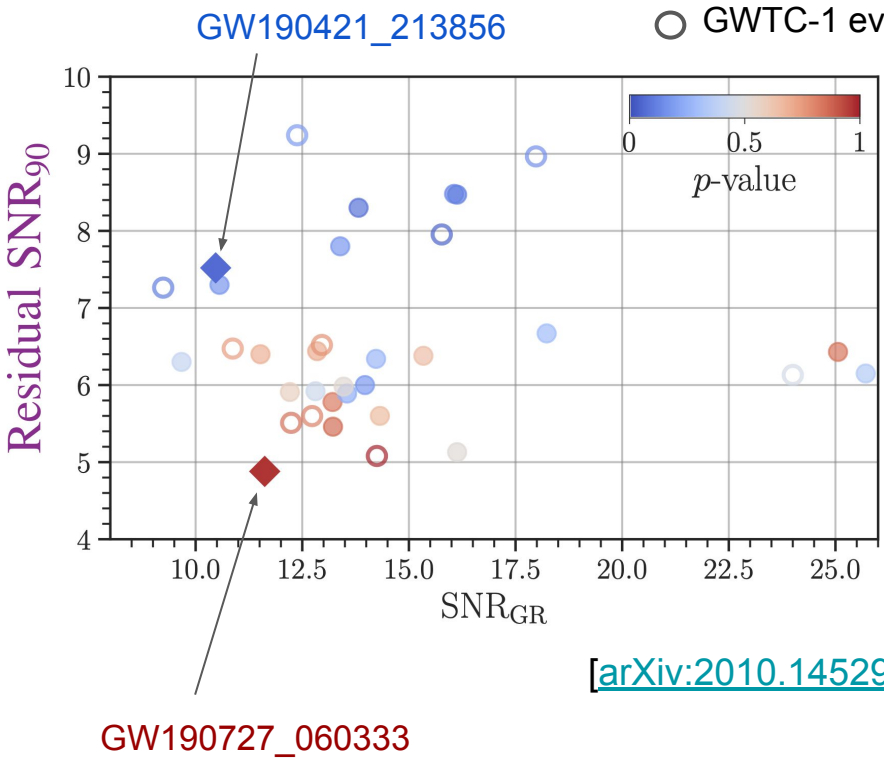


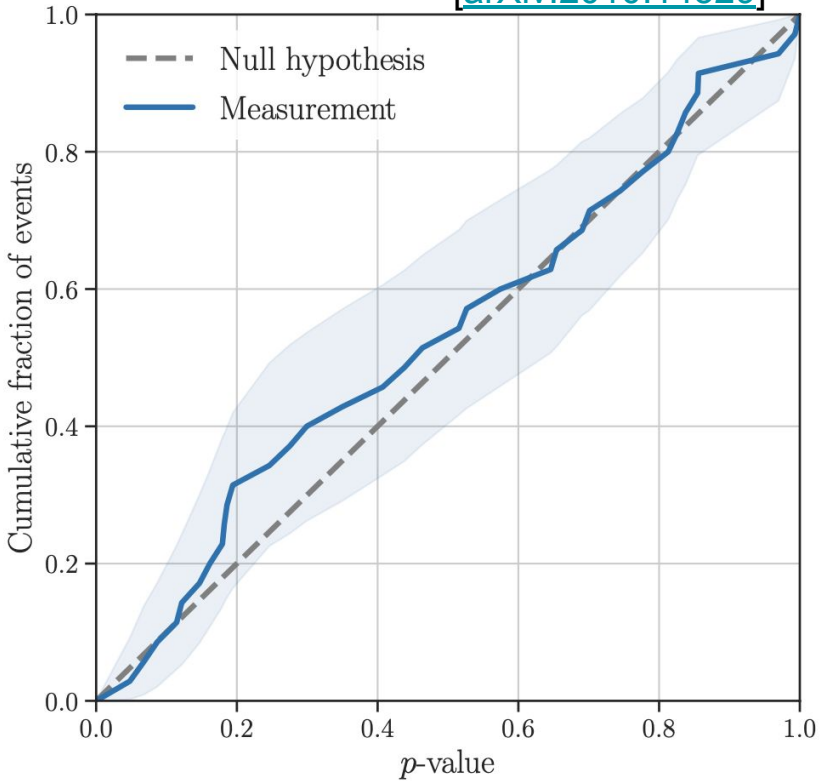
[arXiv:2010.14529]

residuals test

Events	SNR_{GR}	Residual SNR_{90}	FF_{90}	p-value
GW190408_181802	16.06	8.48	0.88	0.15
GW190412	18.23	6.67	0.94	0.30
GW190421_213856	10.47	7.52	0.81	0.07
GW190503_185404	13.21	5.78	0.92	0.83
GW190512_180714	12.81	5.92	0.91	0.44
GW190513_205428	12.85	6.44	0.89	0.70
GW190517_055101	11.52	6.40	0.87	0.69
GW190519_153544	15.34	6.38	0.92	0.65
GW190521	14.23	6.34	0.91	0.28
GW190521_074359	25.71	6.15	0.97	0.35
GW190602_175927	13.22	5.46	0.92	0.86
GW190630_185205	16.13	5.13	0.95	0.52
GW190706_222641	13.39	7.80	0.86	0.18
GW190707_093326	13.55	5.89	0.92	0.25
GW190708_232457	13.97	6.00	0.92	0.19
GW190720_000836	10.56	7.30	0.82	0.18
GW190727_060333	11.62	4.88	0.92	0.97
GW190728_064510	13.47	5.98	0.91	0.53
GW190814	25.06	6.43	0.97	0.84
GW190828_063405	16.13	8.47	0.89	0.12
GW190828_065509	9.67	6.30	0.84	0.41
GW190910_112807	14.32	5.60	0.93	0.65
GW190915_235702	13.82	8.30	0.86	0.09
GW190924_021846	12.21	5.91	0.90	0.57

All p-values consistent with residual SNR produced by noise

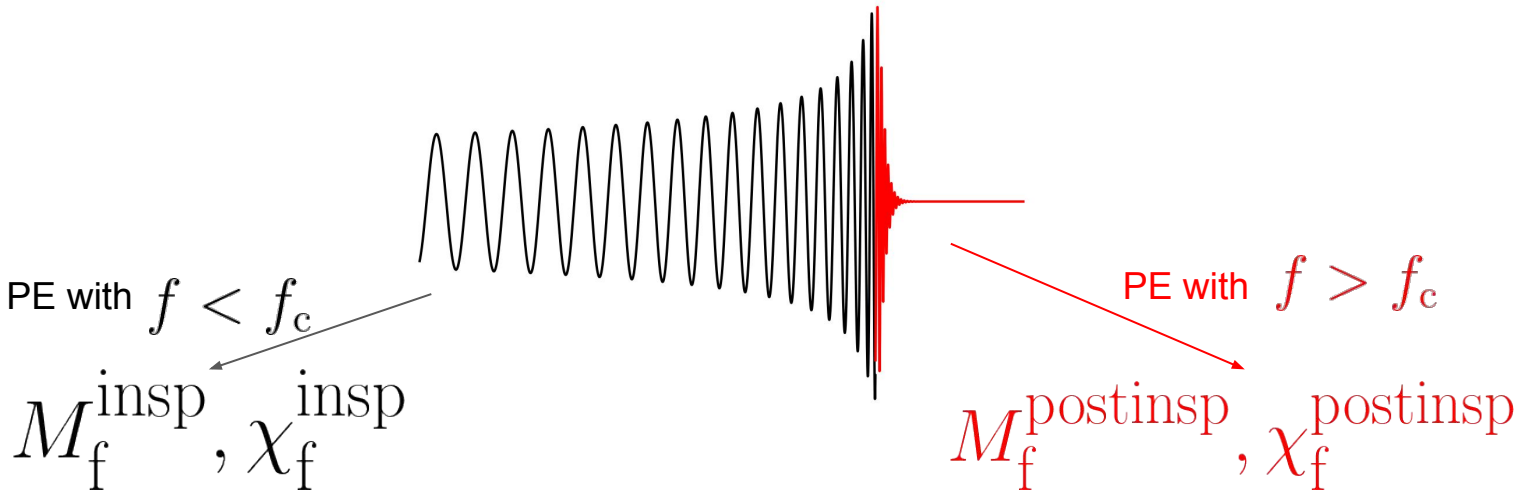
[arXiv:2010.14529]



[arXiv:2010.14529]

inspiral-merger-ringdown (IMR) consistency

- If GR is correct, the final state of a BBH merger is a Kerr BH.
- The final mass and spin of the BH inferred from high and low frequency regimes must be consistent.
- Use parameter estimation on full signal and NR-calibrated fits to infer the final masses and spins, and obtain the cutoff frequency $f_{\rm c}$ splitting signal into inspiral and merger-ringdown regimes.



inspiral-merger-ringdown (IMR) consistency

$$\frac{\Delta M_{\rm f}}{\bar{M}_{\rm f}} = 2\frac{M_{\rm f}^{\rm insp} - M_{\rm f}^{\rm postinsp}}{M_{\rm f}^{\rm insp} + M_{\rm f}^{\rm postinsp}}$$

$$\frac{\Delta \chi_{\rm f}}{\bar{\chi}_{\rm f}} = 2\frac{\chi_{\rm f}^{\rm insp} - \chi_{\rm f}^{\rm postinsp}}{\chi_{\rm f}^{\rm insp} + \chi_{\rm f}^{\rm postinsp}}$$

- For this test to be applicable, the inspiral and merger-ringdown regions of the signal must be informative.
- Impose a cut on SNR: both inspiral and merger ringdown regimes must have optimal SNR > 6.
- Additionally, demand that the detector frame total mass is below 100 solar masses.
- Reweight the posteriors to a prior uniform in deviation parameters.

waveform systematics

- The GR waveform models we use do not exactly correspond to the true GR signal due to:
  - Approximations: theoretical underpinnings (e.g. post-Newtonian theory), modelling choices, incorporation of numerical relativity information, accuracy of NR information itself,...
  - Physical content: modes included, precession, etc.

- Any such systematics will influence tests that seek to measure deviations from GR.
- To estimate the impact of these systematic uncertainties, we usually perform analyses with multiple independent waveform models.

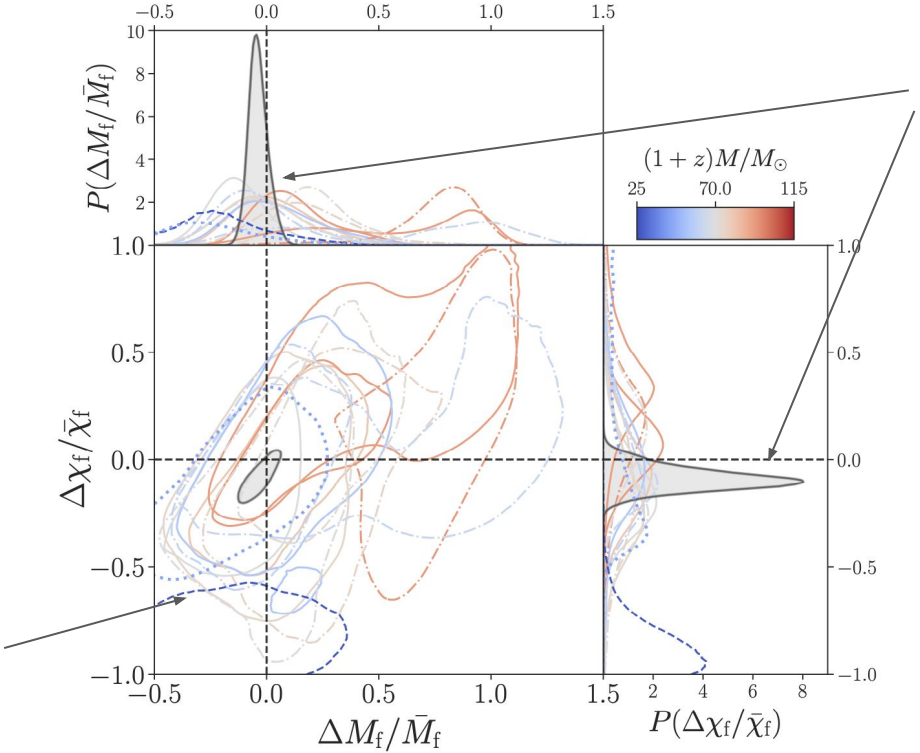
- Three frequently used families:
  - IMRPhenom - phenomenological PN-based models, calibrated to NR
  - SEOB - effective-one-body (EOB) models, calibrated to NR
  - NRSur - directly interpolate NR waveforms

- For the IMR consistency test, we use the precessing model IMRPhenomPv2 and the aligned-spin model SEOBNRv4_ROM, which both include the dominant quadrupolar modes only.

inspiral-merger-ringdown (IMR) consistency

IMRPhenomPv2

Shown are 90% credible regions



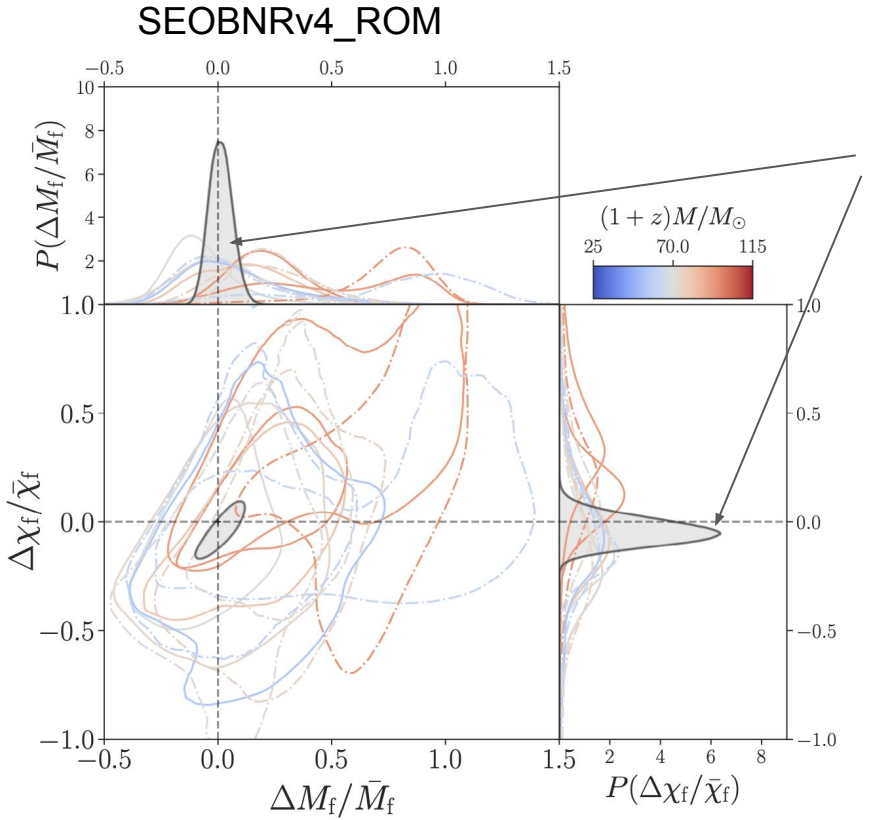
Assuming deviations are the same for all events

GW190814

[arXiv:2010.14529]

inspiral-merger-ringdown (IMR) consistency

Shown are 90% credible regions



Assuming deviations are the same for all events

[arXiv:2010.14529]

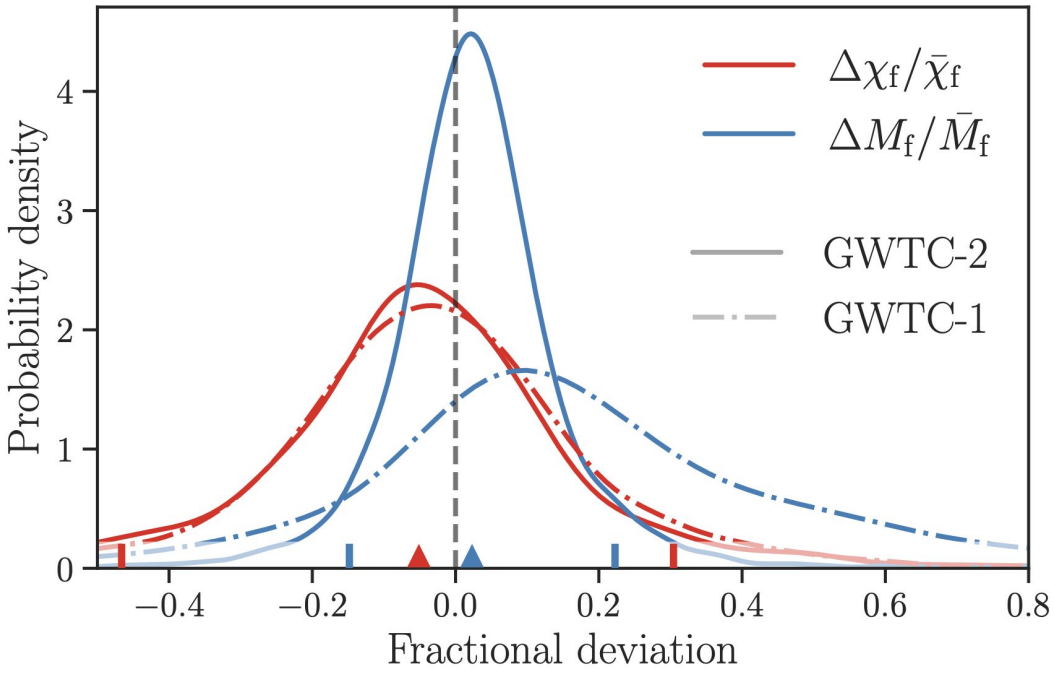
hierarchical analysis

- Hierarchically combine results from individual events.
- Model the deviations as coming from a Gaussian distribution with unknown mean (μ) and standard deviation (σ).
- Marginalise over the population parameters:

$$p(x \mid d) = \int p(x \mid \mu, \sigma)\, p(\mu, \sigma \mid d)\, \mathrm{d}\mu\, \mathrm{d}\sigma$$

$$x = \left\{ \frac{\Delta M_\mathrm{f}}{\bar{M}_\mathrm{f}}, \frac{\Delta \chi_\mathrm{f}}{\bar{\chi}_\mathrm{f}} \right\}$$

Results from the population



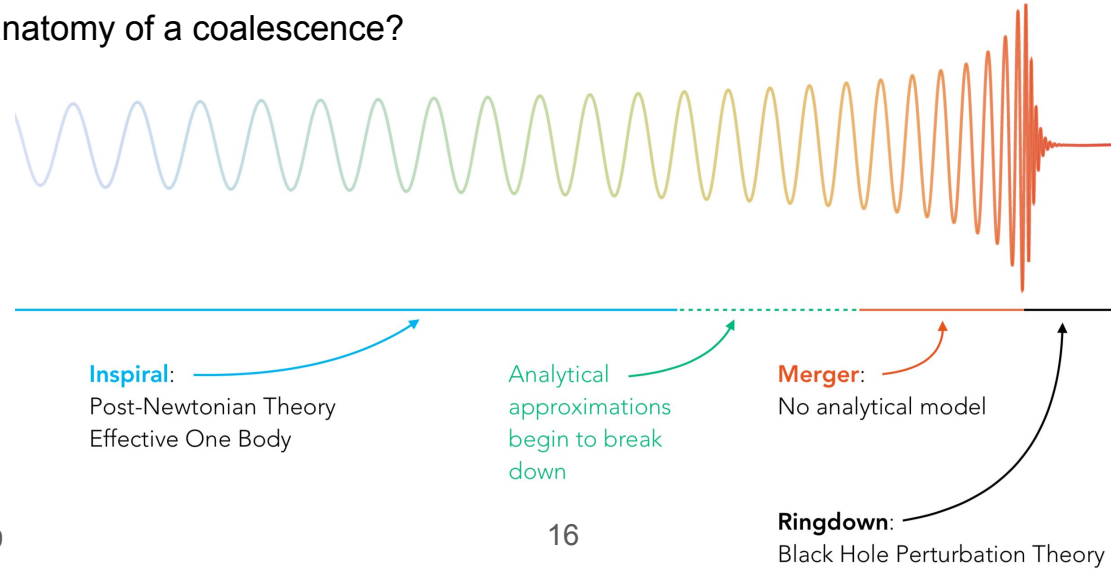
[arXiv:2010.14529]

source dynamics

Geraint Pratten

parameterized Tests

- Why parameterized tests?
  - Lack of mature alternative theories: Well-posed? Physically viable? Well-defined predictions for GW signal?
  - Significant work required before widespread use of beyond-GR models in GW data analysis
- So what strategies can we adopt?
  - Quantify *generic* deviations from GR predictions → constrain degree to which deviations agree with data
- Insights from the anatomy of a coalescence?



parameterized Tests

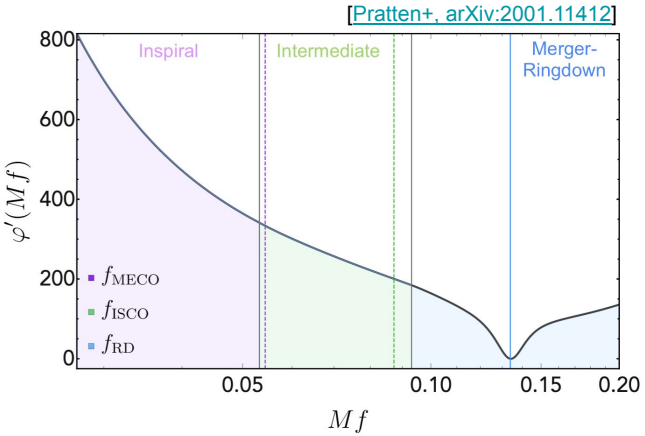
- Inspiral-Merger-Ringdown (IMR) waveform model written as frequency-dependent amplitude and phase

$$\tilde{h}(f) = \mathcal{A}(f)\, e^{i\varphi(f)}$$

- Parameterize phase corrections in 3 distinct regions:
  - Inspiral $\varphi_{\rm Ins}(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} + \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} + \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots$

Coefficients analytically known in GR

[Pratten+, arXiv:2001.11412]



- *Phenom*enological Coefficients
  - Intermediate $\varphi_{\rm Int} = \frac{1}{\eta}\left(\beta_0 + \beta_1 f + \beta_2 \log(f) - \frac{\beta_3}{3} f^{-3}\right)$
  - Merger-Ringdown $\varphi_{\rm MR} = \frac{1}{\eta}\left\{\alpha_0 + \alpha_1 f - \alpha_2 f^{-1} + \frac{4}{3}\alpha_3 f^{3/4} + \alpha_4 \tan^{-1}\left(\frac{f - \alpha_5 f_{\rm RD}}{f_{\rm damp}}\right)\right\}$

Caution: Coefficients calibrated against NR but are not expressed in parameters relevant to GR or modified theories of gravity...

Parameterized Tests

- Constrain deviations with *parametric deformations* to GR model varying one coefficient at a time

$$p_i \to (1 + \delta\hat{p}_i)p_i \qquad p_i = \{\varphi_i, \beta_i, \alpha_i\}$$

  - Variant of parameterized post-Einsteinian (pPE) framework

- Use *two independent* approaches with *two different* waveform models:
  - Directly modify PN and phenomenological coefficients in *Phenom*
  - Add deformations corresponding to the inspiral coefficients to an underlying *SEOB* waveform

- 10 Inspiral Coefficients (*Phenom* and *SEOB*):

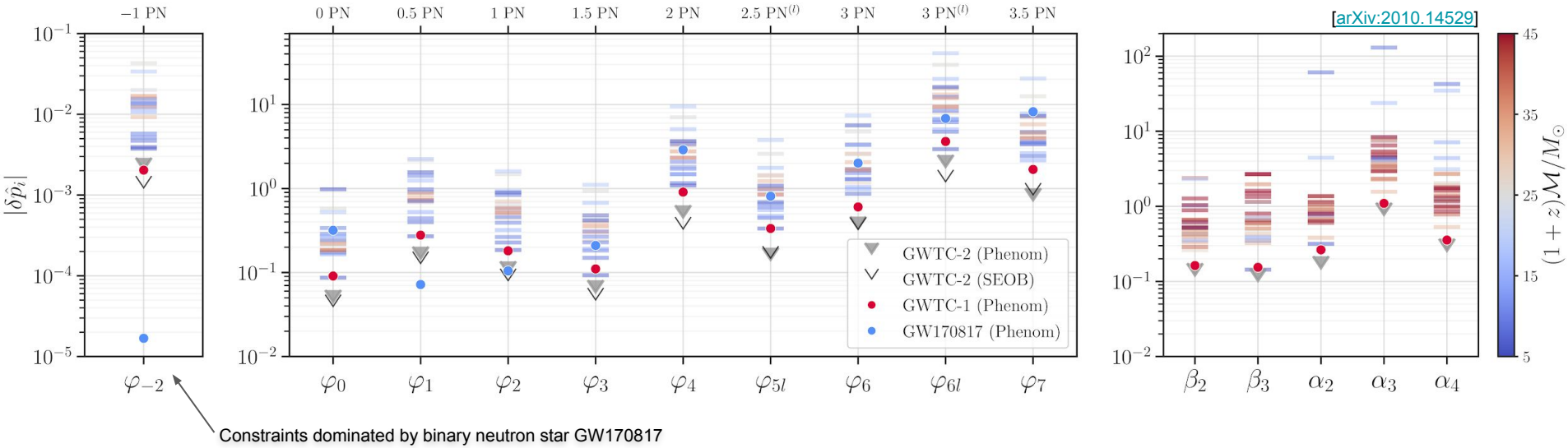
$$\{\delta\hat{\varphi}_{-2}, \delta\hat{\varphi}_0, \delta\hat{\varphi}_1, \delta\hat{\varphi}_2, \delta\hat{\varphi}_3, \delta\hat{\varphi}_4, \delta\hat{\varphi}_{5l}, \delta\hat{\varphi}_6, \delta\hat{\varphi}_{6l}, \delta\hat{\varphi}_7\} \propto f^{(i-5)/3}$$

- 5 Post-inspiral Coefficients (*Phenom*):

$$\{\beta_2, \beta_3\}, \{\alpha_2, \alpha_3, \alpha_4\}$$

parameterized Tests

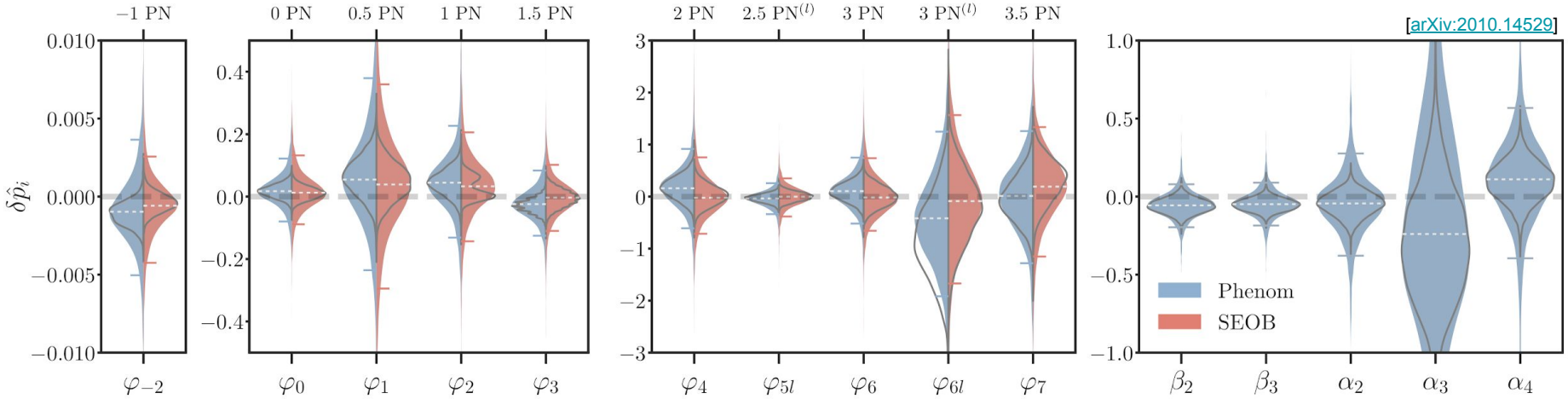
- 90% upper bounds on absolute magnitude of GR violating parameters
- Lighter (*heavier*) binaries *typically* have better constraining power for inspiral (*post-inspiral*) coefficients
- Improvements consistent with increased sample size - broad improvement over GWTC-1



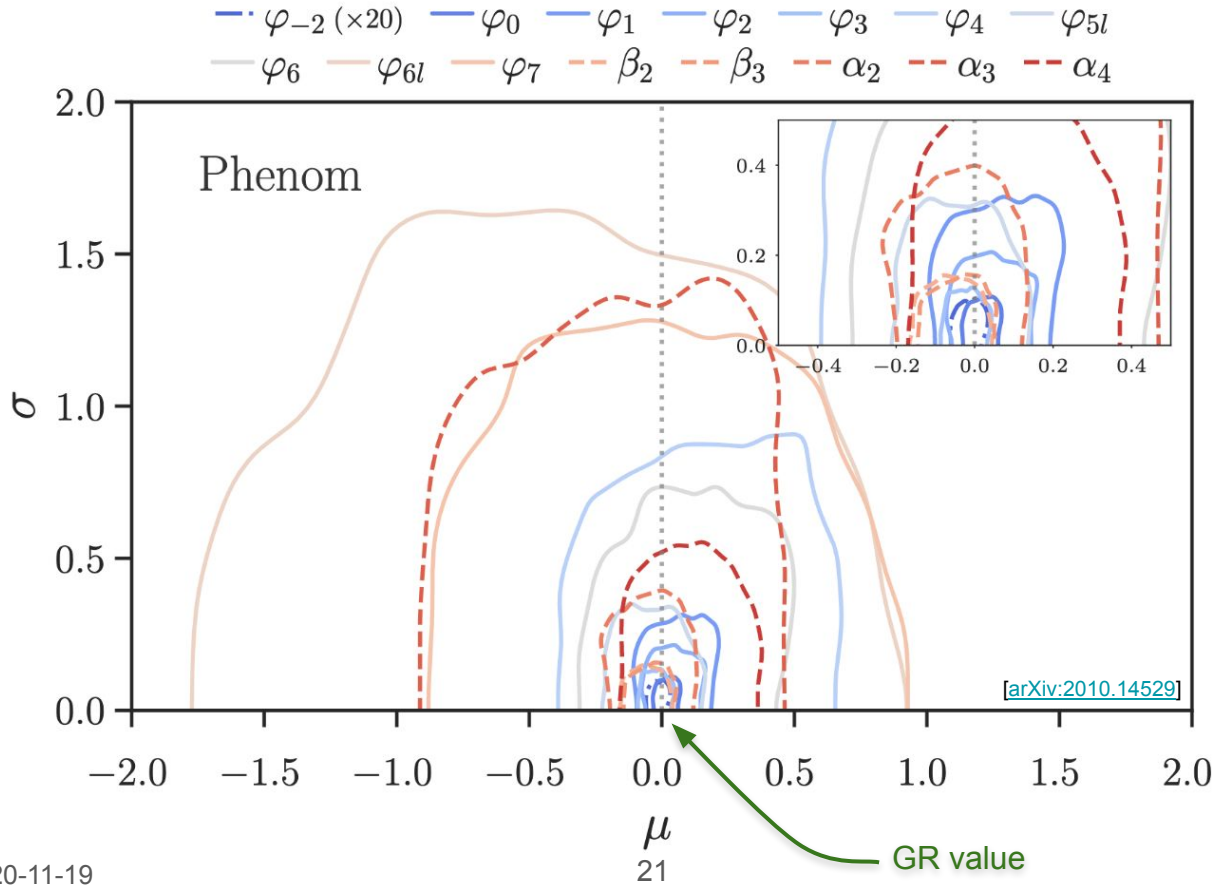
parameterized Tests

- Construct joint posteriors using two approaches:
  - Shared common value of deviation parameter
  - Hierarchical analysis
- Distributions and hyperparameters must be consistent with GR: $\delta\hat{p}_i = 0, \mu = \sigma = 0$

- Dashed horizontal line is GR limit (vanishing deformations)
- Shaded regions: population-marginalized expectations from hierarchical analysis for *Phenom* and *SEOB*
- Black distributions: events share common value of parameter



parameterized Tests



- Hyperparameters for parameterized deviation-coefficients
- GR limit:

$$\mu = \sigma = 0$$

- Similar result for SEOB

spin-induced quadrupole moment

- Spinning motion of a compact object creates a distortion in the mass distribution
- Induces a distortion in the gravitational field measured by the quadrupole-moment tensor $\mathcal{Q}$
- Effect imprinted in emitted GW radiation at specific PN orders - specialized variant of parameterized test
  - Include leading order correction at 2PN and a correction at 3PN
- For a compact object of mass m and spin χ

$$Q = -(1 + \delta\kappa)\,\chi_A^2 m_A^3$$

Coefficient depends on the equation of state, mass and spin of compact object...

Enables us to test the black hole nature of the compact object!

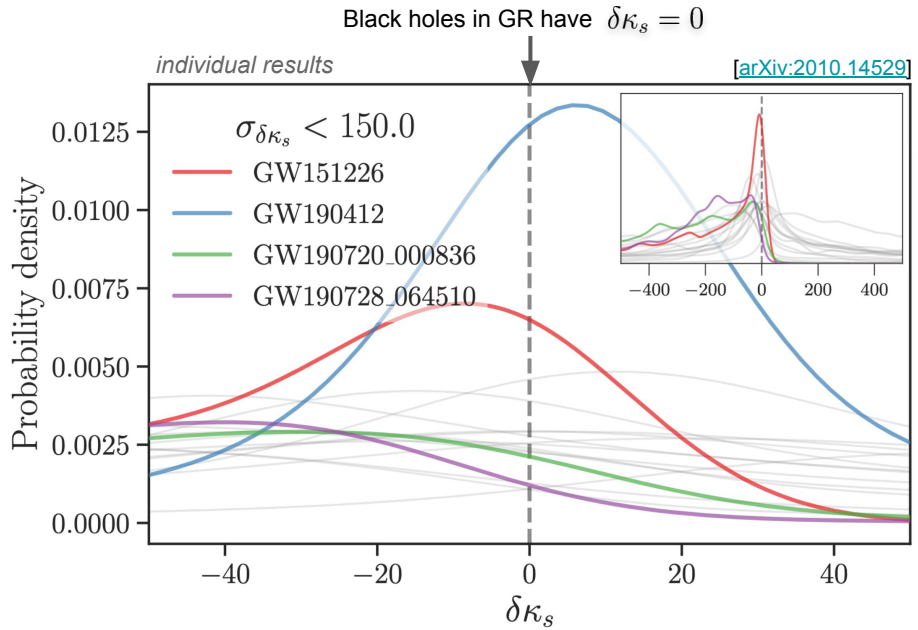
Black Holes (*no-hair conjecture*)	$\delta\kappa$ = 0 [Poisson '98]
Neutron Stars	$\delta\kappa$ ~ 1 - 13 [Laarakkers '97, Pappas '12]
Boson Stars	$\delta\kappa$ ~ 10 - 150 [Ryan '97]

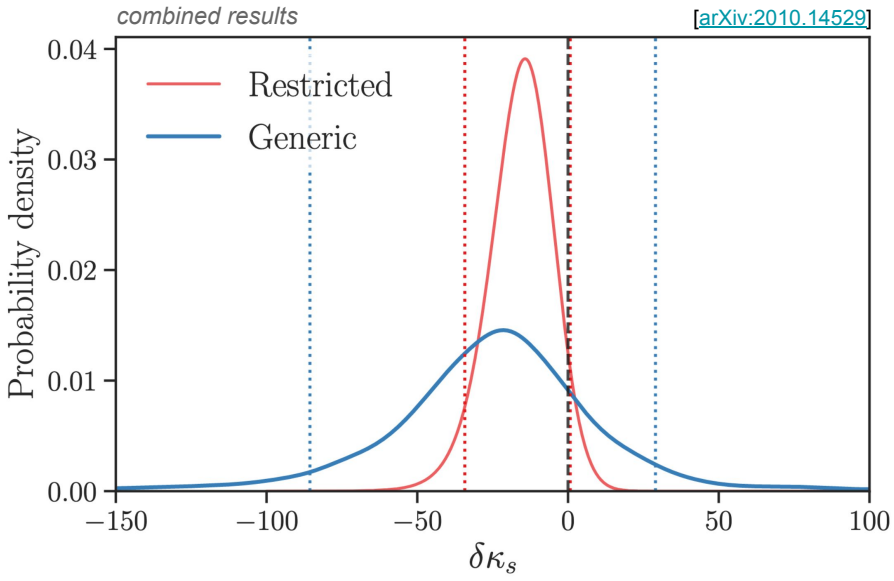
spin-induced quadrupole moment

- Highly correlated with masses and spins, adopt an alternative parameterisation (cf $\chi_{\rm eff}$)

$$\kappa_s = (\kappa_1 + \kappa_2)/2$$
$$\kappa_a = (\kappa_1 - \kappa_2)/2$$

For black holes the coefficients are $\kappa = 1$, so we set this term to zero



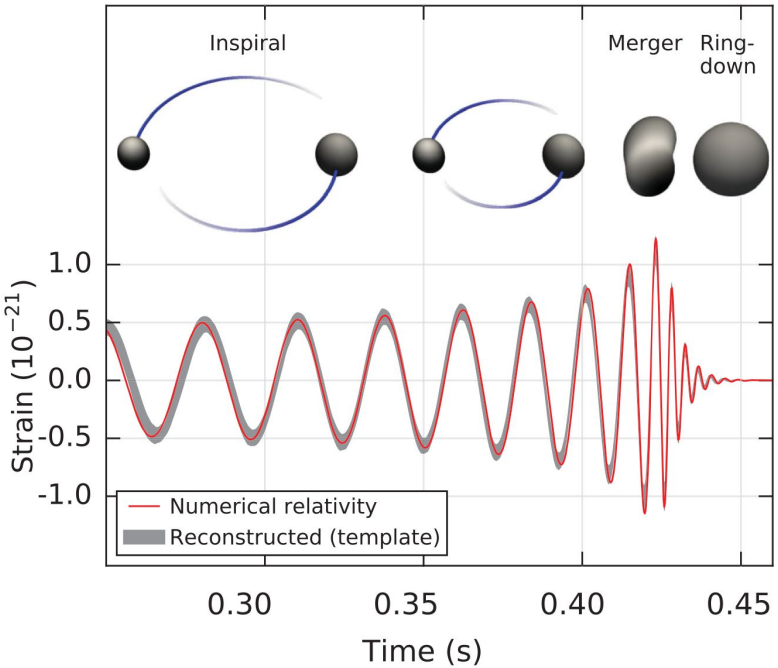


remnant properties

Rico Lo

ringdown

- Ringdown: quasi-normal modes (QNMs) with set frequencies and damping times
  - **Infer final mass and final spin** independent of inspiral
  - **Constrain deviations from GR** predictions of the frequencies and damping times
- Key results (qualitatively):
  - Measurements of the final mass and the spin **consistent** with the measurements using the full IMR signals
  - Inferred QNM frequencies and damping times **consistent** with BH perturbation theory calculations

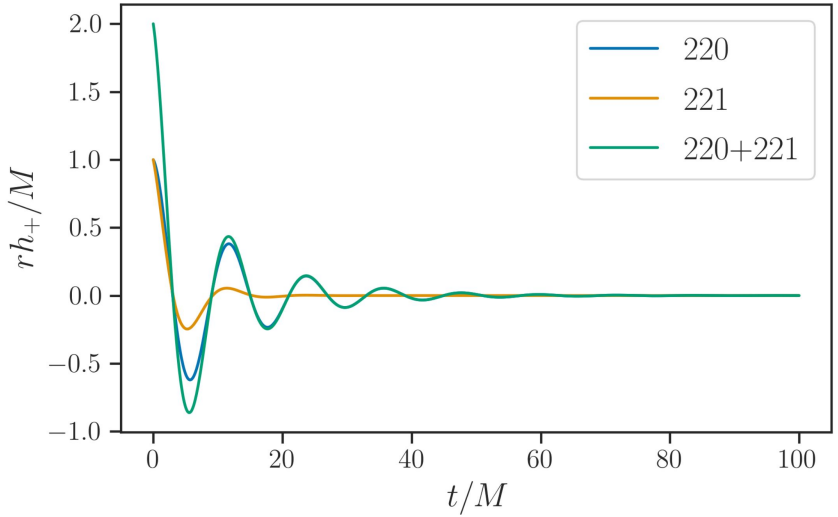


Credit: Phys. Rev. Lett. 116, 061102 (2016)

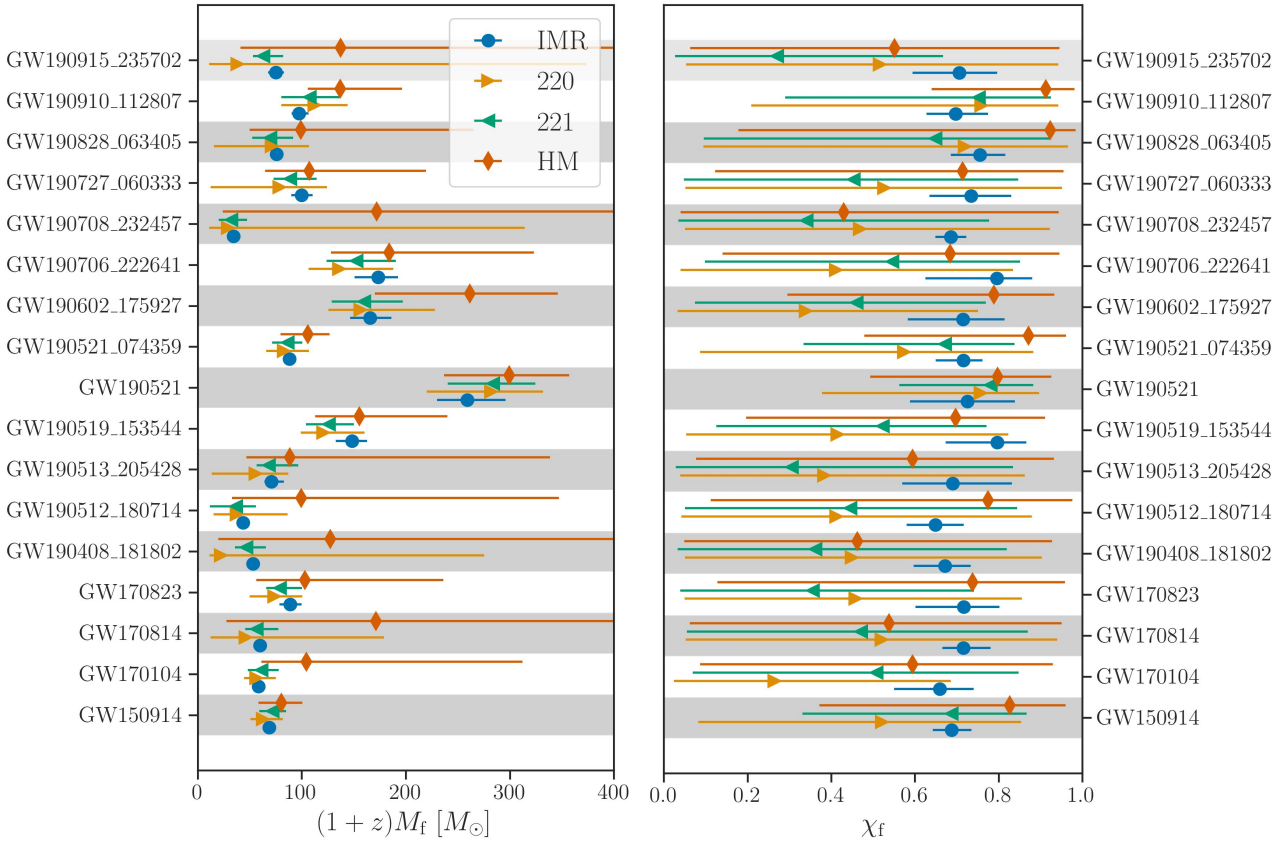
ringdown

$$h_+(t) - ih_\times(t) = \sum_{\ell=2}^{+\infty} \sum_{m=-\ell}^{\ell} \sum_{n=0}^{+\infty} \mathcal{A}_{\ell mn} \exp\left[-\frac{t-t_0}{(1+z)\tau_{\ell mn}}\right] \exp\left[\frac{2\pi i f_{\ell mn}(t-t_0)}{1+z}\right] {}_{-2}S_{\ell mn}(\theta, \phi, \chi_f)$$

- Mass and spin measurement using 3 different ringdown-only waveforms
  - Kerr$_{220}$: include only $\ell = 2, |m| = 2, n = 0$ mode
  - Kerr$_{221}$: include both $\ell = 2, |m| = 2, n = 0, 1$ mode
  - Kerr$_{HM}$: include all the fundamental modes ($n = 0$) for $\ell \leq 4$



ringdown


IMR
220
221
HM
GW190915_235702
GW190910_112807
GW190828_063405
GW190727_060333
GW190708_232457
GW190706_222641
GW190602_175927
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GW190521
GW190519_153544
GW190513_205428
GW190512_180714
GW190408_181802
GW170823
GW170814
GW170104
GW150914
0
100
200
300
400
$(1+z)M_{\rm f}$ $[M_\odot]$
0.0
0.2
0.4
0.6
0.8
1.0
$\chi_{\rm f}$

ringdown

No significant evidence for HM in ringdown

Event	Redshifted final mass $(1+z)M_f$ [$M_\odot$]				Final spin χ_f				Higher modes	Overtones	
	IMR	Kerr_{220}	Kerr_{221}	$\mathrm{Kerr}_{\mathrm{HM}}$	IMR	Kerr_{220}	Kerr_{221}	$\mathrm{Kerr}_{\mathrm{HM}}$	$\log_{10}\mathcal{B}^{\mathrm{HM}}_{220}$	$\log_{10}\mathcal{B}^{221}_{220}$	$\log_{10}\mathcal{O}^{\mathrm{modGR}}_{\mathrm{GR}}$
GW150914	$68.8^{+3.6}_{-3.1}$	$62.7^{+19.0}_{-12.1}$	$71.7^{+13.2}_{-12.5}$	$80.3^{+20.1}_{-21.7}$	$0.69^{+0.05}_{-0.04}$	$0.52^{+0.33}_{-0.44}$	$0.69^{+0.18}_{-0.36}$	$0.83^{+0.13}_{-0.45}$	0.03	0.63	−0.34
GW170104	$58.5^{+4.6}_{-4.1}$	$56.2^{+19.1}_{-11.6}$	$61.3^{+16.7}_{-13.2}$	$104.3^{+207.7}_{-43.1}$	$0.66^{+0.08}_{-0.11}$	$0.26^{+0.42}_{-0.24}$	$0.51^{+0.34}_{-0.44}$	$0.59^{+0.34}_{-0.51}$	0.26	−0.20	−0.23
GW170814	$59.7^{+3.0}_{-2.3}$	$46.1^{+133.0}_{-33.6}$	$56.6^{+20.9}_{-11.1}$	$171.2^{+268.7}_{-143.5}$	$0.72^{+0.07}_{-0.05}$	$0.52^{+0.42}_{-0.47}$	$0.47^{+0.40}_{-0.42}$	$0.54^{+0.41}_{-0.48}$	0.04	−0.19	−0.11
GW170823	$88.8^{+11.2}_{-10.2}$	$73.8^{+26.8}_{-23.7}$	$79.0^{+21.3}_{-13.2}$	$103.0^{+133.1}_{-46.7}$	$0.72^{+0.09}_{-0.12}$	$0.46^{+0.40}_{-0.41}$	$0.36^{+0.38}_{-0.32}$	$0.74^{+0.22}_{-0.61}$	0.02	−0.98	−0.07
GW190408_181802	$53.1^{+3.2}_{-3.4}$	$22.4^{+253.0}_{-11.1}$	$46.6^{+18.8}_{-10.9}$	$127.4^{+327.7}_{-107.6}$	$0.67^{+0.06}_{-0.07}$	$0.45^{+0.45}_{-0.40}$	$0.36^{+0.46}_{-0.33}$	$0.46^{+0.47}_{-0.41}$	−0.05	−1.02	−0.02
GW190512_180714	$43.4^{+4.1}_{-2.8}$	$37.6^{+48.9}_{-22.4}$	$36.7^{+19.3}_{-24.8}$	$99.4^{+247.6}_{-66.5}$	$0.65^{+0.07}_{-0.07}$	$0.41^{+0.47}_{-0.37}$	$0.45^{+0.40}_{-0.39}$	$0.77^{+0.20}_{-0.66}$	0.09	−0.42	0.03
GW190513_205428	$70.8^{+12.2}_{-6.9}$	$55.5^{+31.5}_{-42.1}$	$68.5^{+28.2}_{-11.8}$	$88.7^{+250.0}_{-41.9}$	$0.69^{+0.14}_{-0.12}$	$0.38^{+0.48}_{-0.34}$	$0.31^{+0.53}_{-0.28}$	$0.59^{+0.34}_{-0.52}$	0.09	−0.54	−0.05
GW190519_153544	$148.2^{+14.5}_{-15.5}$	$120.7^{+39.7}_{-21.5}$	$125.9^{+24.3}_{-21.7}$	$155.4^{+84.4}_{-42.5}$	$0.80^{+0.07}_{-0.12}$	$0.42^{+0.41}_{-0.36}$	$0.52^{+0.25}_{-0.40}$	$0.70^{+0.21}_{-0.50}$	0.21	−0.00	−0.11
GW190521	$259.2^{+36.6}_{-29.0}$	$282.2^{+50.0}_{-61.9}$	$284.0^{+40.4}_{-43.9}$	$299.3^{+57.7}_{-62.4}$	$0.73^{+0.11}_{-0.14}$	$0.76^{+0.14}_{-0.38}$	$0.78^{+0.10}_{-0.22}$	$0.80^{+0.13}_{-0.30}$	0.12	−0.86	−0.50
GW190521_074359	$88.1^{+4.3}_{-4.9}$	$83.0^{+24.0}_{-17.2}$	$86.4^{+14.1}_{-14.8}$	$105.9^{+20.8}_{-26.4}$	$0.72^{+0.05}_{-0.07}$	$0.57^{+0.31}_{-0.49}$	$0.67^{+0.17}_{-0.34}$	$0.87^{+0.09}_{-0.39}$	−0.04	1.29	−0.27
GW190602_175927	$165.6^{+20.5}_{-19.2}$	$156.4^{+71.4}_{-30.6}$	$160.0^{+37.4}_{-31.2}$	$261.7^{+84.4}_{-91.5}$	$0.71^{+0.10}_{-0.13}$	$0.34^{+0.41}_{-0.31}$	$0.46^{+0.31}_{-0.39}$	$0.79^{+0.14}_{-0.49}$	0.61	−1.56	0.32
GW190706_222641	$173.6^{+18.8}_{-22.9}$	$136.0^{+52.0}_{-29.3}$	$152.5^{+37.8}_{-28.4}$	$184.0^{+139.2}_{-55.8}$	$0.80^{+0.08}_{-0.17}$	$0.41^{+0.42}_{-0.37}$	$0.55^{+0.31}_{-0.45}$	$0.68^{+0.26}_{-0.54}$	−0.06	−0.64	−0.45
GW190708_232457	$34.4^{+2.7}_{-0.7}$	$28.9^{+285.4}_{-17.9}$	$32.3^{+15.0}_{-12.2}$	$171.9^{+307.6}_{-147.8}$	$0.69^{+0.04}_{-0.04}$	$0.47^{+0.45}_{-0.42}$	$0.34^{+0.44}_{-0.31}$	$0.43^{+0.51}_{-0.39}$	−0.11	−0.17	−0.02
GW190727_060333	$100.0^{+10.5}_{-10.0}$	$78.7^{+45.7}_{-66.4}$	$88.8^{+25.7}_{-16.0}$	$107.4^{+112.1}_{-42.7}$	$0.73^{+0.10}_{-0.10}$	$0.53^{+0.42}_{-0.47}$	$0.45^{+0.39}_{-0.41}$	$0.71^{+0.24}_{-0.59}$	−0.02	−1.65	−0.40
GW190828_063405	$75.9^{+6.0}_{-5.2}$	$71.2^{+35.8}_{-55.5}$	$69.6^{+22.0}_{-17.3}$	$99.0^{+166.0}_{-49.1}$	$0.76^{+0.06}_{-0.07}$	$0.72^{+0.25}_{-0.62}$	$0.65^{+0.27}_{-0.55}$	$0.92^{+0.06}_{-0.74}$	0.05	−0.72	−0.05
GW190910_112807	$97.3^{+9.4}_{-7.1}$	$112.2^{+32.0}_{-31.7}$	$107.7^{+28.6}_{-27.4}$	$137.1^{+59.5}_{-31.4}$	$0.70^{+0.08}_{-0.07}$	$0.76^{+0.18}_{-0.55}$	$0.75^{+0.17}_{-0.46}$	$0.91^{+0.07}_{-0.27}$	−0.10	−0.64	−0.40
GW190915_235702	$75.0^{+7.7}_{-7.3}$	$38.3^{+335.1}_{-27.4}$	$63.0^{+19.1}_{-9.9}$	$137.3^{+324.1}_{-96.2}$	$0.71^{+0.09}_{-0.11}$	$0.52^{+0.43}_{-0.46}$	$0.27^{+0.40}_{-0.24}$	$0.55^{+0.39}_{-0.49}$	0.06	−0.37	−0.04

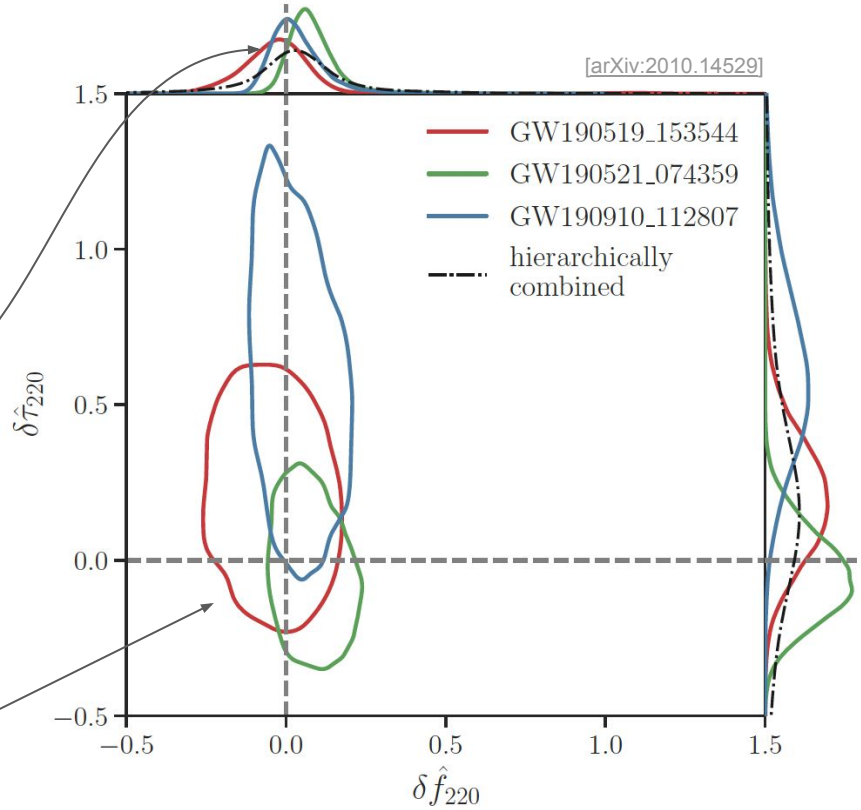
ringdown

Mass and spin of the final BH *inferred from the inspiral part of the signal*

$\delta\hat{f}_{220} = 0.03^{+0.38}_{-0.35}$

constrained using hierarchical analysis with a set of BBHs

contour for 90% credible region



220 mode, i.e.

$(\ell = 2, |m| = 2, n = 0)$

Fundamental mode

$f_{220} = f_{220}^{\rm GR}(1 + \delta\hat{f}_{220})$

$\tau_{220} = \tau_{220}^{\rm GR}(1 + \delta\hat{\tau}_{220})$

$\delta\hat{\tau}_{220} = 0.16^{+0.98}_{-0.98}$

with a wider uncertainty

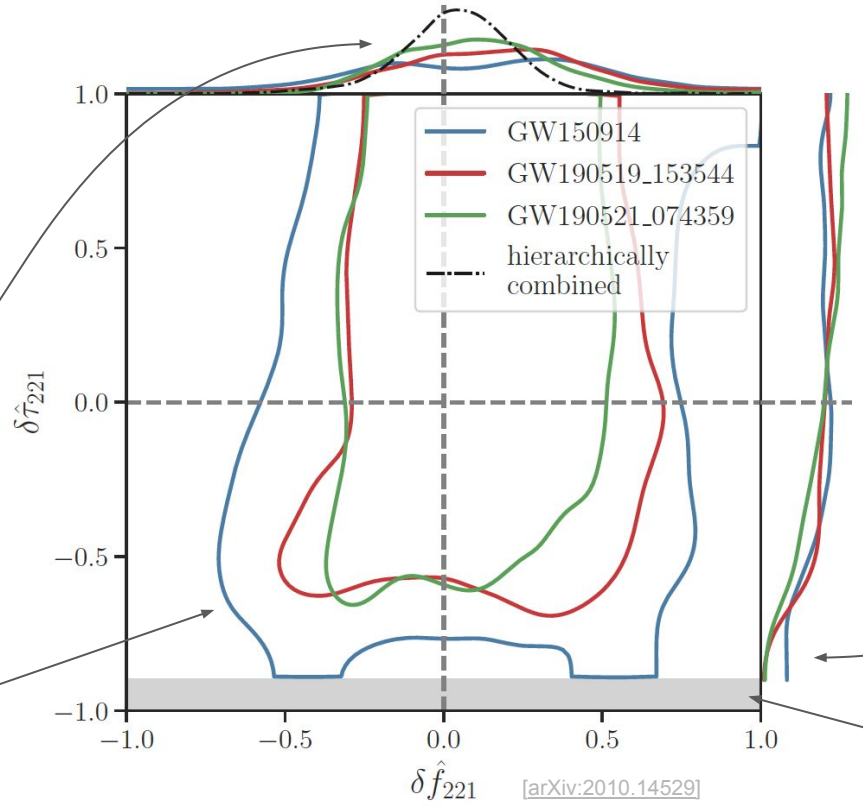
ringdown

Mass and spin of the final BH *inferred from the fundamental mode*

$\delta\hat{f}_{221} = 0.04^{+0.27}_{-0.32}$

constrained using hierarchical analysis with a set of BBHs

contour for 90% credible region



[arXiv:2010.14529]

221 mode, i.e.

$(\ell = 2, |m| = 2, n = 1)$

First overtone

$$f_{221} = f_{221}^{\rm GR}(M_{\rm f}, \chi_{\rm f})(1 + \delta\hat{f}_{221})$$
$$\tau_{221} = \tau_{221}^{\rm GR}(M_{\rm f}, \chi_{\rm f})(1 + \delta\hat{\tau}_{221})$$

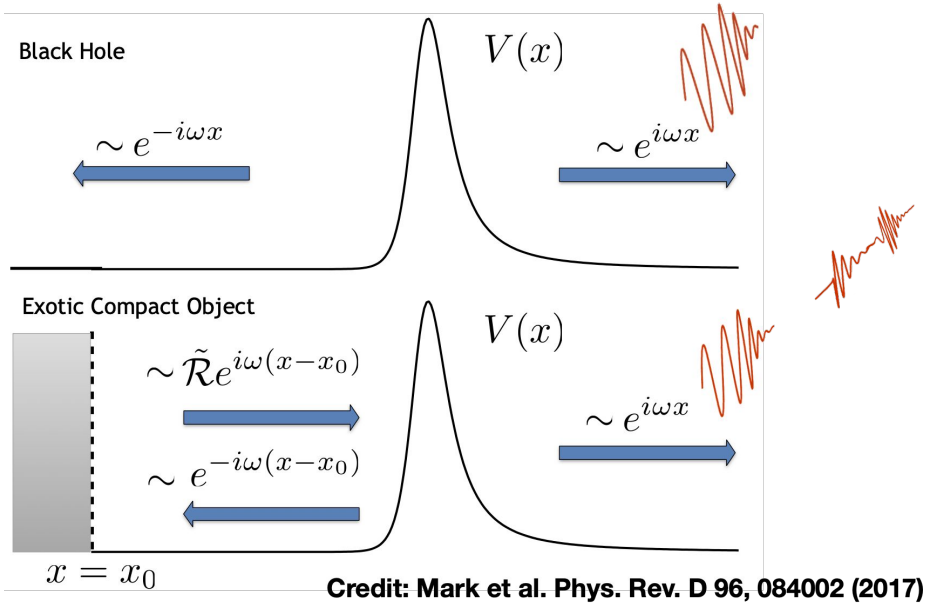
$\delta\hat{\tau}_{221}$

virtually unconstrained

excluded by prior

echoes

- What if the remnant compact object is ***not*** a classical BH?
- **Exotic compact objects (ECOs)**: event horizon replaced by a reflective surface
- GWs reflecting back and forth between the surface and the light ring ⇒ **GW echoes**
- Inspiral + Merger + Ringdown + Echoes (IMRE)
- Smoking-gun evidence for a BH mimicker if detected



Credit: Mark et al. Phys. Rev. D 96, 084002 (2017)

echoes

- Analyzed 31 BBHs from GWTC-2 *(O1+O2+O3a)* passing the FAR threshold
- Positive log Bayes factor: the IMRE model is preferred over the IMR model by the observed data, vice versa
- **No significant evidence of GW echoes found**
- Most ‘significant’ event: GW190915_235702, the log Bayes factor is *merely 0.17*
- Not shown in the table (not passing the selection threshold): for GW151012 in O1 and for GW170729 in O2, both have negative log Bayes factor

Event	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$	Event	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$
GW150914	−0.57	GW170809	−0.22
GW151226	−0.08	GW170814	−0.49
GW170104	−0.53	GW170818	−0.62
GW170608	−0.44	GW170823	−0.34
GW190408_181802	−0.93	GW190706_222641	−0.10
GW190412	−1.30	GW190707_093326	0.08
GW190421_213856	−0.11	GW190708_232457	−0.87
GW190503_185404	−0.36	GW190720_000836	−0.45
GW190512_180714	−0.56	GW190727_060333	0.01
GW190513_205428	−0.03	GW190728_064510	0.01
GW190517_055101	0.16	GW190828_063405	0.10
GW190519_153544	−0.10	GW190828_065509	−0.01
GW190521	−1.82	GW190910_112807	−0.22
GW190521_074359	−0.72	GW190915_235702	0.17
GW190602_175927	0.13	GW190924_021846	−0.03
GW190630_185205	0.08		

dispersion & polarizations

Anuradha Gupta

dispersion

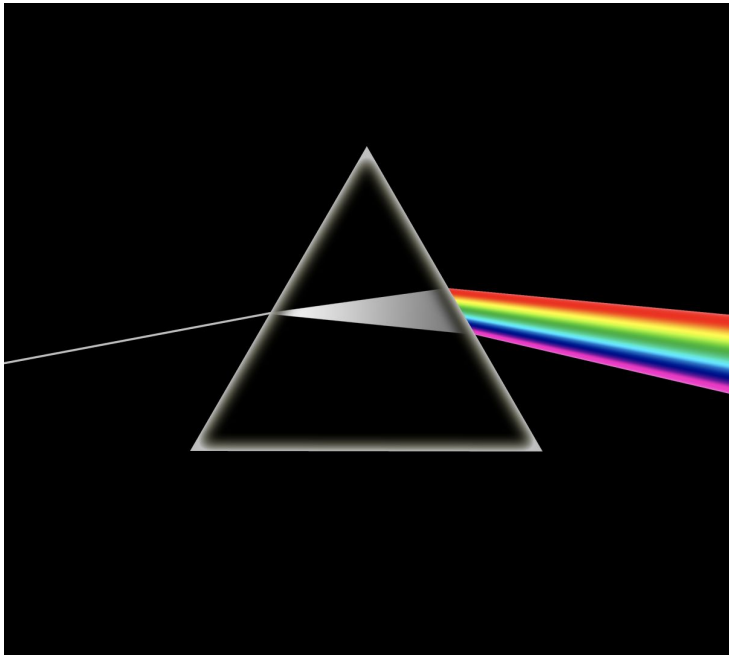
Generalized Dispersion Relation:

$$E^2 = p^2\,c^2 + A_\alpha\,p^\alpha\,c^\alpha$$

E = Energy
p = momentum
c = speed of light
A_α, α = phenomenological parameters

GR	**Extensions of GR**
$A_\alpha = 0,\ \text{for all}\ \alpha$	Massive gravity theory:
$m_g = 0$	$\alpha = 0,\ A_\alpha > 0,\ m_g = A_0^{1/2} c^{-2}$

m_g = graviton mass



https://commons.wikimedia.org/wiki/File:Optical-dispersion_(1).png

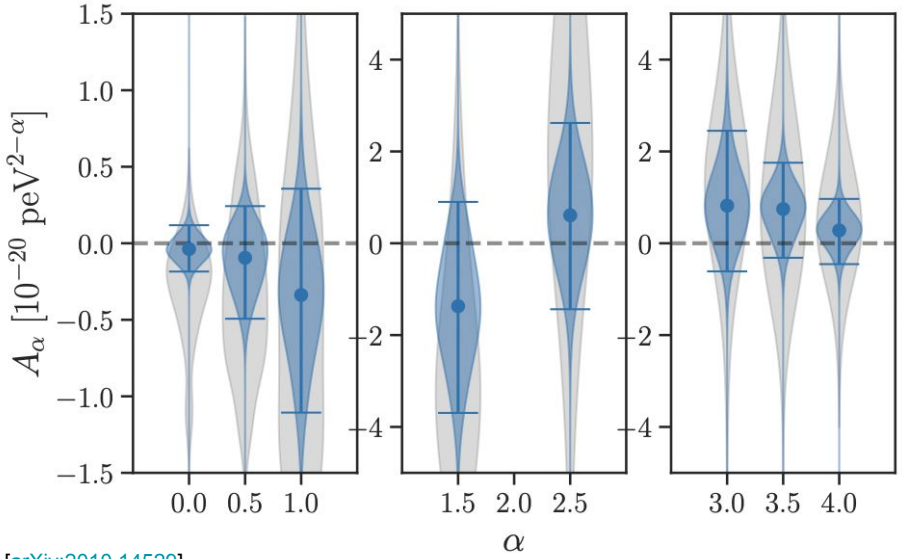
Dispersion of light wave

dispersion

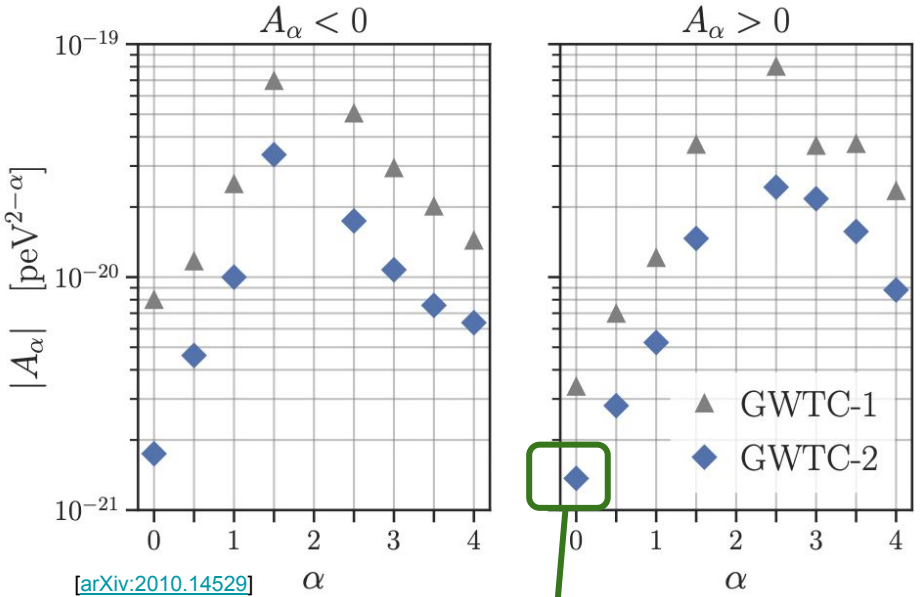
$$\alpha = 0,\ 0.5,\ 1.0,\ 1.5,\ 2.5,\ 3,\ 3.5,\ 4.0$$
$$A_\alpha < 0,\ A_\alpha > 0$$

- Assume that the signal close to the source is given by GR, all modifications come from propagation
- Leads to the dephasing of the entire GW signal, proportional to A_α, and roughly to the distance
- A_α and m_g are analysis parameters
  - flat prior in A_α
  - flat prior in m_g
- Since A_α and m_g have same values for all events, posteriors from individual events are multiplied to obtain the combined results

dispersion



[arXiv:2010.14529]



[arXiv:2010.14529]

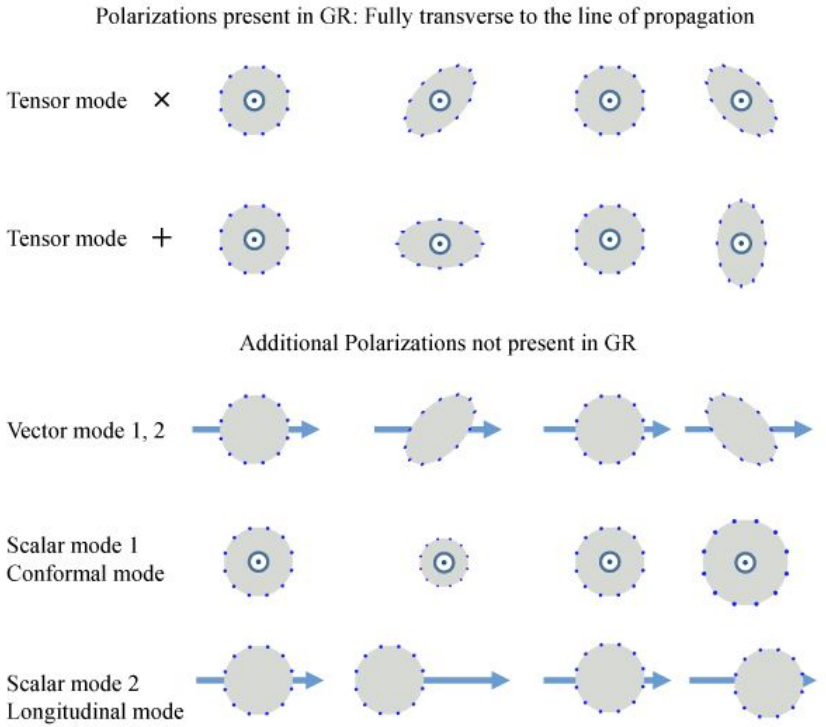
gives graviton mass

dispersion

- Noticeable improvement in the upper bound of $|A_\alpha|$ as compared to GWTC-1
- A factor of ~2.6 improvement, consistent with the increase in number of events from GWTC-1 to GWTC-2
- $m_g \leq 1.76 \times 10^{-23}\,\mathrm{eV/c^2}$, with 90% credibility
- A factor of ~2.7 improvement as compared to GWTC-1
- 1.8 times more stringent than the recent Solar System bound of $3.16 \times 10^{-23}\,\mathrm{eV/c^2}$ with 90% credibility [Phys. Rev. D 102, 021501 (2020)]

polarizations

- Generic metric theories of gravity allow up to *six* GW polarizations
  - two tensor modes (helicity ±2), allowed in GR
  - two vector modes (helicity ±1)
  - two scalar modes (helicity 0)
- Polarization content is imprinted in the relative amplitudes of the output at different detectors
- Used to reconstruct the GW polarization content in the data
- Five-detector network would be ideal for this test
- We used three-detector network to distinguish between specific subsets of all the possible polarization combinations



Credit: Claudia de Rham, LRR, 17 (2014).

polarizations

- Extreme polarization hypotheses:
  - full-tensor vs full-vector
  - full-tensor vs full-scalar
- Null-stream based polarization test, does not rely on specific waveform models
  - *Null-stream*: linear combination of data streams from different detectors
    - Free of true GW signal with a given helicity and sky-location
    - Marginalized over sky-location
  - Any excess power in the *null stream* must be produced by a different helicity and sky-location
  - Quantify the excess power by *null energy*

polarizations

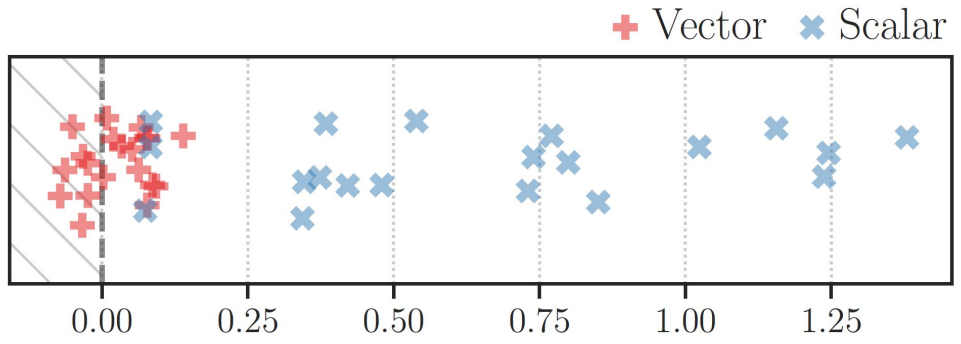
Event	$\log_{10} \mathcal{B}^T_V$	$\log_{10} \mathcal{B}^T_S$
GW170809	0.078	0.421
GW170814	−0.032	0.740
GW170818	0.002	0.344
GW190408_181802	0.076	0.480
GW190412	0.079	0.539
GW190503_185404	−0.072	1.245
GW190512_180714	−0.024	0.346
GW190513_205428	0.139	1.380
GW190517_055101	0.008	0.730
GW190519_153544	0.067	0.799
GW190521	0.093	1.156
GW190602_175927	−0.064	0.373
GW190706_222641	0.052	0.771
GW190720_000836	0.034	0.074
GW190727_060333	0.087	1.024
GW190728_064510	−0.024	0.083
GW190828_063405	0.063	0.851
GW190828_065509	−0.034	0.084
GW190915_235702	0.020	1.238
GW190924_021846	−0.051	0.384

highest Bayes factor

lowest Bayes factors

$\mathcal{B}^T_V$ = Bayes factor for full-tensor vs full-vector hypotheses

$\mathcal{B}^T_S$ = Bayes factor for full-tensor vs full-scalar hypotheses



[arXiv:2010.14529]

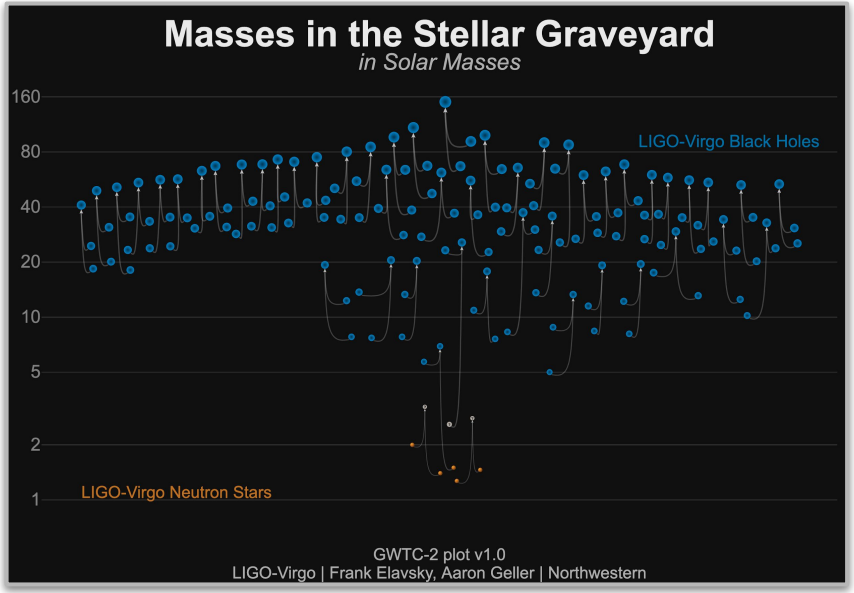
conclusion

Max Isi

conclusion

- ➔ no statistically significant deviations from GR, or unaccounted systematics
- ➔ improved GWTC–1 constraints by factors of ~2–3
- ➔ introduced new analyses, and statistical techniques

more to come!




LIGO
VIRGO