LIGO-G2301164-v4

TESTS OF GENERAL RELATIVITY BY THE LIGO-VIRGO-KAGRA COLLABORATION:

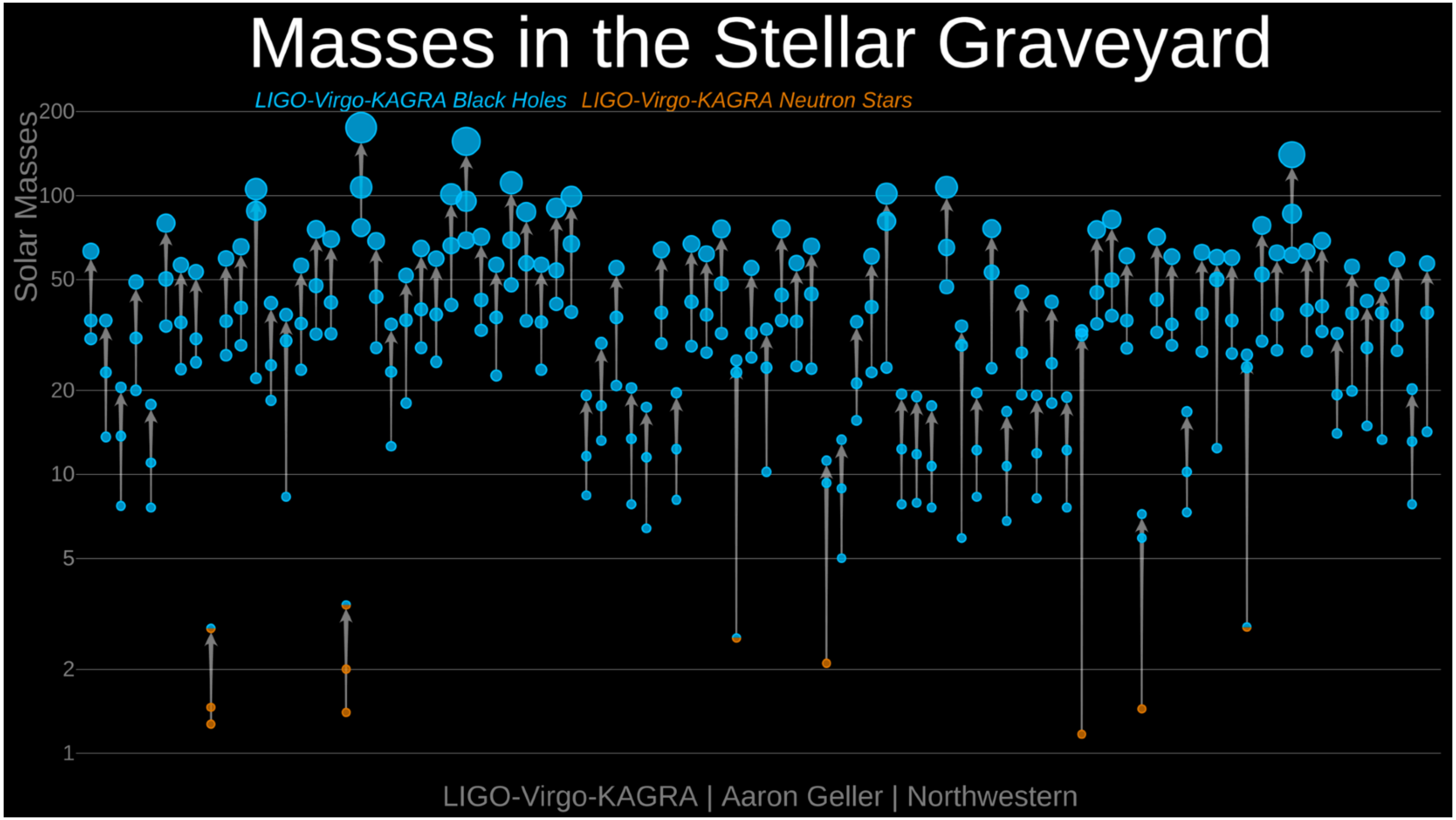
CURRENT RESULTS AND O4 PROSPECTS

CONNECTING THE DOTS WORKSHOP
AEI POTSDAM
14.6.23

See LVK, arXiv:2112.06861 for the latest results

N. K. JOHNSON-MCDANIEL, FOR THE LVK

MOTIVATION



About 90 compact binary coalescences detected through O3.

How can we use the most significant of these to test GR?

OVERVIEW OF LVK TESTS OF GR [THROUGH O3]

No waveform models

Uses waveform models

PARAMETERIZED TESTS

- Variations in PN coefficients/ other waveform:parameters:

  TIGER, FTI, spin-induced quadrupole
- Modified dispersion relation
- modified QNM frequencies: pSEOBNR

Analyzes full signal

NONTENSORIAL POLARIZATIONS

CONSISTENCY TESTS

- Residuals
- IMR consistency
- [Waveform reconstructions]

MODELED ECHOES

Also some multimessenger tests of speed of gravity, etc. with GW170817/GRB 170817A

Analyzes only post-merger signal

UNMODELED ECHOES

TIME-DOMAIN RINGDOWN ANALYSIS (PYRING)

SELECTION OF EVENTS FOR TESTING GR

- **Each analysis has its own selection criteria of which events to analyze.**

  There are also overall criteria to make sure that only high-significance events are considered:

- **Detection by at least two interferometers with a false alarm rate of less than 1 in 1000 years in any of the offline detection pipelines used for the catalogue paper.**

  For O3b, this was three modeled searches (GstLAL, MBTA, and PyCBC) and one minimally modeled [i.e., without templates] coherent WaveBurst (cWB) search.

  This gives 48 total BBHs, as well as 1 NSBH (GW200115_042309) and 1 BNS (GW170817).

SIGNIFICANT SELECTION EFFECTS FAVORING GR?

- **Do these criteria exclude some potential signals with a GR deviation?**

  Probably so: The deviation could be significant enough that the signals lose significant SNR when filtered with GR waveforms, and/or are downranked by the signal consistency test.

- **The inclusion of cWB will help mitigate this—it only assumes a chirping signal, which is a generic prediction for compact binaries, though cWB is only sensitive to higher-mass binaries.**

- **Also, Ghosh, NKJ-M, et al. (CQG, 2018) found that a non-GR signal with a fairly significant GR deviation had no signal consistency penalty and would likely be detected by the matched filter searches.**

- **Looking towards the future, templated searches for non-GR or other exotic signals are starting to be developed (e.g., H. Narola et al. PRD 2023 for signals with deviation in PN coefficients; H. S. Chia et al. arXiv 2023 for binaries with BBH masses but nonzero tides).**

COMBINING TOGETHER RESULTS FROM MANY EVENTS

- **If the dependence of the GR deviation on the binary's parameters is known, one can combine together the results optimally by multiplying the likelihoods on the deviation parameter.**

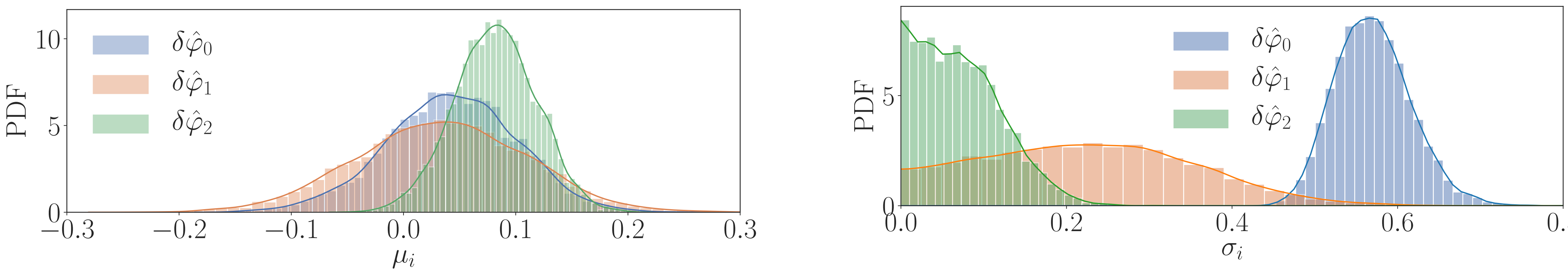
  This is the case for the modified dispersion relation, where the dependence on distance is known.

- **One can still multiply the likelihoods for more generic tests, but this gives overly constraining results, in general** (see, e.g., A. Zimmerman et al., PRD 2019).

COMBINING TOGETHER RESULTS FROM MANY EVENTS: HIERARCHICAL COMBINATION

- **Alternatively, one can infer the distribution of non-GR parameters in the detected population hierarchically, as in Isi et al. (PRL, 2019).**
- **Here one infers the parameters describing the population distribution of non-GR parameters, currently taken to be a Gaussian for simplicity, so one infers a mean and variance: Both should be consistent with zero if the population is consistent with GR.**
- **The Gaussian distribution is in principle sufficient to detect any possible deviations from GR in the population—see Isi et al. (PRD, 2022) for a toy model example of inference of a very non-Gaussian distribution—though it is possible that a more complicated distribution might be more efficient for some realistic cases—this will be studied in the future. The current version is just 1d, but there will be at least a 2d version for O4.**
- **The LVK uses both likelihood multiplication and hierarchical methods to combine most results, for comparison.**

Inferred distributions of mean and variance for toy model populations with GR deviations in $\delta\hat{\phi}_0$ and $\delta\hat{\phi}_2$ from Isi et al. (PRL, 2019)

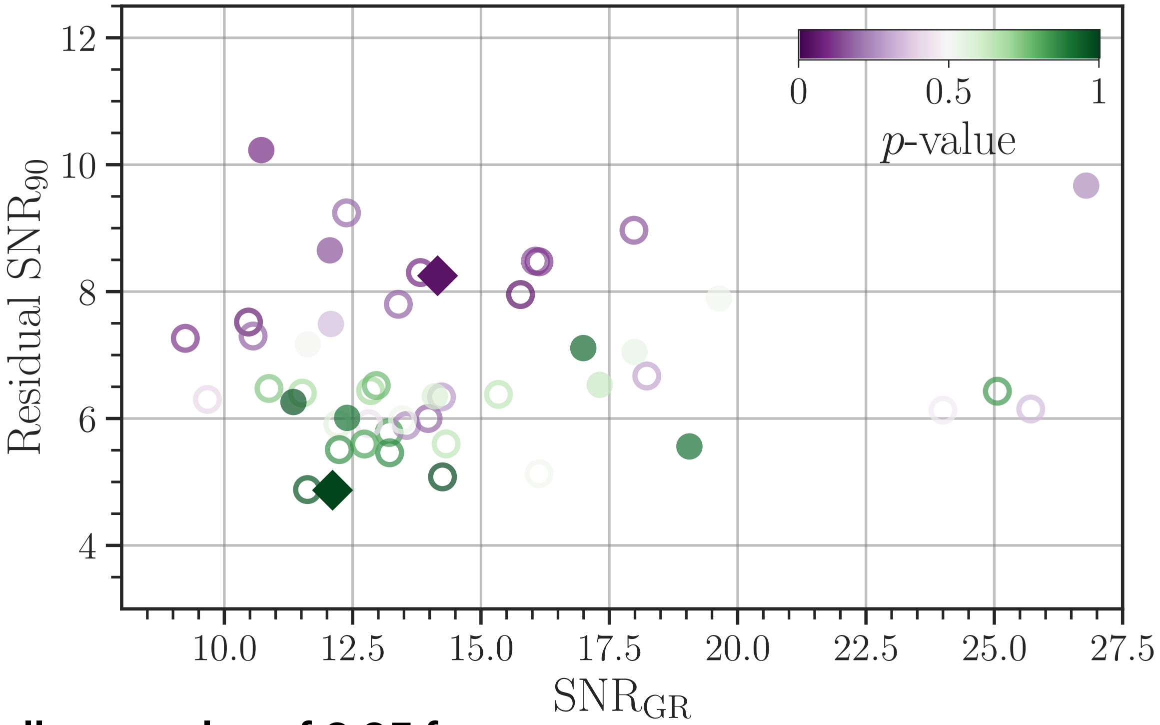


RESIDUALS TEST

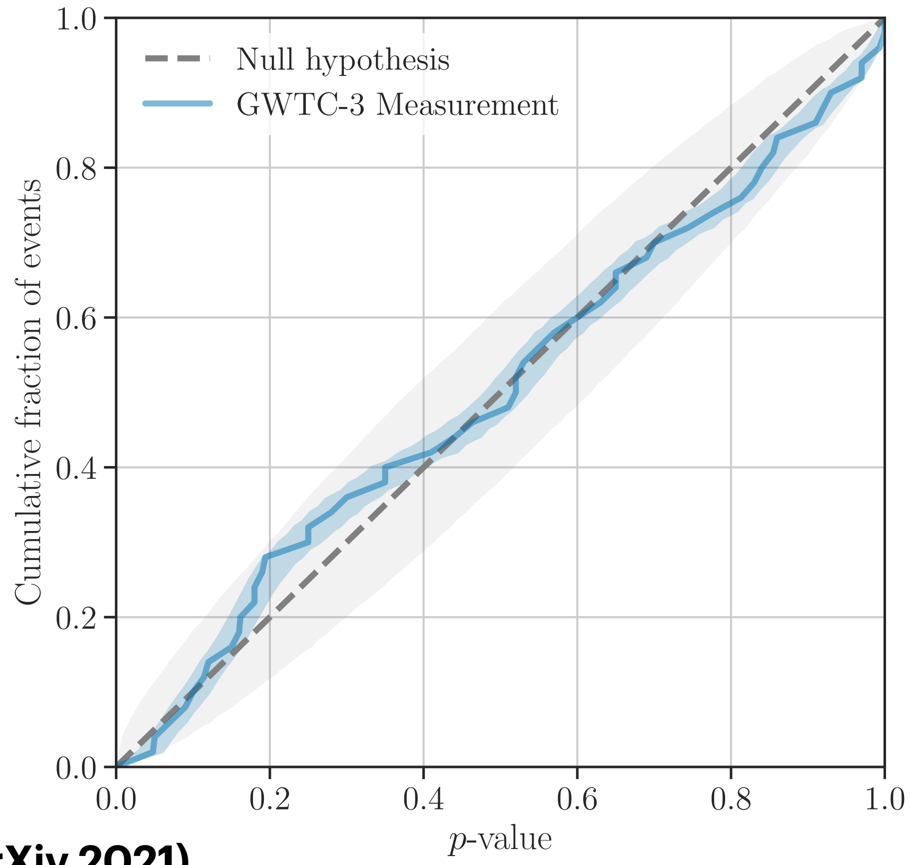
- **Subtracts the maximum likelihood waveform from the GR analysis from the data and computes the SNR of the residuals using BayesWave (which models the signal as a superposition of wavelets).**

- **Computes the p-value based on SNR distribution in noise background around event.**

solid circles are O3b events; diamonds are extremal p-values



Smallest p-value of 0.05 for GW200225_060421



GWTC-3 results (LVK, arXiv 2021)

- **Very general test, but only sensitive to extreme deviations from GR even at relatively large SNRs (~50)—see NKJ-M et al. (PRD, 2022). Sensitive to more reasonable deviations at very large SNRs (≳75)—see Okounkova et al. (PRD, 2023).**

INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST

- Divides the signal into low- and high-frequency parts (dividing at ca. the median $m = 2$ GW frequency of the ISCO of the final black hole from the analysis of the full signal). These correspond roughly to the inspiral and postinspiral for the dominant mode of the signal.

  Requires sufficient SNR (> 6) in both inspiral and postinspiral, so not applicable to too low-mass or too high-mass signals.

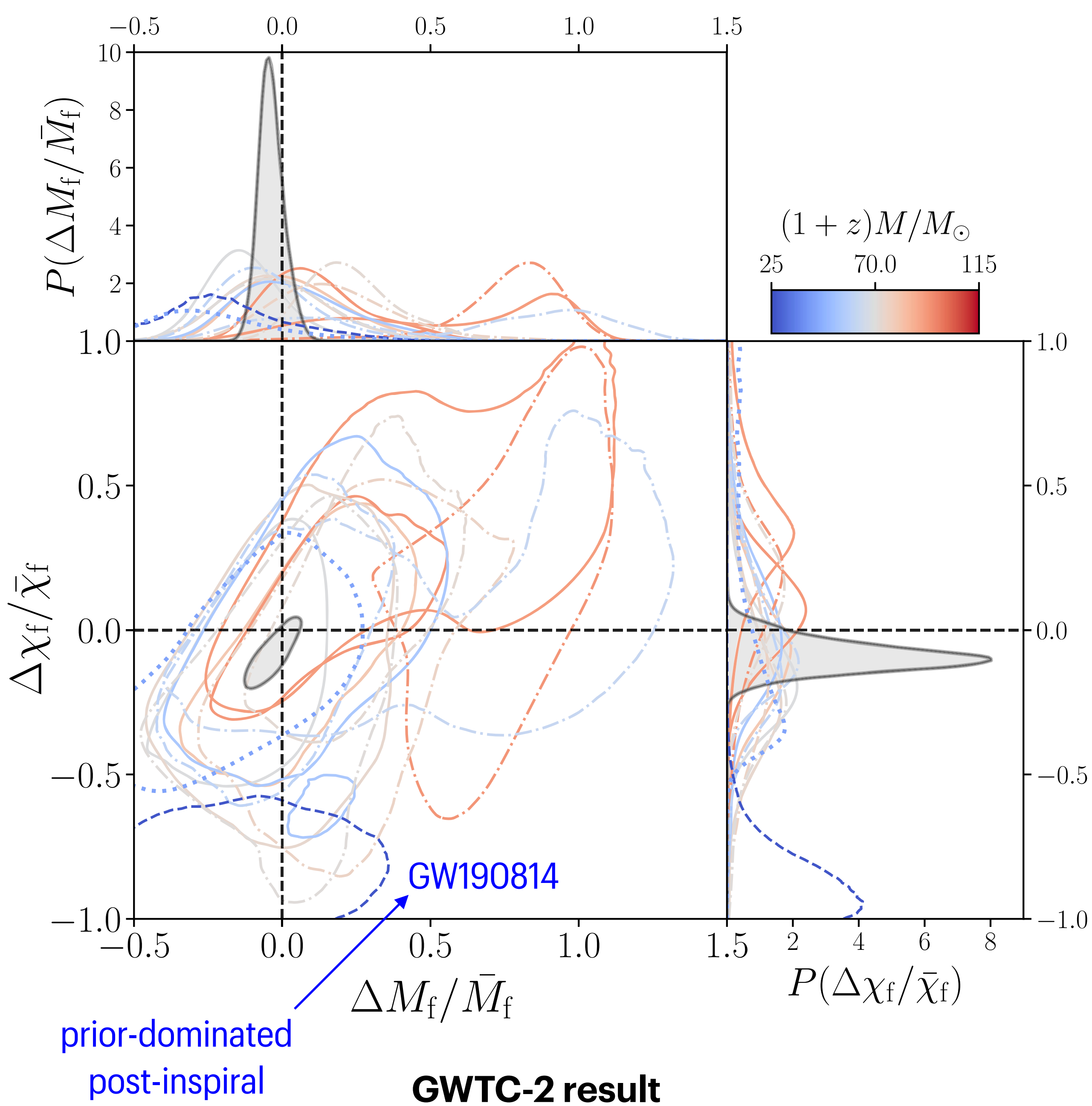
- Infers the final mass and spin from each portion of the signal using a standard GR analysis with the restricted frequency range, and applies NR fits to get the final mass and spin from the binary's individual masses and spins.

- Defines two deviation parameters that are consistent with zero in GR:

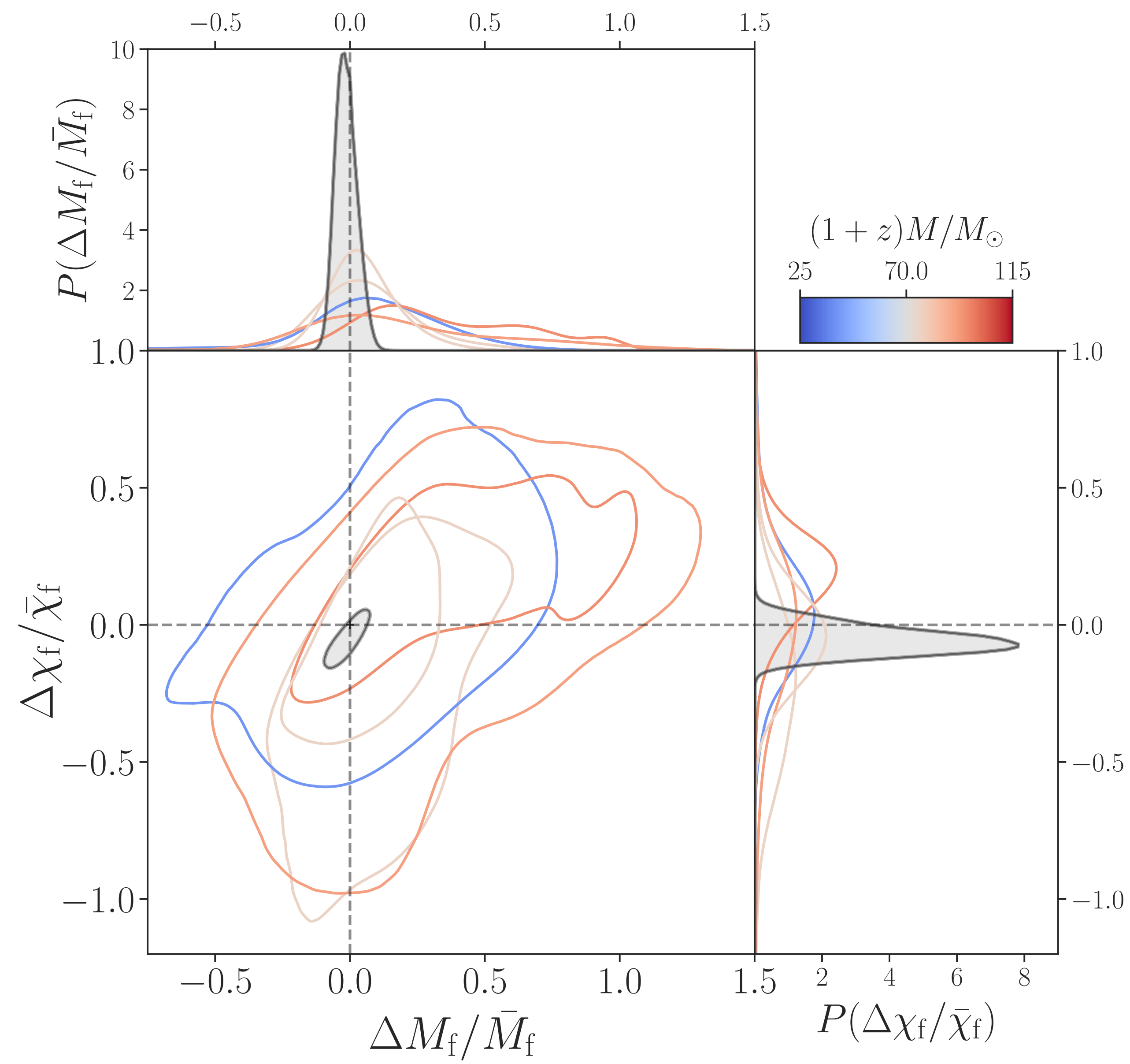
$$\frac{\Delta M_{\rm f}}{\bar{M}_{\rm f}} = 2\frac{M_{\rm f}^{\rm insp} - M_{\rm f}^{\rm postinsp}}{M_{\rm f}^{\rm insp} + M_{\rm f}^{\rm postinsp}}, \qquad \frac{\Delta \chi_{\rm f}}{\bar{\chi}_{\rm f}} = 2\frac{\chi_{\rm f}^{\rm insp} - \chi_{\rm f}^{\rm postinsp}}{\chi_{\rm f}^{\rm insp} + \chi_{\rm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

See Ghosh, NKJ-M, et al. (CQG, 2018) for details

INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST: RESULTS



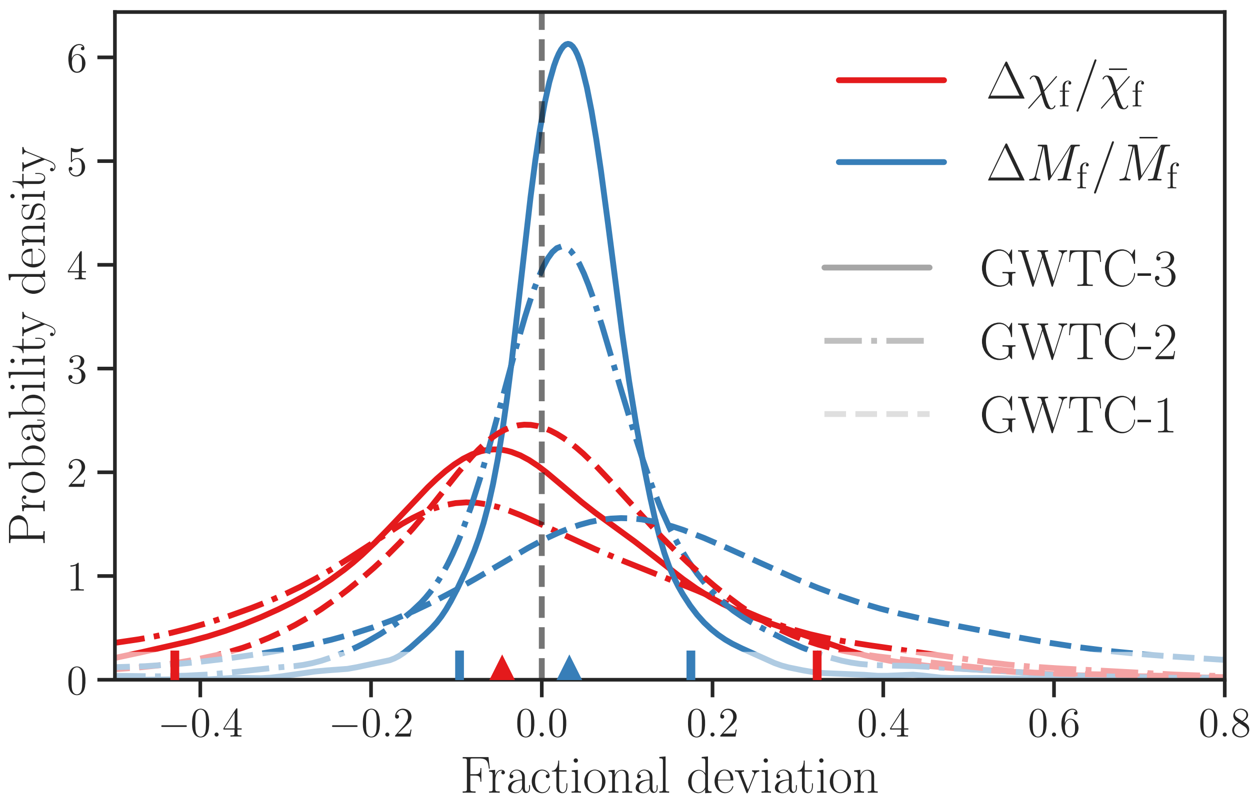
GWTC-2 result
(LVK, PRD 2021)

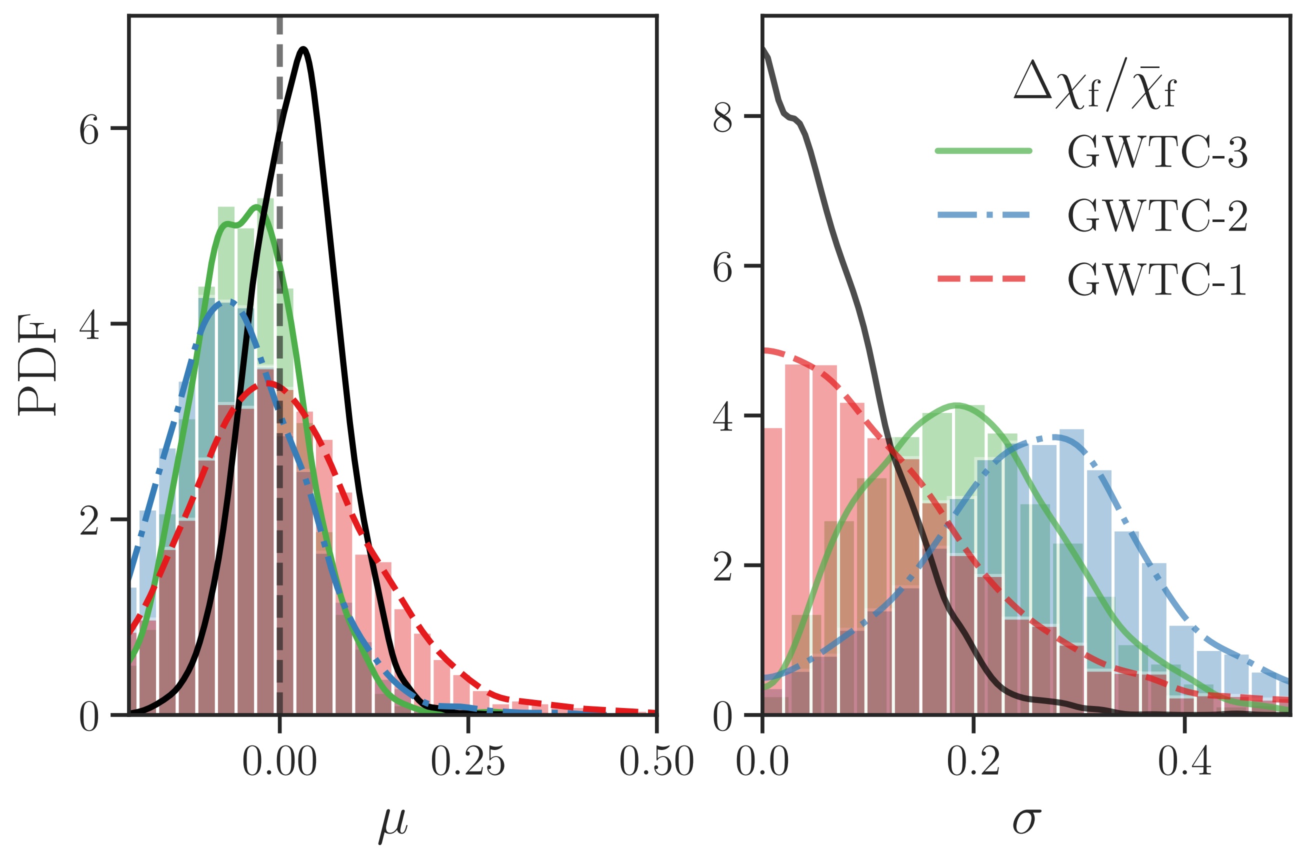


GWTC-3 result
(LVK, arXiv 2021)

dot-dashed contours are for O1 and O2 events

INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST: HIERARCHICAL RESULTS





Black traces exclude GW190814

GWTC-3 result
([LVK, arXiv 2021](#))

PARAMETERIZED TESTS: TIGER AND FTI

- Constrain deviations added to the frequency-domain phase of the waveform

  Deviations are added in the PN coefficients for both TIGER and FTI and in the phenomenological intermediate and merger-ringdown coefficients for TIGER

- TIGER [see Meidam et al. PRD (2018)] is based on IMRPhenomPv2 (with deviations added to IMRPhenomD before twisting up); an IMRPhenomXP-based version will be used for O4

- FTI [see A. K. Mehta et al. PRD (2023)] is applicable to any frequency-domain waveform in its dominant-mode-only version, but applied to SEOBNRv4_ROM in the LVK analyses. It is currently only applicable to SEOBNRv4HM_ROM in its higher-mode version.

PARAMETERIZED TESTS: TIGER AND FTI

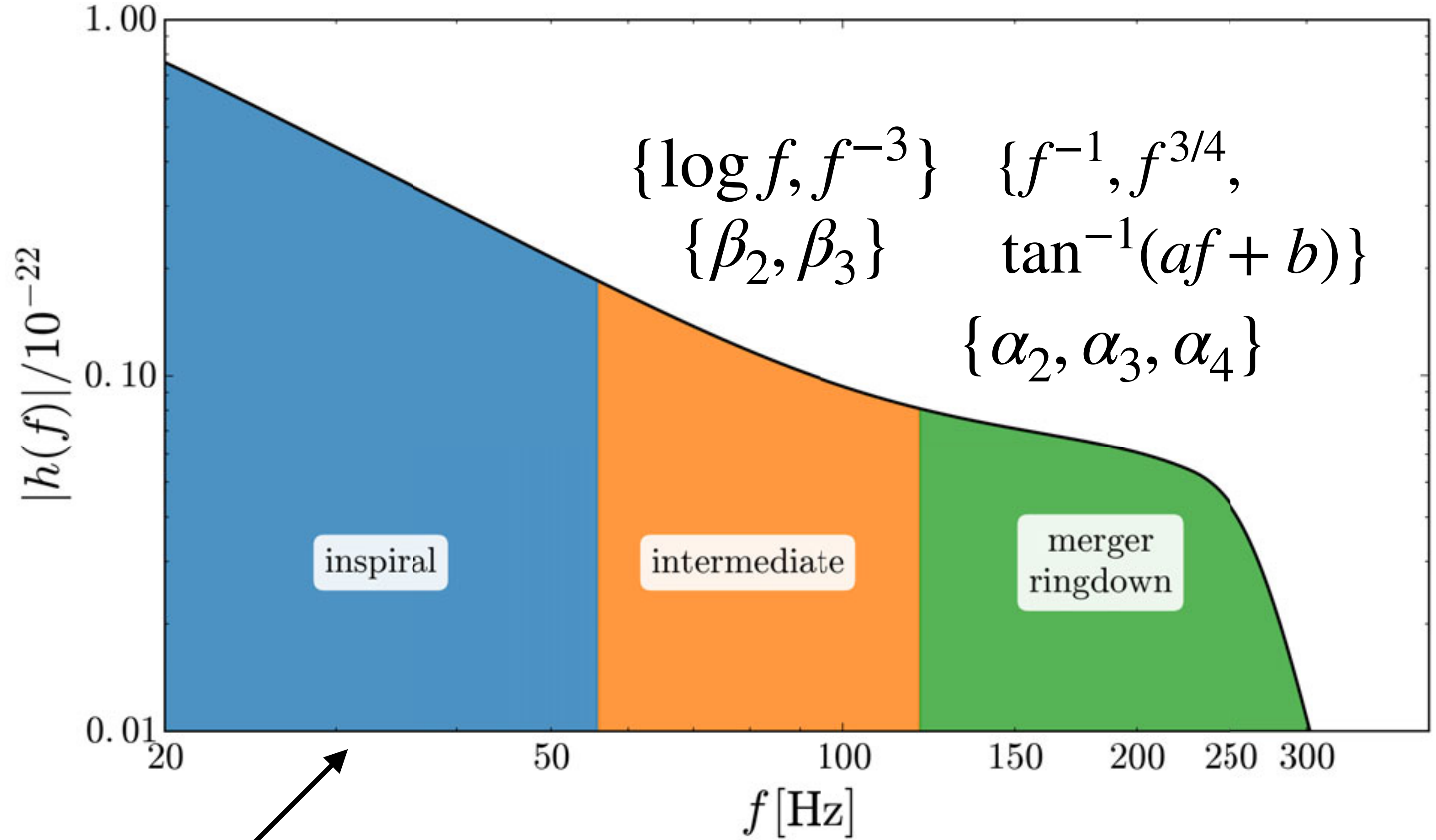
- TIGER allows the lower-frequency deviations to affect the higher-frequency parts of the waveform through the C^1 matching in the IMRPhenomD construction.

  FTI tapers the deviations to zero above some frequency.

- Both analyses currently only vary one testing parameter at a time. Sufficient to detect deviations from GR, but in general not to measure individual PN coefficients, even when using the leading-order deviation as the testing parameter (see NKJ-M et al. PRD 2022). [The postinspiral portion also affects the measurement of PN coefficients.]

  There is work on principal component analysis for multi-parameter tests (e.g., Saleem et al., PRD 2022).

PARAMETERIZED TESTS: TIGER AND FTI



PhenomD amplitude; illustration from Meidam et al. PRD (2018)

PN phasing

$$\Phi(f) = \frac{3}{128\eta(\pi M_z f)^{5/3}} \sum_{k=0}^{7} [\varphi_k + \varphi_{kl} \ln(\pi M_z f)](\pi M_z f)^{k/3}$$

(PhenomD inspiral includes higher-order phenomenological coefficients where there are no testing parameters added)

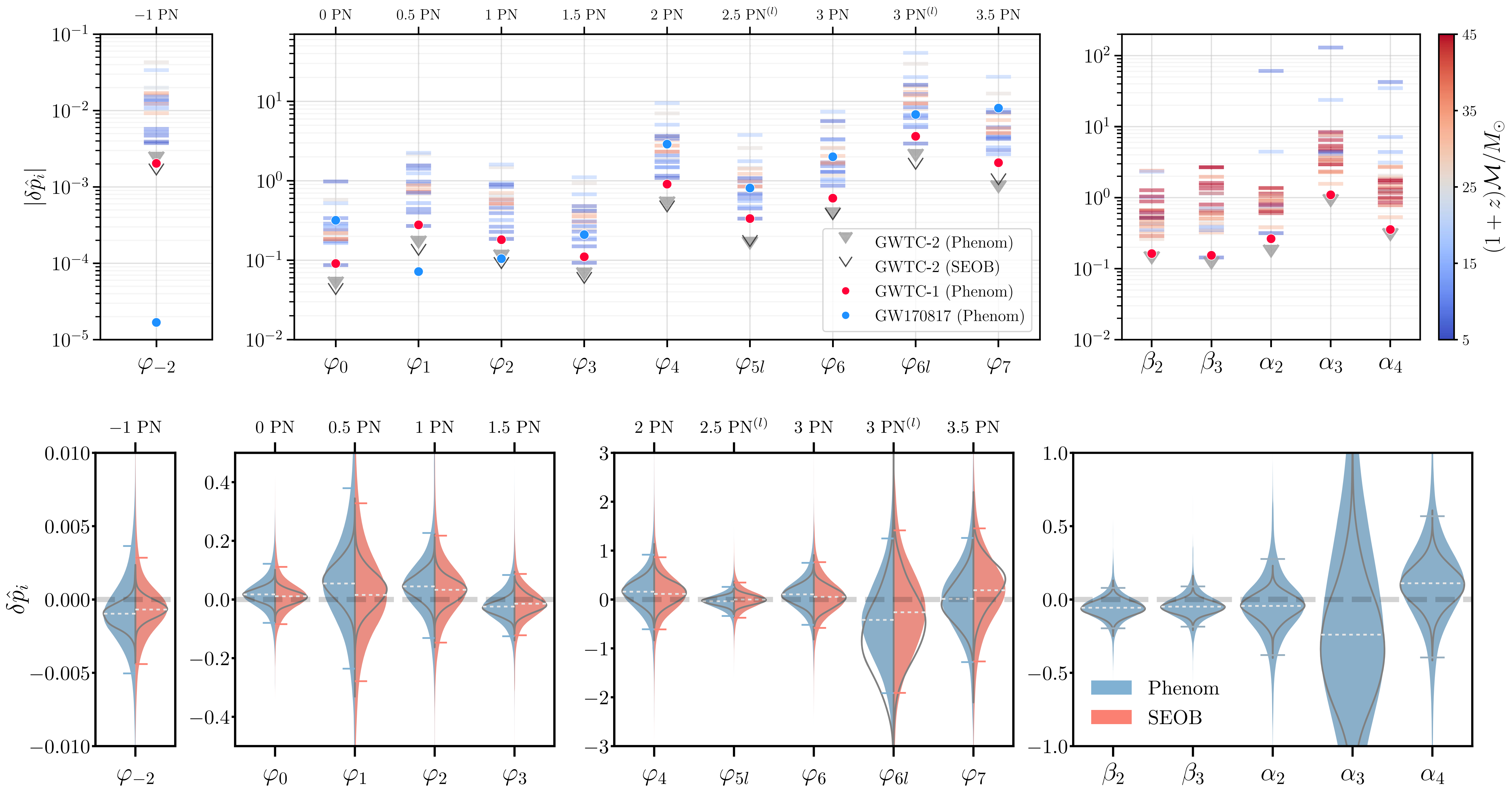
Introduction of testing parameters

(-1PN and 0.5PN parameters normalized by Newtonian phase coefficient)

$$p_k \to p_k(1 + \delta\hat{p}_k)$$

$$p_k \in \{\varphi_k, \varphi_{kl}, \alpha_k, \beta_k\}$$

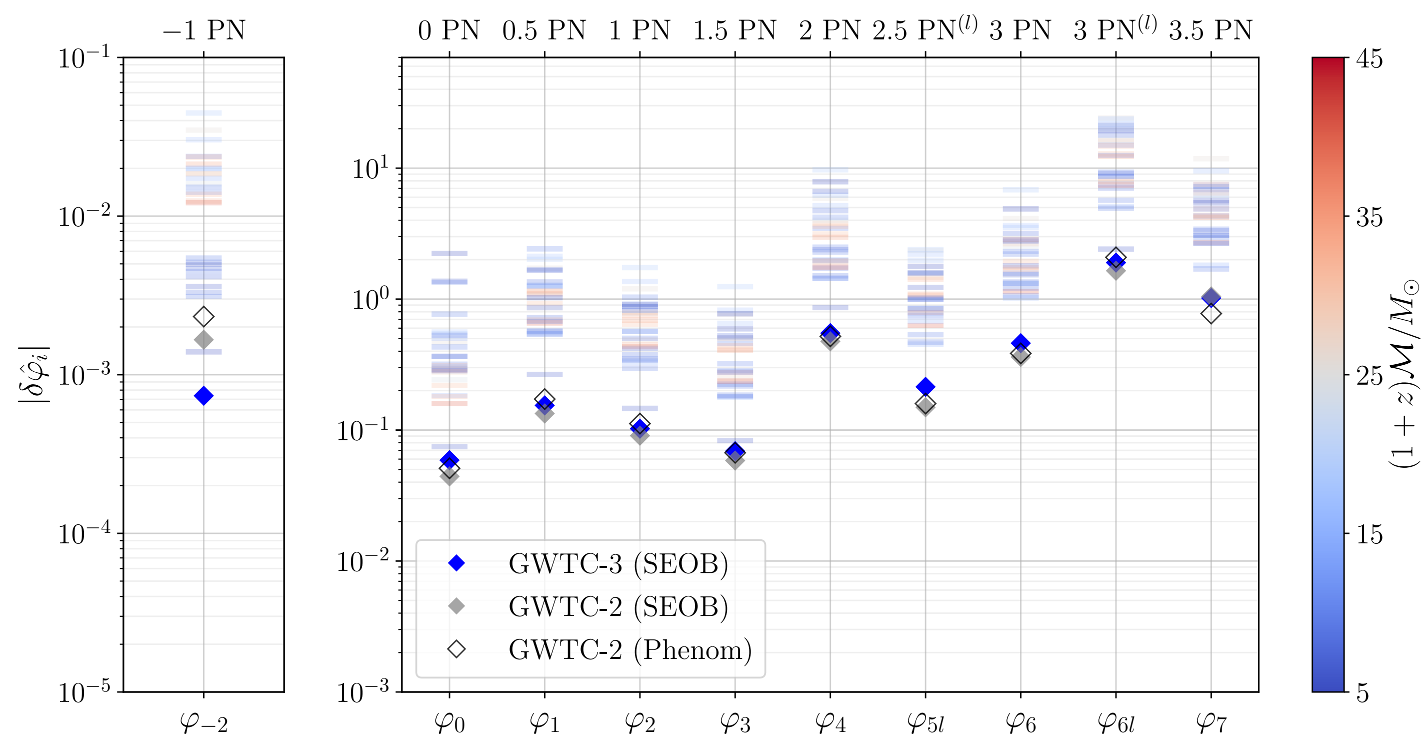
PARAMETERIZED TESTS: TIGER AND FTI RESULTS FROM GWTC-2

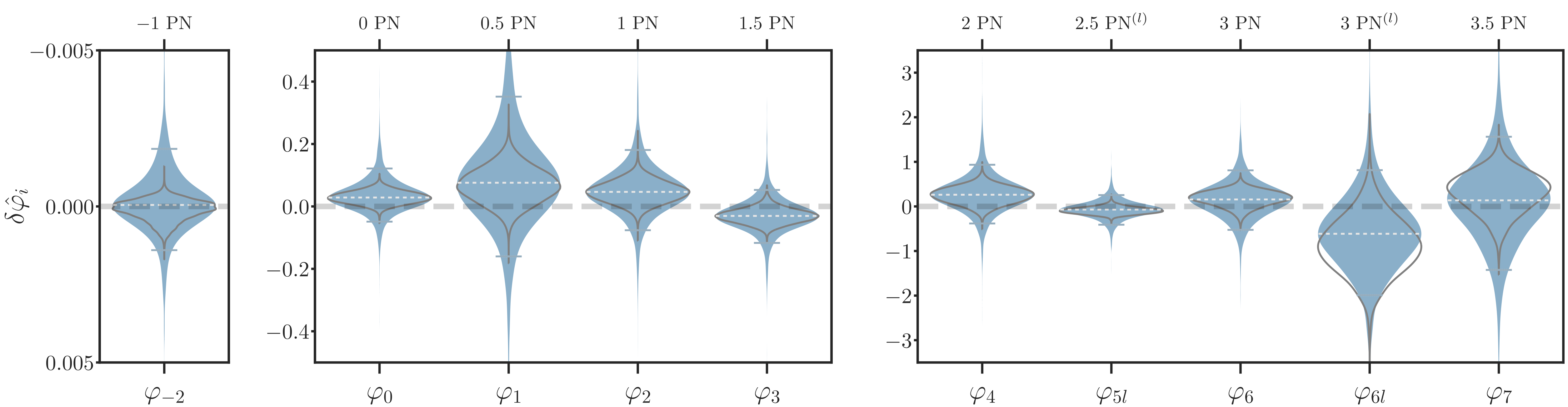


unfilled violins: likelihood multiplication

LVK, PRD (2021)

PARAMETERIZED TESTS: FTI RESULTS FROM GWTC-3





unfilled violins: likelihood multiplication

LVK, arXiv (2021)

PARAMETERIZED TESTS: MODIFIED DISPERSION

- Constrain A_α parameter in a phenomenological modified dispersion relation (generically Lorentz violating) [from Mirshekari et al., PRD (2012)]

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

$\alpha = 0, A_0 > 0$ gives a massive graviton; $\alpha = 2.5;\ 4$ correspond to leading-order predictions of multifractal space-time; Hořava-Lifshitz and extra dimensional theories, respectively.

- The LVK thus considers α from 0 to 4 in steps of 0.5, except for 2, which is nondispersive.

- One can also obtain this type of dispersion from dark energy theories (see Harry & Noller, GRG 2022), though there $\alpha < 0$ is also of interest and will be considered in the future.

PARAMETERIZED TESTS: MODIFIED DISPERSION

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

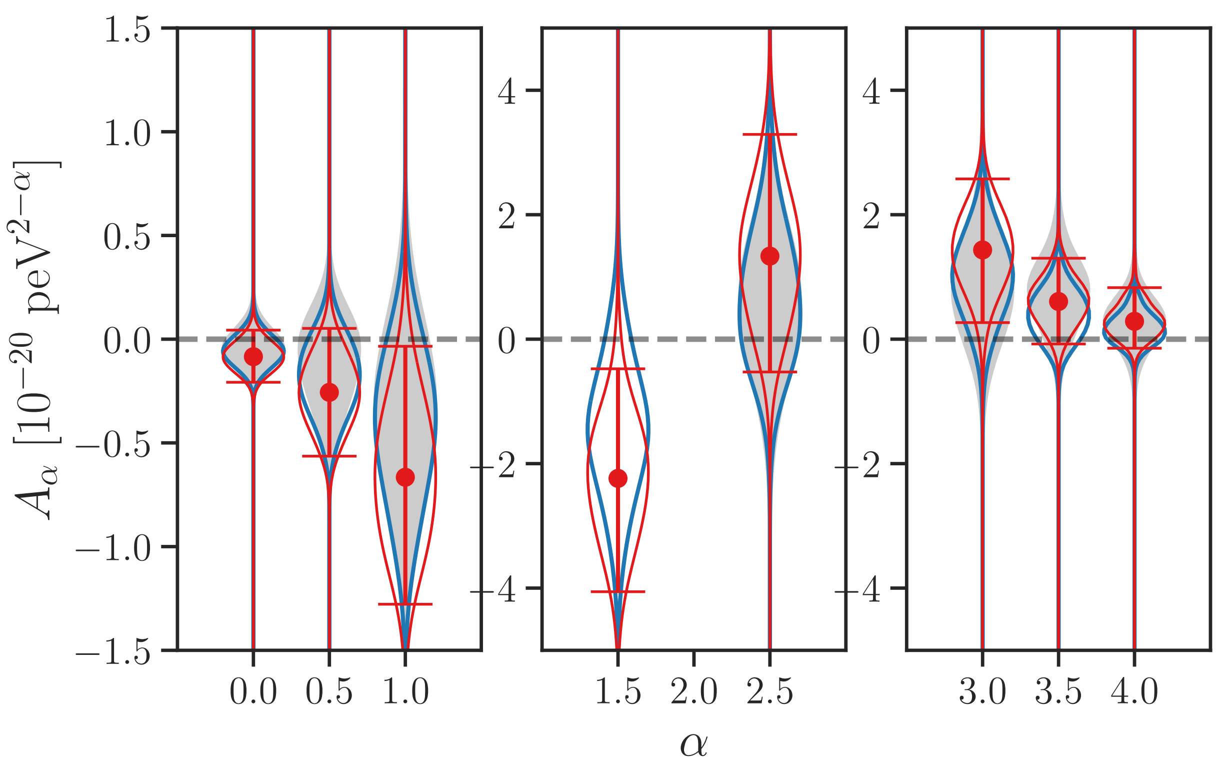
- This gives a frequency-domain dephasing $\propto A_\alpha f^{\alpha-1}$ that increases with increasing distance.

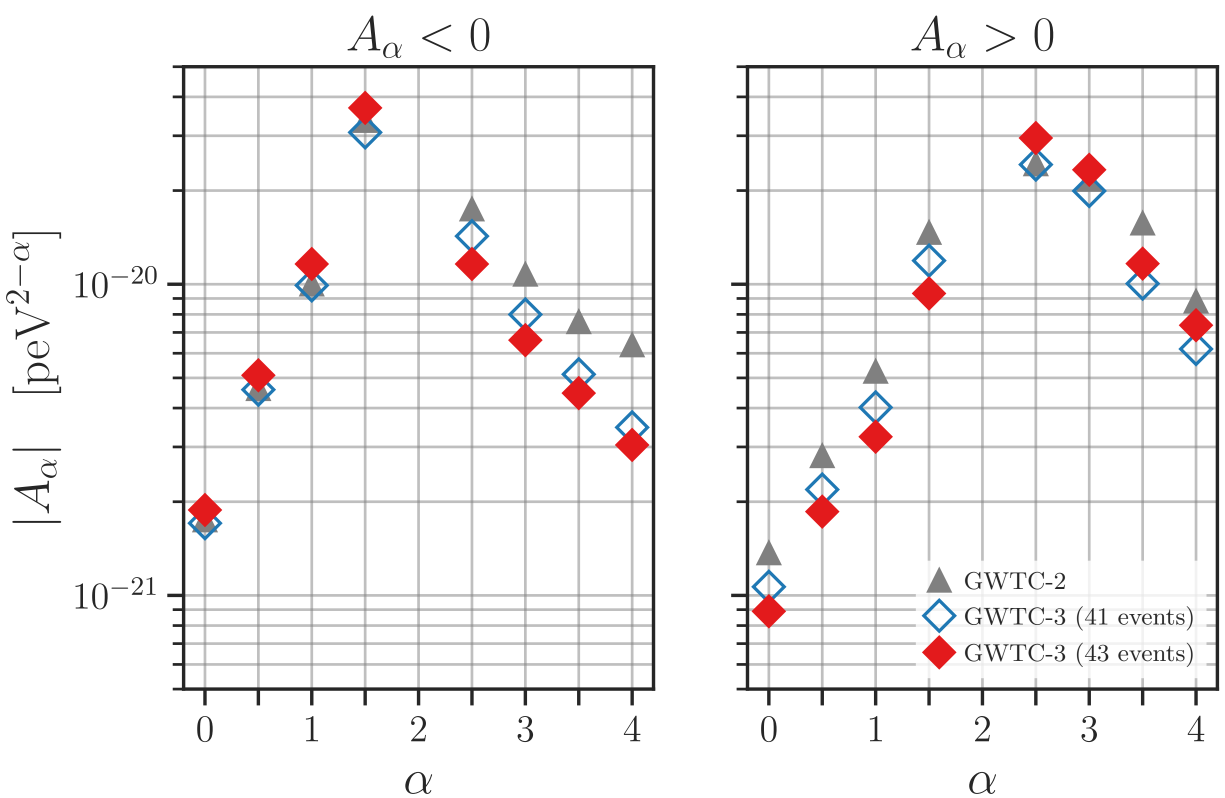
The current implementation has the $\log f$ dependence for $\alpha = 1$ that comes from the particle velocity expression used in Mirshekari et al., PRD (2012). However, in O4 the LVK will use the group velocity expression, as in Ezquiaga et al., JCAP 2022, which gives a constant dephasing for $\alpha = 1$—observable when including higher modes—and a rescaling of the other cases.

- One assumes that the waveform close to the source is the same as in GR to a good approximation (e.g., the Yukawa length scale is constrained to be > 3 pc in the massive graviton case).

PARAMETERIZED TESTS: MODIFIED DISPERSION RESULTS

Red curves include all GWTC-3 events analyzed, while blue results exclude GW200219_094415 and GW200225_060421, which have the two smallest p-values in the residuals test and were biasing the combined results





Graviton mass constrained to $\leq 1.27 \times 10^{-23}\,\mathrm{eV}^2/c^2$ **at 90% credibility**

GWTC-3 results (LVK, arXiv 2021)

RINGDOWN TESTS: PYRING AND PSEOBNR

- **General QNM signal:**

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

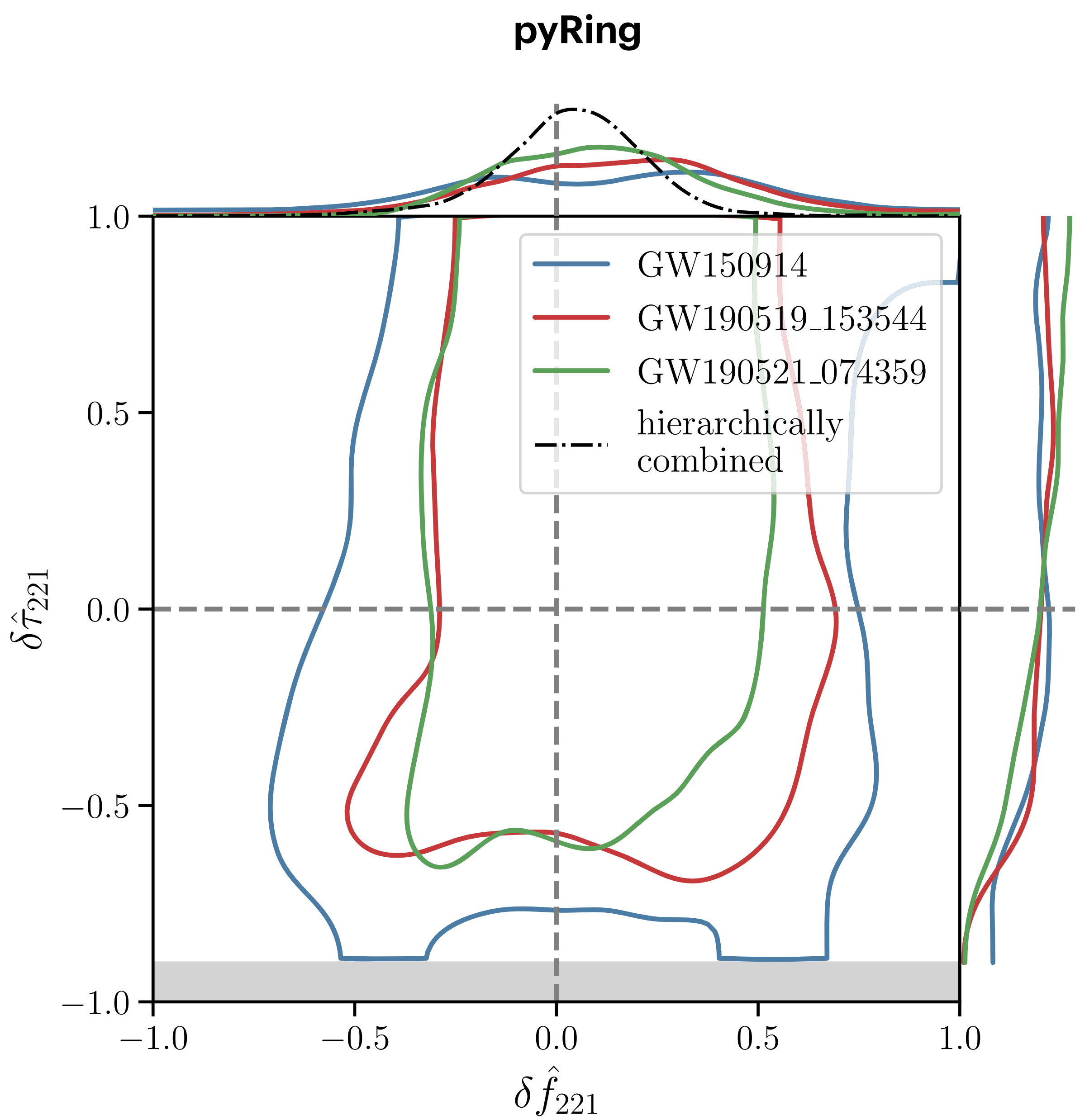
- **pyRing [Carullo et al. PRD (2019)] is a time-domain analysis, allowing it to consider just the post-merger signal. It carries out various analyses, from just a damped sinusoid, to a template with higher modes fit to NR amplitudes (from L. London, PRD 2020).**

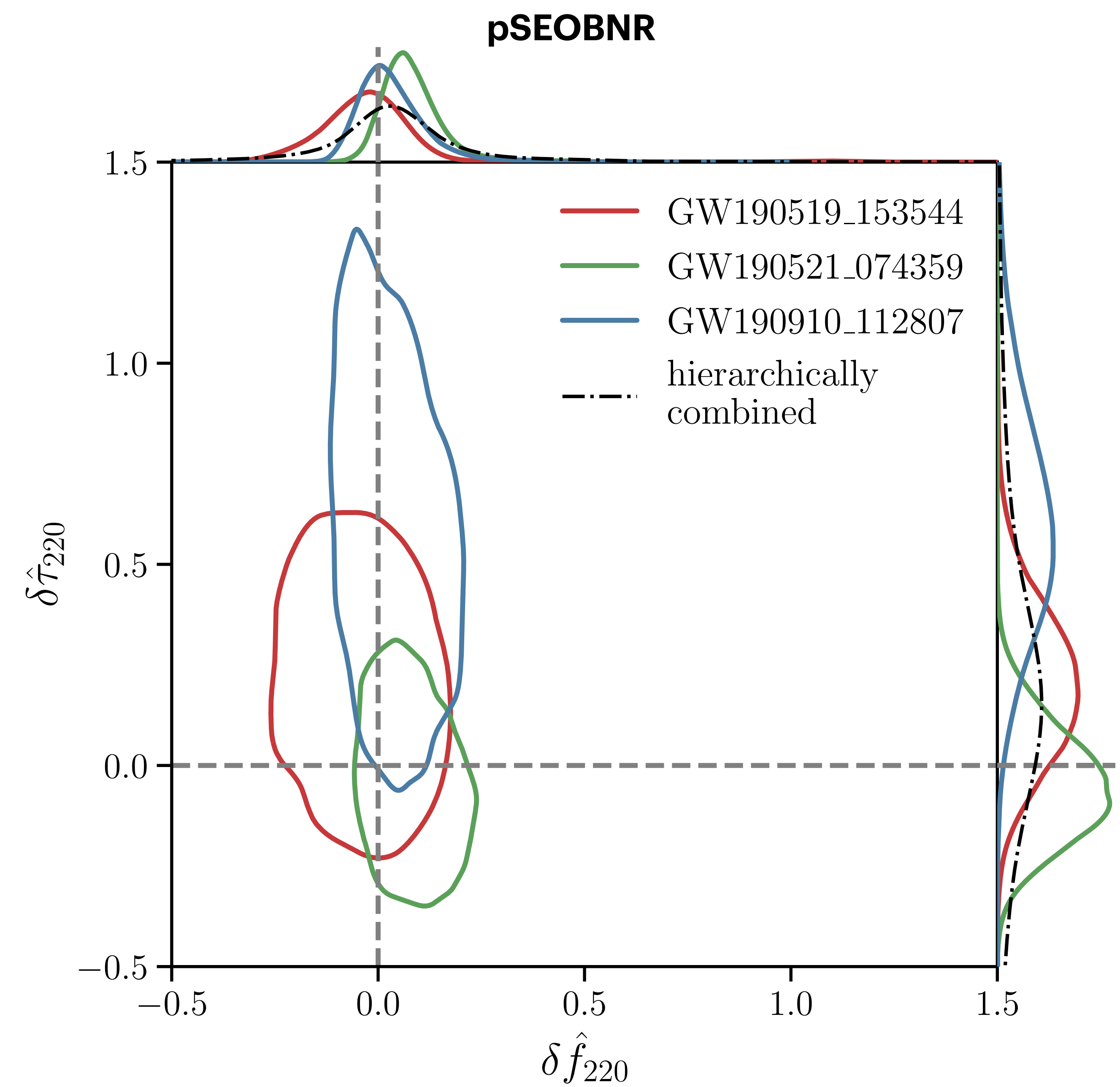
  However, the most direct test of GR is given by the analysis that includes the 220 and 221 QNMs (least-damped quadrupole mode and first overtone), with free mass and spin as well as free amplitude, phase, frequency, and damping time.

  This constrains deviations in the 221 frequency and damping time.

- **pSEOBNR[v4HM] [A. Ghosh et al. PRD (2021)] is a frequency-domain analysis that adds deviations in the QNM spectrum of the SEOBNRv4HM model (currently just in the 220 mode, both frequency and damping time), but analyzes the entire signal.**

RINGDOWN TESTS: pyRING AND pSEOBNR RESULTS





GWTC-3 result
(LVK, arXiv 2021)

MODELED ECHOES TEST

- Look for possible echoes following the merger using the Abedi et al. (PRD, 2017) template. Employed for GWTC-2.
- This analyzes the full signal and repeats the merger-ringdown portion to give the echoes, with five additional parameters:
  - The relative amplitude of the first echo to the merger
  - The damping factor between echoes
  - The start time of ringdown
  - The delay from merger to the first echo.
  - The time delay between echoes.
- Performs Bayesian model comparison with GR model.

Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$	Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$
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		

GWTC-2 results
LVK, PRD (2021)

Negative numbers favor GR

UNMODELED ECHOES TEST

- Uses BayesWave, with combs of decaying sine-Gaussians as the basis functions; see K. W. Tsang et al. (PRD, 2018). Employed for GWTC-3.
- Sine-Gaussians have amplitude, central frequency, damping time, and phase as parameters.
- There are also echo parameters:

  - Time delay for the first echo

  - Time separation of the sine-Gaussians

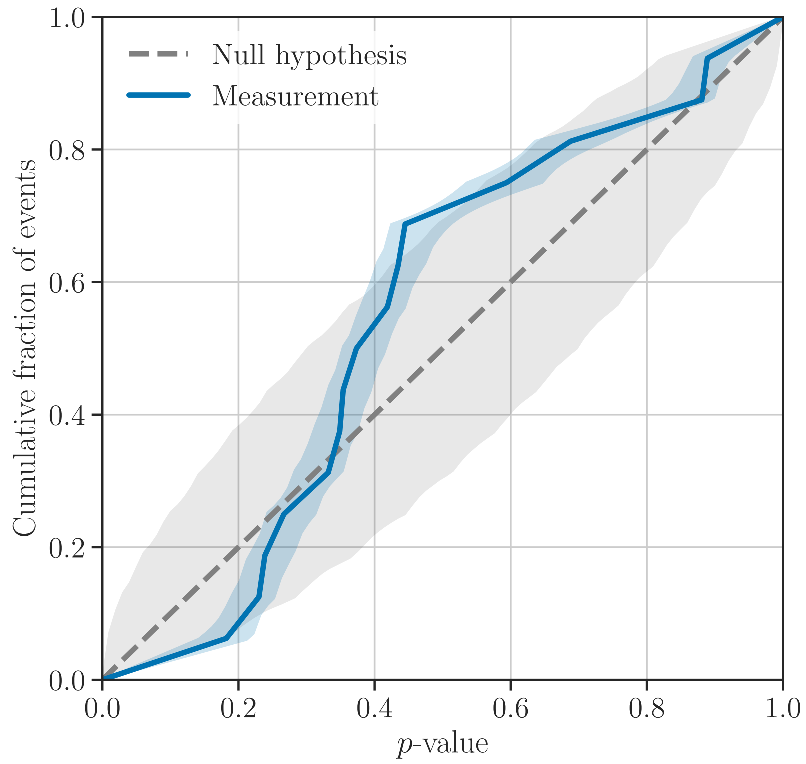
  - Phase difference

  - Amplitude damping factor

  - Broadening factor
- Compares the signal-to-noise Bayes factor to the background around the event to obtain a p-value.

Event	p-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27

GWTC-3 result (LVK, arXiv 2021)



SUMMARY

- There are a considerable variety of tests of GR carried out by the LVK (and even more proposed for O4).
- These are all null tests of one sort of another—none is testing a specific theory
- However, in addition to basic consistency tests, they cover a considerable variety of possible deviations from GR:
  - Parameterized deviations in the waveform's phasing (e.g., in PN coefficients)
  - Dispersive propagation
  - Additional polarizations
  - Modified QNM spectrum
  - Post-merger echoes
- So far, all results are consistent with GR

PROSPECTS FOR Q4

TESTING GR GROUP MOCK DATA CHALLENGES

- Check the performance of the analyses proposed for O4 on:
  - GR signals (to test systematics) - input from Geraint
  - non-GR signals
  - signals affected by glitches - led by Rico Lo, taking over from Jack Kwok, who did all the heavy initial work

- Currently have GW150914-like and GW170608-like GR signals (aligned-spin and precessing) created with TEOBResumS v3-GIOTTO and some precessing SXS injections.

- Non-GR signals are also use the same GR parameters and are based on TEOBResumS v3-GIOTTO.

TESTING GR GROUP MOCK DATA CHALLENGES

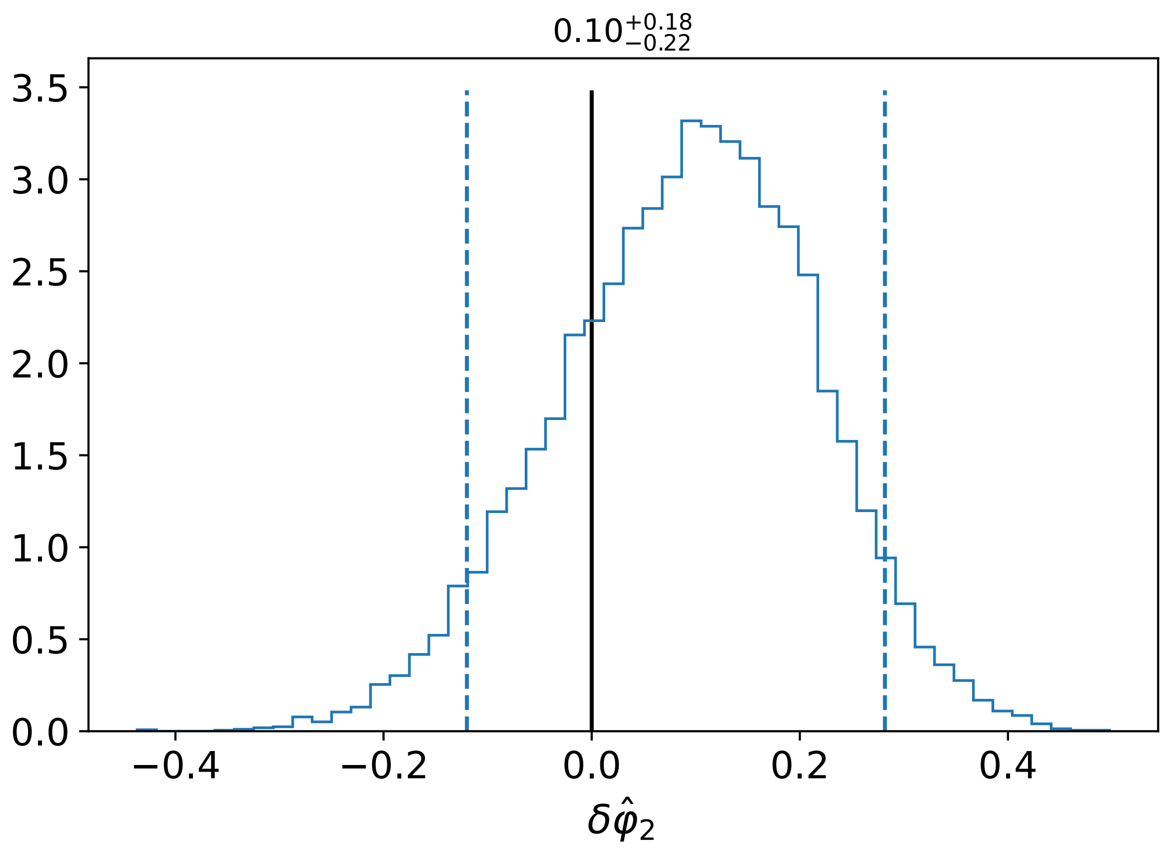
- The glitch MDC adds the precessing waveforms to O3 noise with a glitch in one of the LIGO detectors recolored to the forecast O4 sensitivity (Gaussian noise with forecast O4 sensitivity in Virgo).

- The other MDCs use a no-noise realization, analyzing the results with the forecast O4 sensitivity for the LIGO-Virgo network.

- The forecast O4 sensitivity is a bit optimistic compared to the sensitivities we are currently seeing, with a BNS range of 175 Mpc for LIGO, compared to the current ranges of ~140 and ~150 Mpc for H1 and L1.

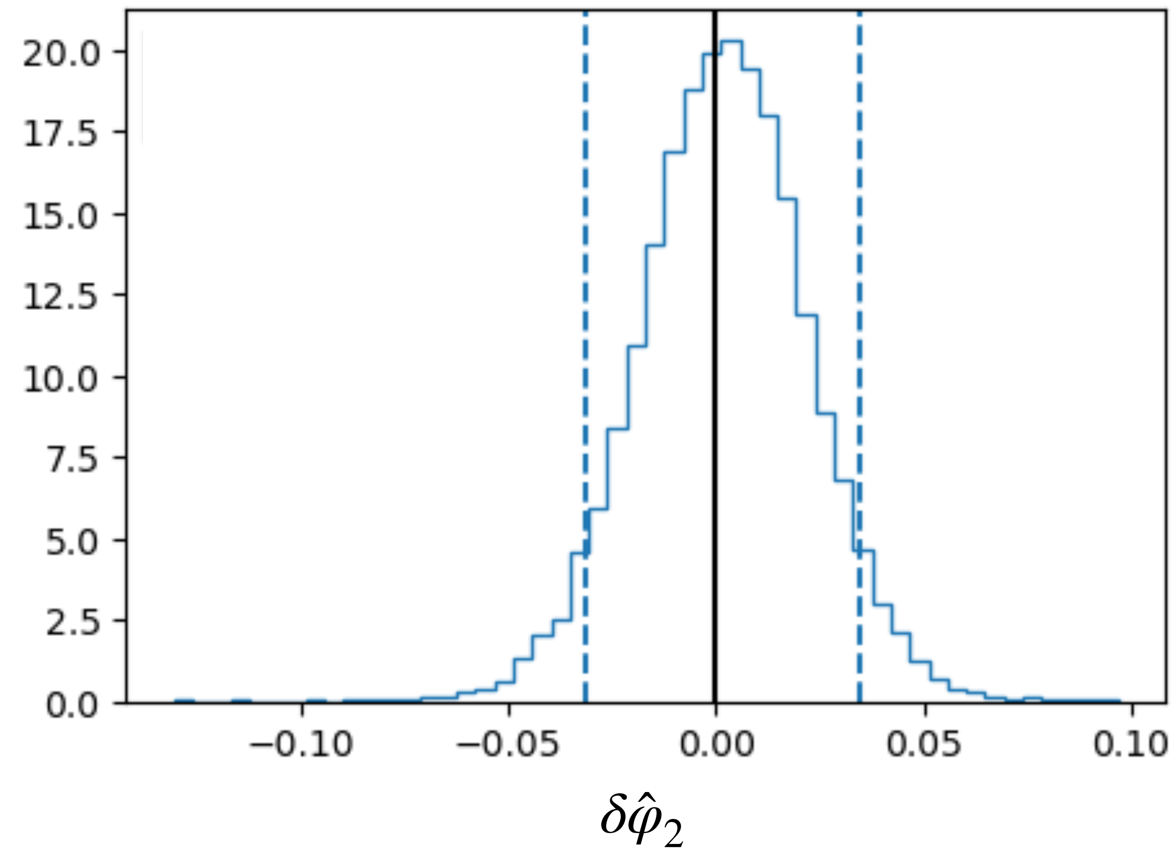
RESULTS FOR GR SIGNALS: GW150914-LIKE ALIGNED-SPIN (SNR 42)

TIGER, 1PN



Thanks to Soumen Roy

FTI, 1PN

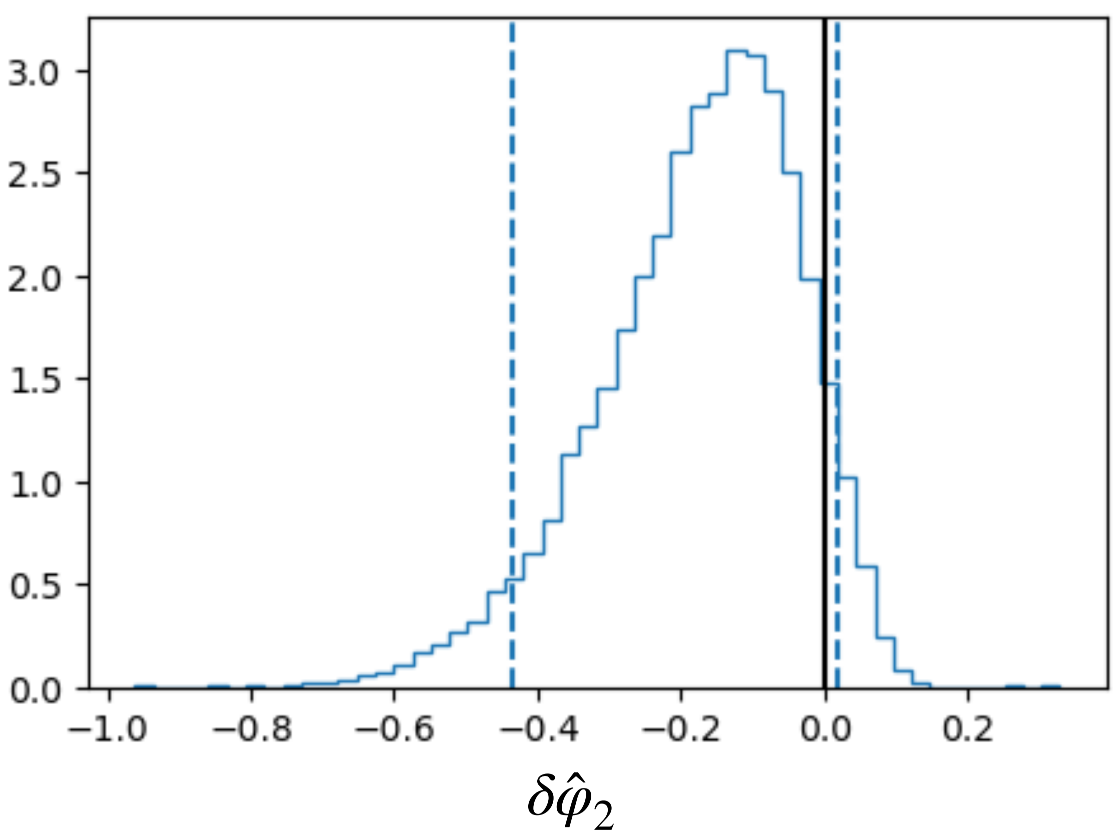


SEOBNRv4HM_ROM injection

Thanks to Elise Sänger

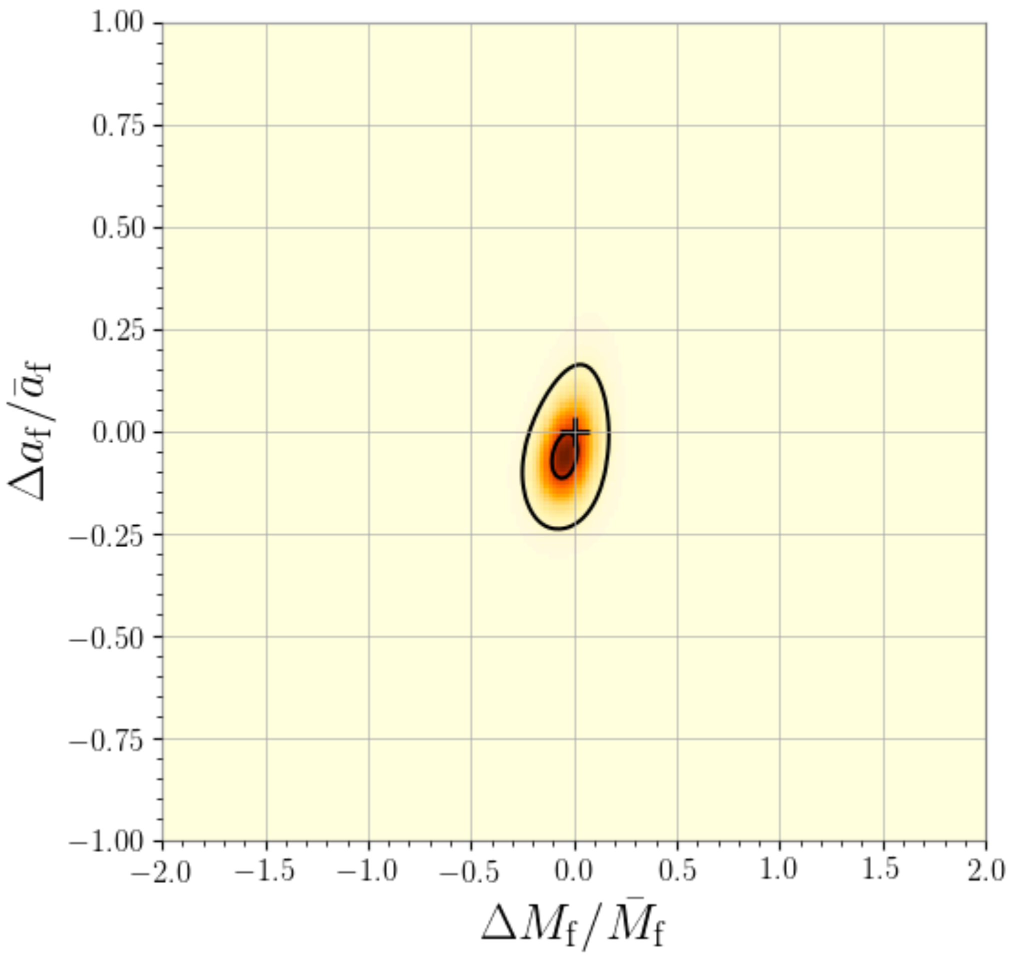
RESULTS FOR GR SIGNALS: GW150914-LIKE PRECESSING (SNR 41)

FTI, 1PN



Thanks to Elise Sänger

IMRCT (GR quantile: 43%)



Thanks to Mukesh Kumar Singh

NON-GR SIGNALS

- General philosophy: Introduce GR deviations we are interested in testing in a controlled way—do not try to emulate any realistic alternative theory, but also try to avoid just using a deviation used in an analysis.

- Massive graviton dispersion (only case where the deviation is used in an analysis)

- Modified energy flux: Multiplies the $(3, \pm 2)$ and $(4, \pm 4)$ modes by a constant factor, so the modification starts at 2PN.

  Sets the final mass and spin self-consistently to satisfy energy and angular momentum balance.

  Two versions: One that multiplies the modes in the waveform and one that considers the additional energy to be lost in a field that doesn't couple to GW detectors.

NON-GR SIGNALS (CONT.)

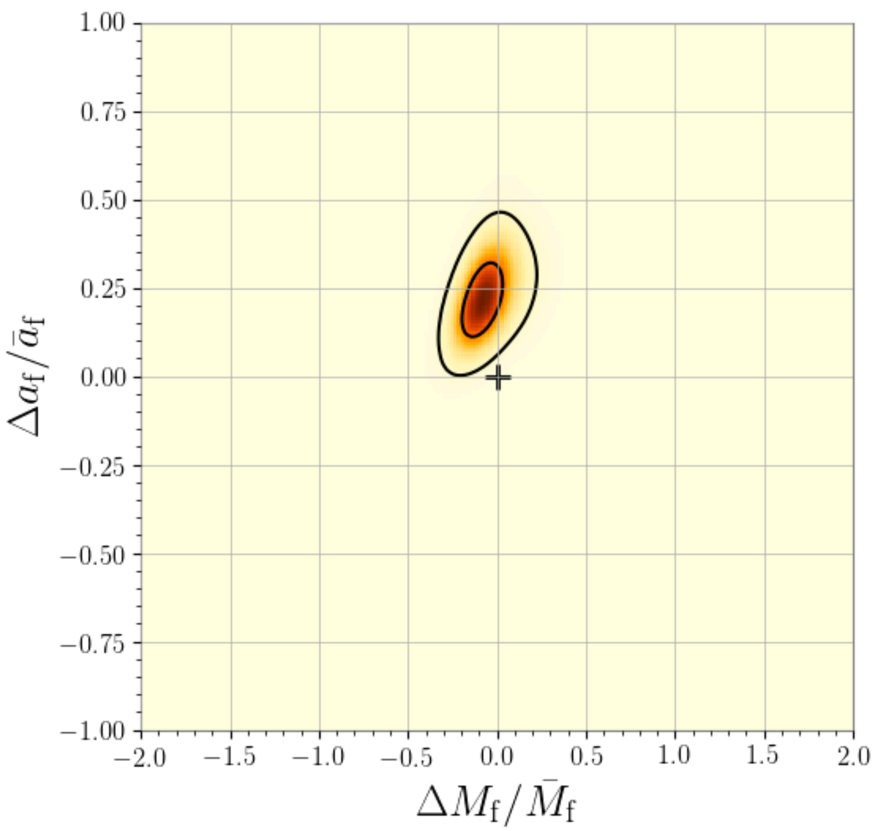
- **Modified QNM spectrum: Uses the Kerr-Newman QNM spectrum to model the deviations expected in an alternative theory. Sets final mass and spin self-consistently.**

- **Scalar-tensor polarizations: Add scalar polarization following the expectations for a scalar-tensor theory. However, does not modify the phasing.**

- **Scaled BNS waveforms: Scale BNS waveforms (TEOBResumS + BAM hybrids) to BBH-like total masses to emulate a binary of black hole mimickers.**

NON-GR SIGNALS: GW150914-LIKE MASSIVE GRAVITON

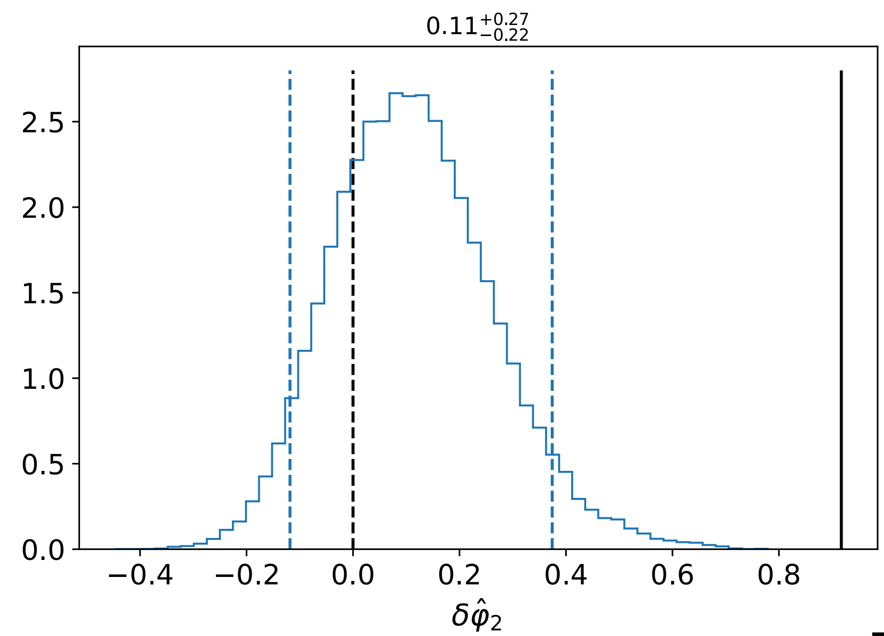
IMR consistency (GR quantile: 99.9%)



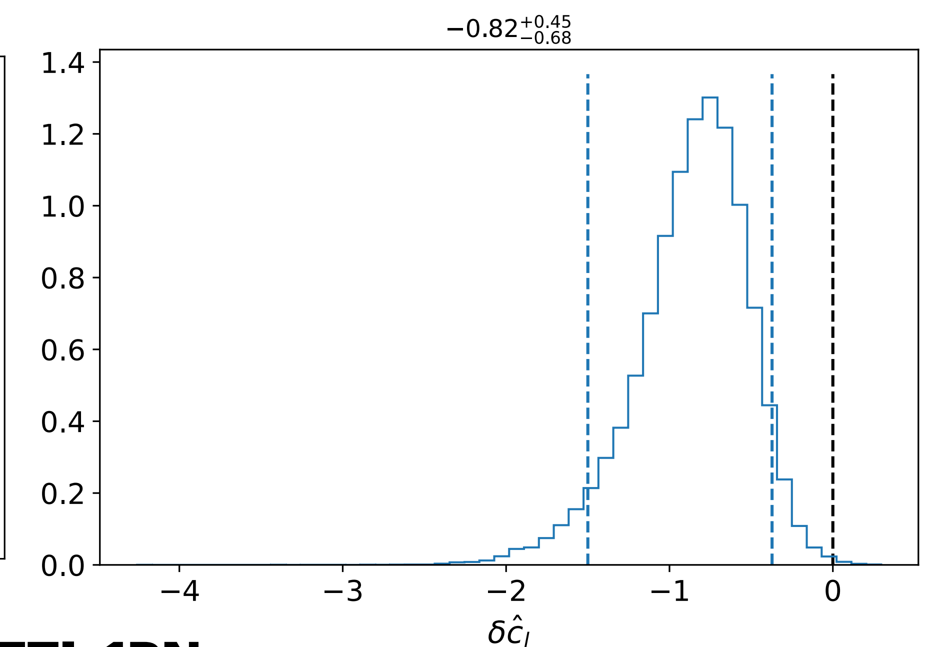
Thanks to Mukesh Kumar Singh

Thanks to Soumen Roy

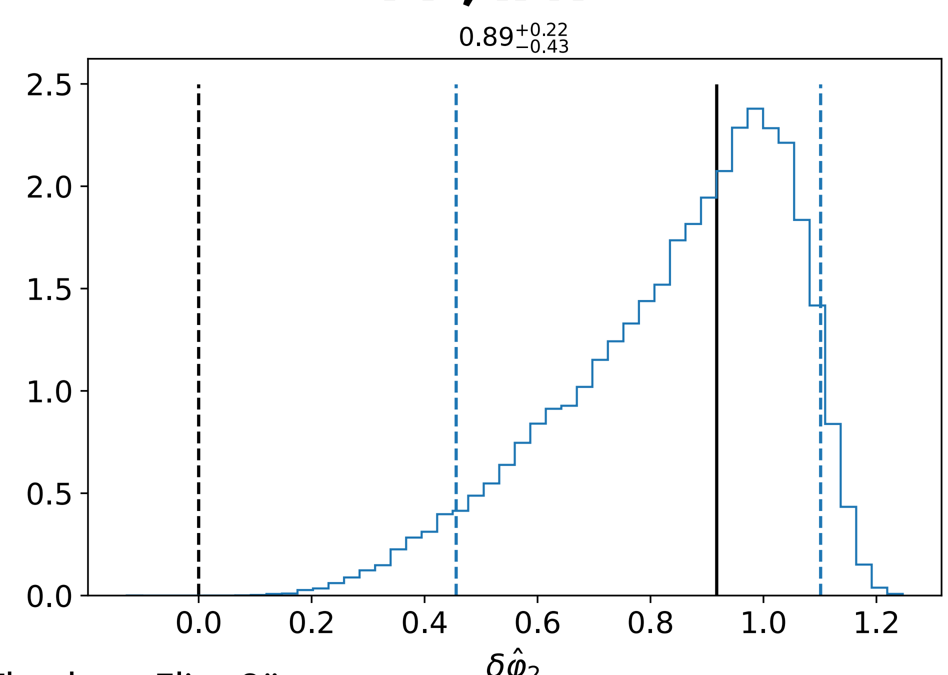
TIGER, 1PN



TIGER, c_l ringdown parameter



FTI, 1PN



Thanks to Elise Sänger

Aligned-spin

Graviton mass of $2.6 \times 10^{-22}\,\mathrm{eV}^2/c^2$, so ~20 times the constraint from all events to date

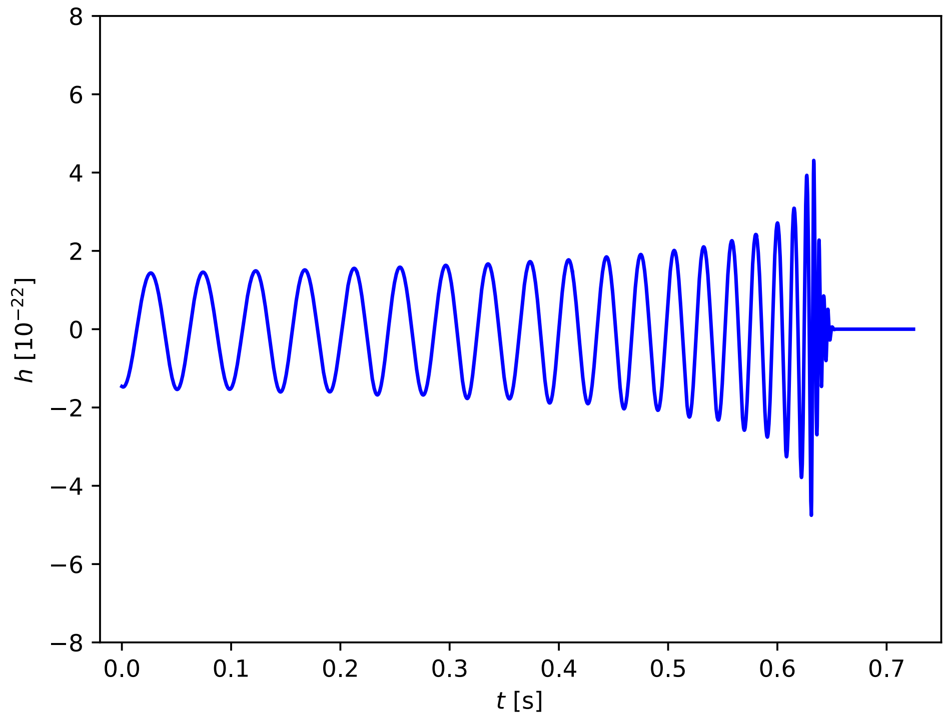
[Chosen to give a significant deviation in many tests]

$\delta\hat{\varphi}_2 \simeq 0.9$, recovered by FTI, but excluded by TIGER at high credibility

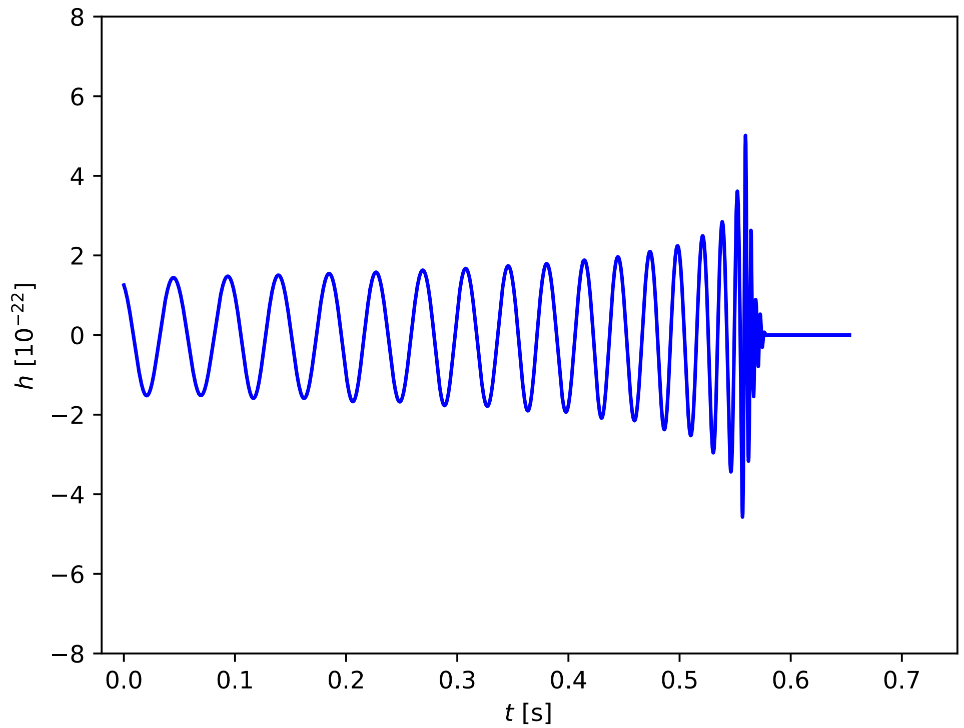
[fixed sign of expected value compared to presented version]

NON-GR SIGNALS: GW150914-LIKE MODIFIED ENERGY FLUX

GR



non-GR



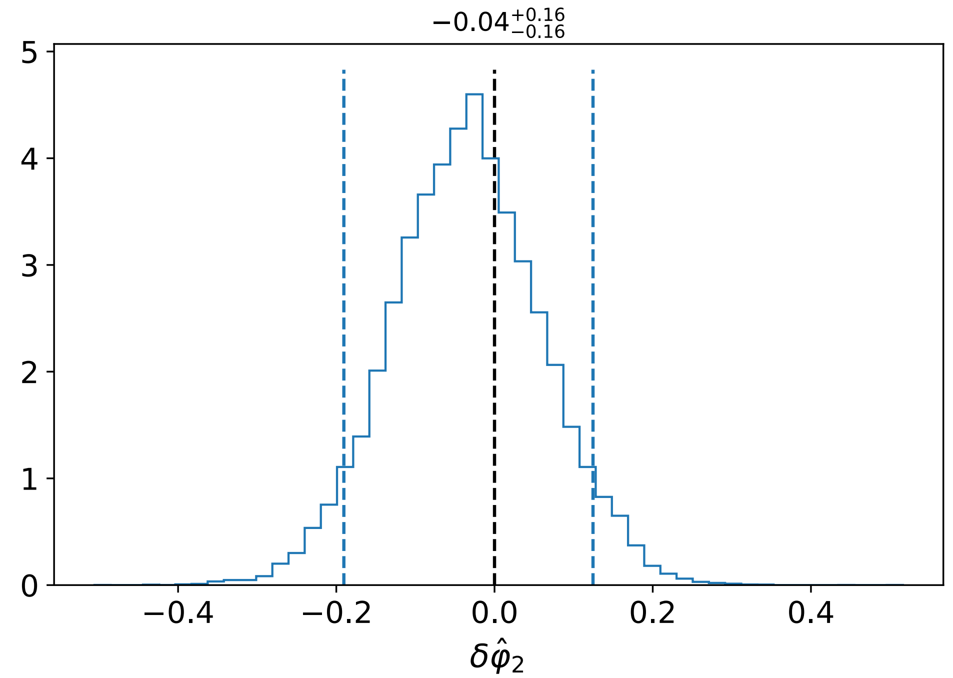
Aligned-spin, factor 10 multiplying modes, extra energy goes into a field that doesn’t couple to GW detectors

Final mass and spin reduced by ~0.3% and ~4%, respectively, compared to GR

NON-GR SIGNALS:
GW150914-LIKE MODIFIED ENERGY FLUX

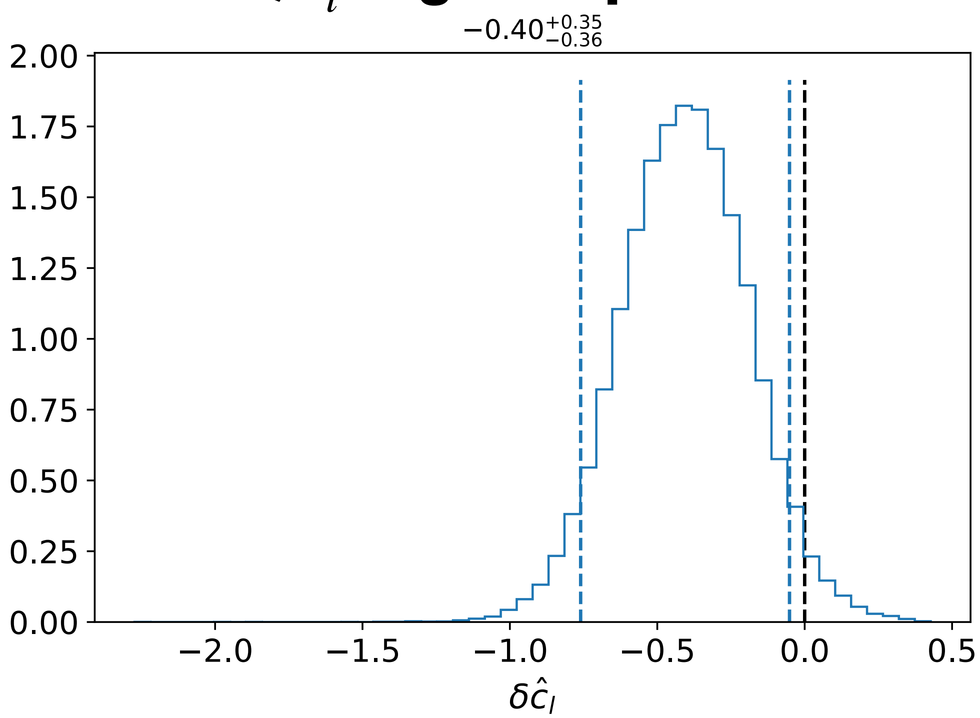
Thanks to Soumen Roy

TIGER, 1PN



(2PN also peaks at zero)

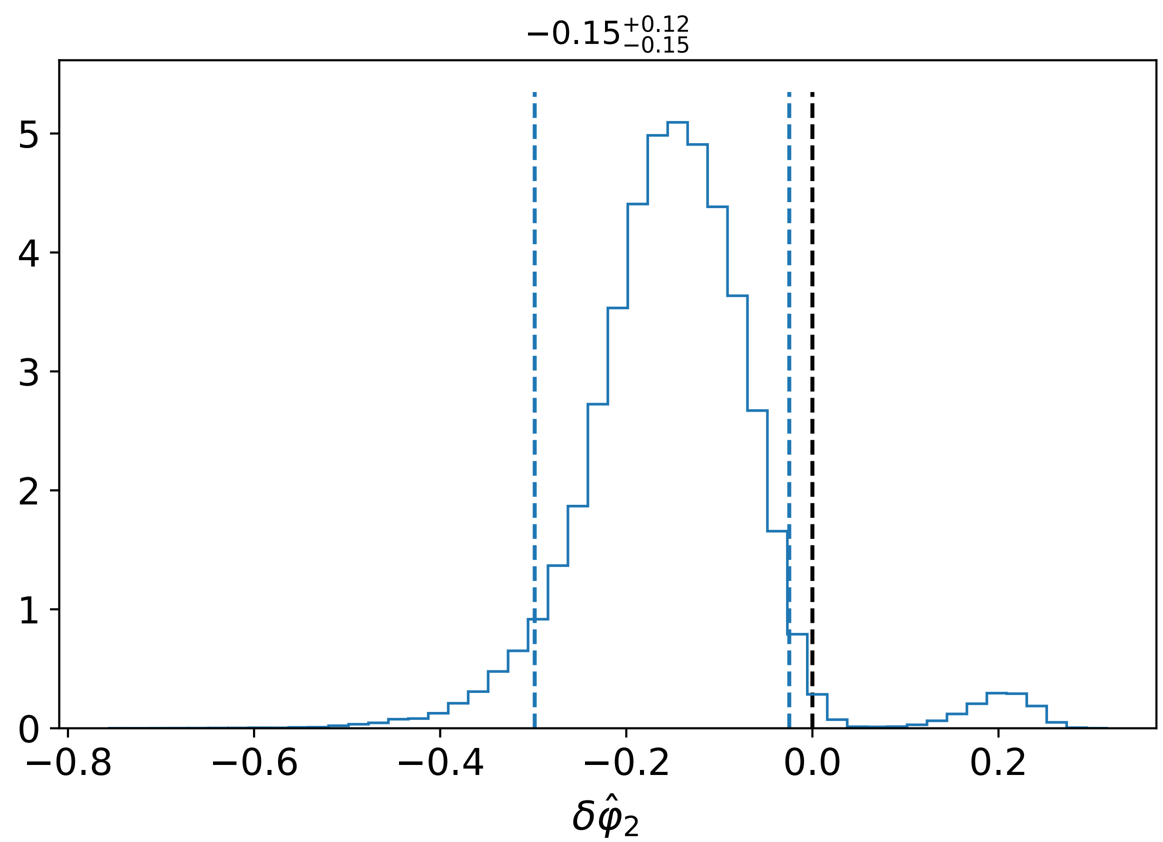
TIGER, c_l ringdown parameter



Aligned-spin, factor 10 multiplying modes, extra energy goes into a field that doesn't couple to GW detectors

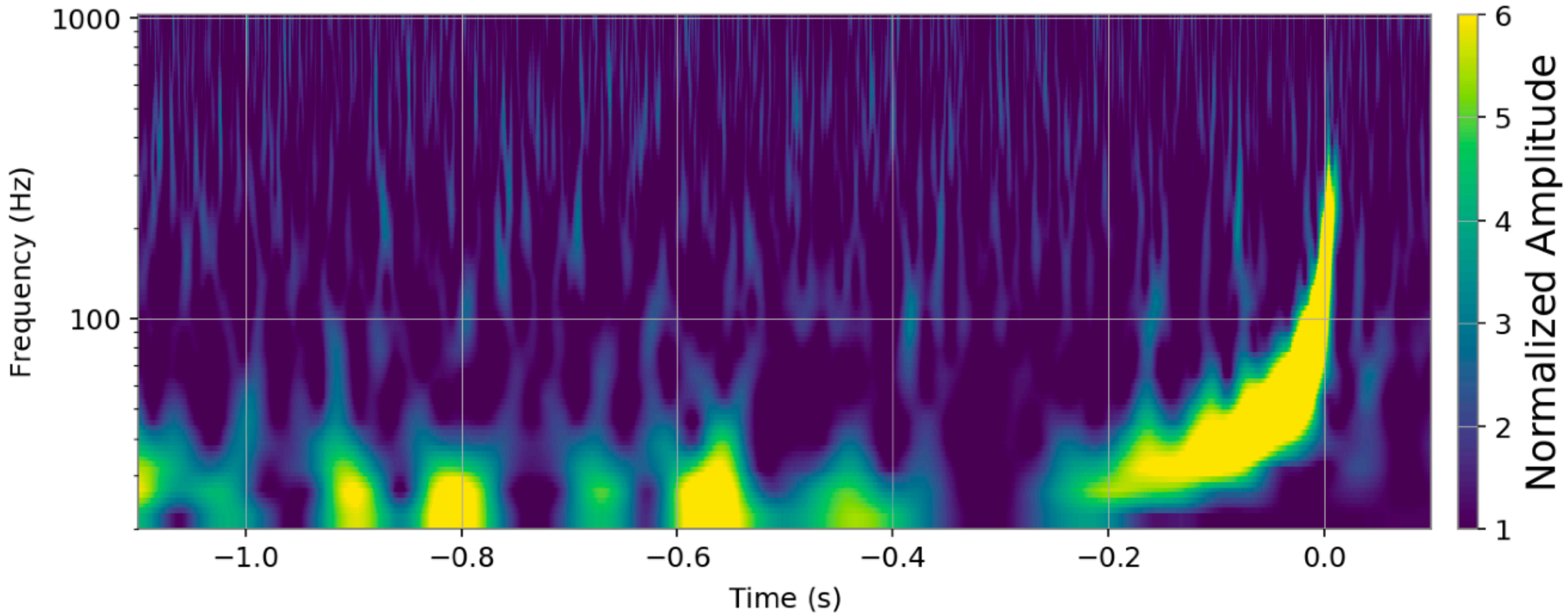
Injected $\delta\hat{\varphi}_4 \simeq -4.3$ excluded at very high credibility by TIGER (FTI has not run this one)

FTI, 1PN

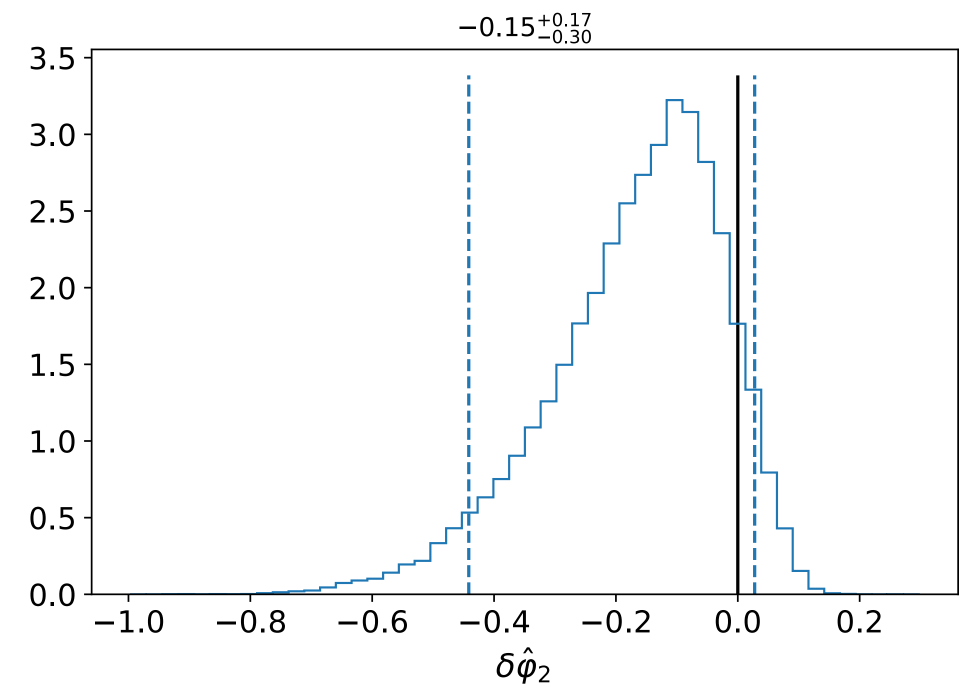


Thanks to Elise Sänger

GLITCH CASE: GW150914-LIKE WITH SCATTERED LIGHT

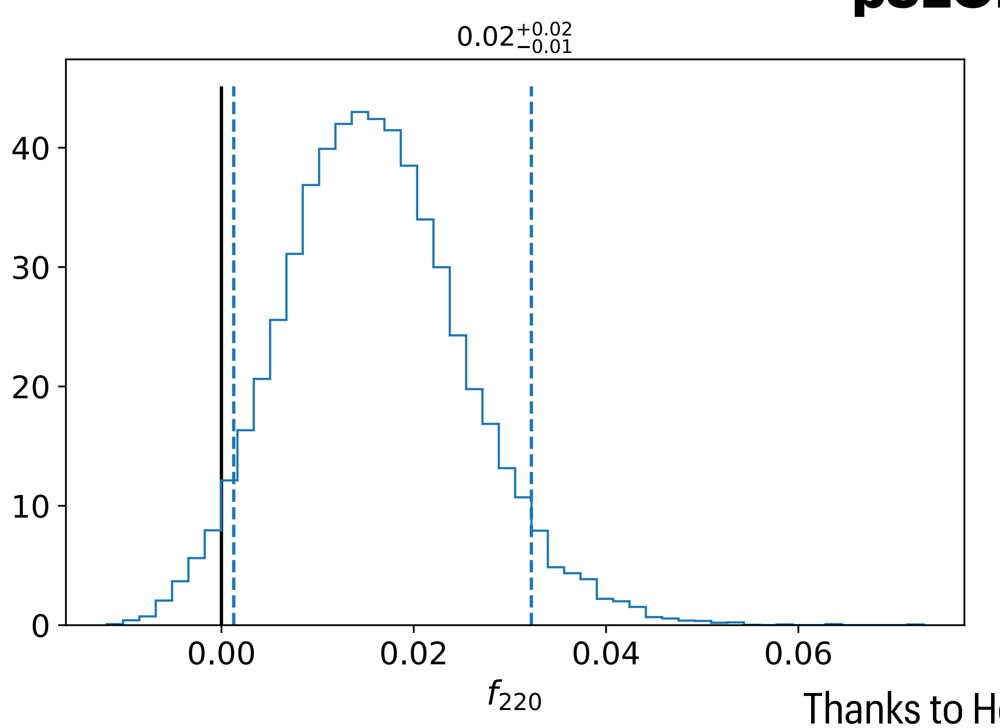


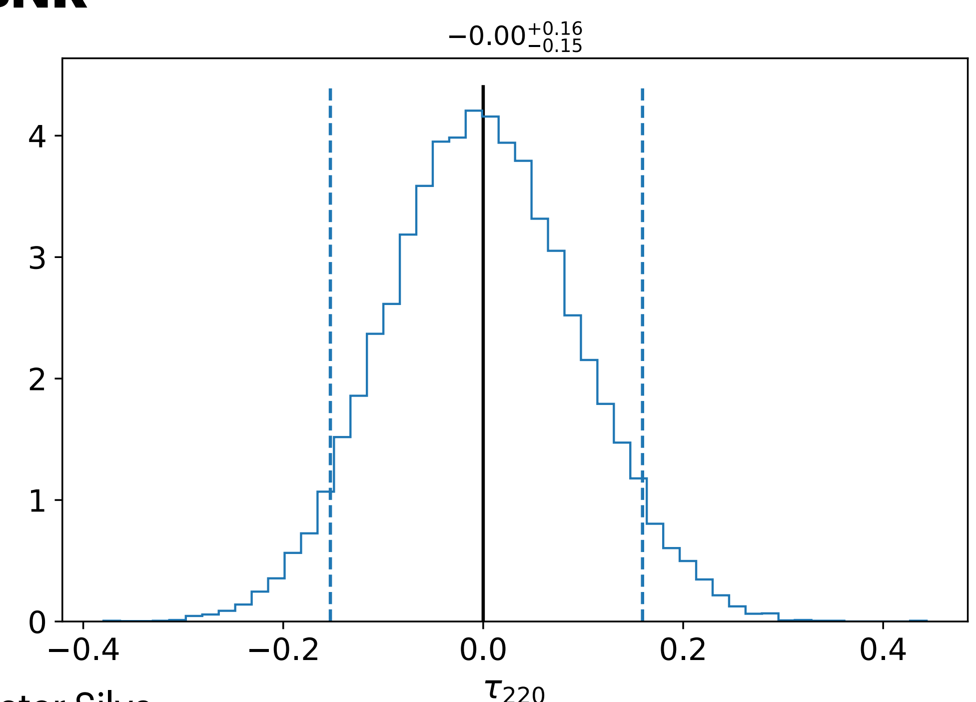
FTI, 1PN



Thanks to Elise Sänger

pSEOBNR





Thanks to Hector Silva

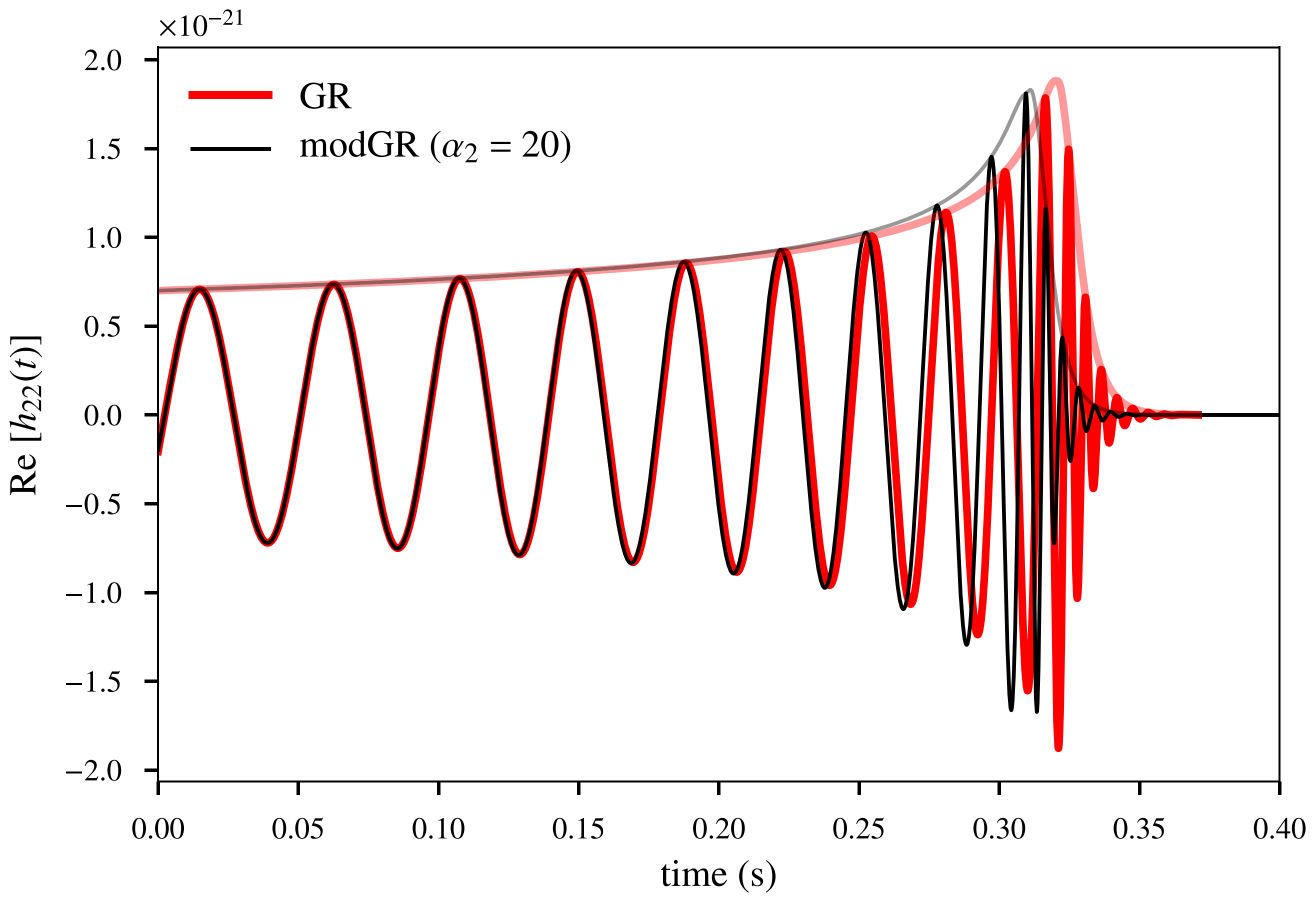
SUMMARY

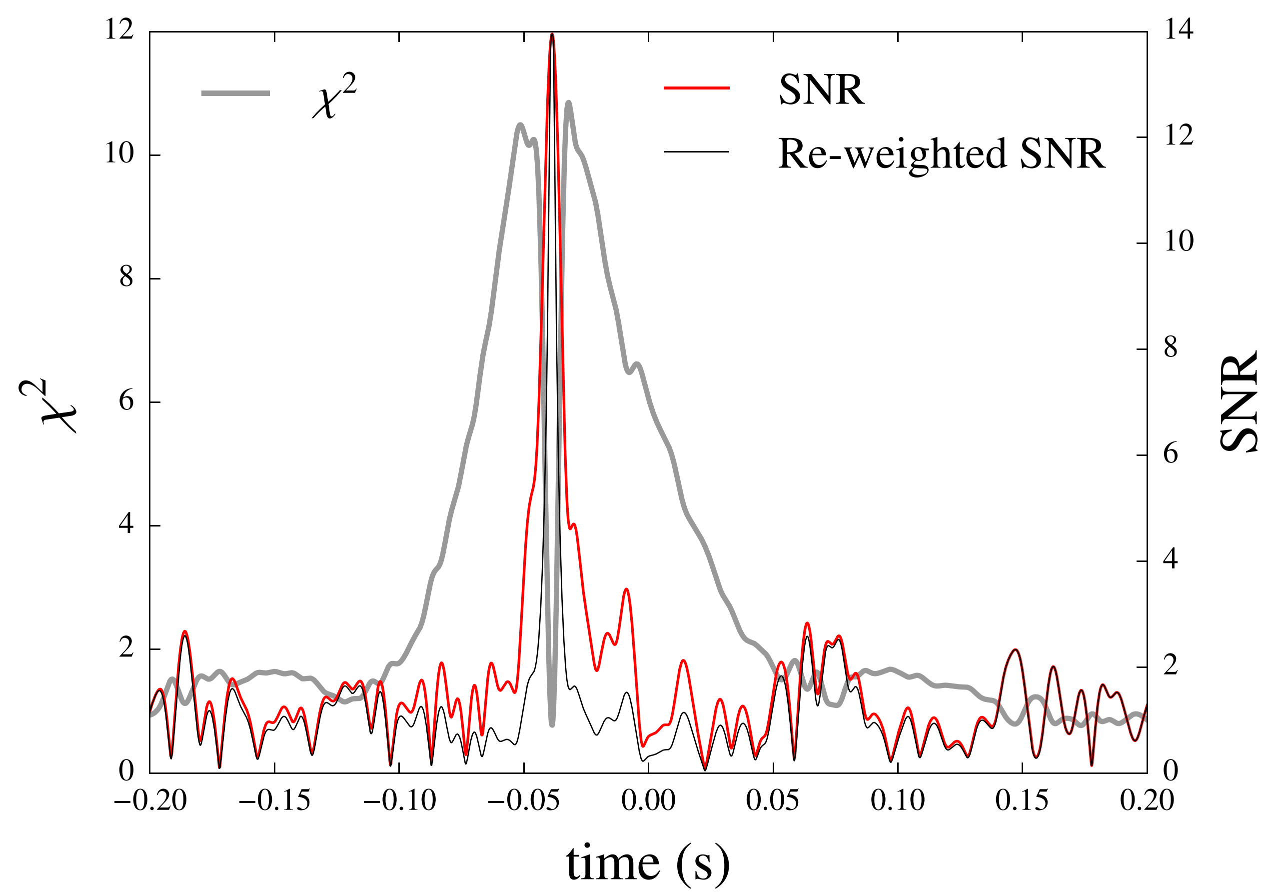
- We find that the prospects for O4 are promising, with a GW150914-like signal giving constraints in the 1PN coefficient at the forecast sensitivity that are comparable to or better than those obtained from all the detections to date.
- We also find that the tests are sensitive to a number of different possible deviations from GR.
- However, one also has to be concerned about waveform systematics and the effects of glitches.
- Thus, we look forward to the O4 TGR results, but will also need to have increased care.

EXTRA SLIDES

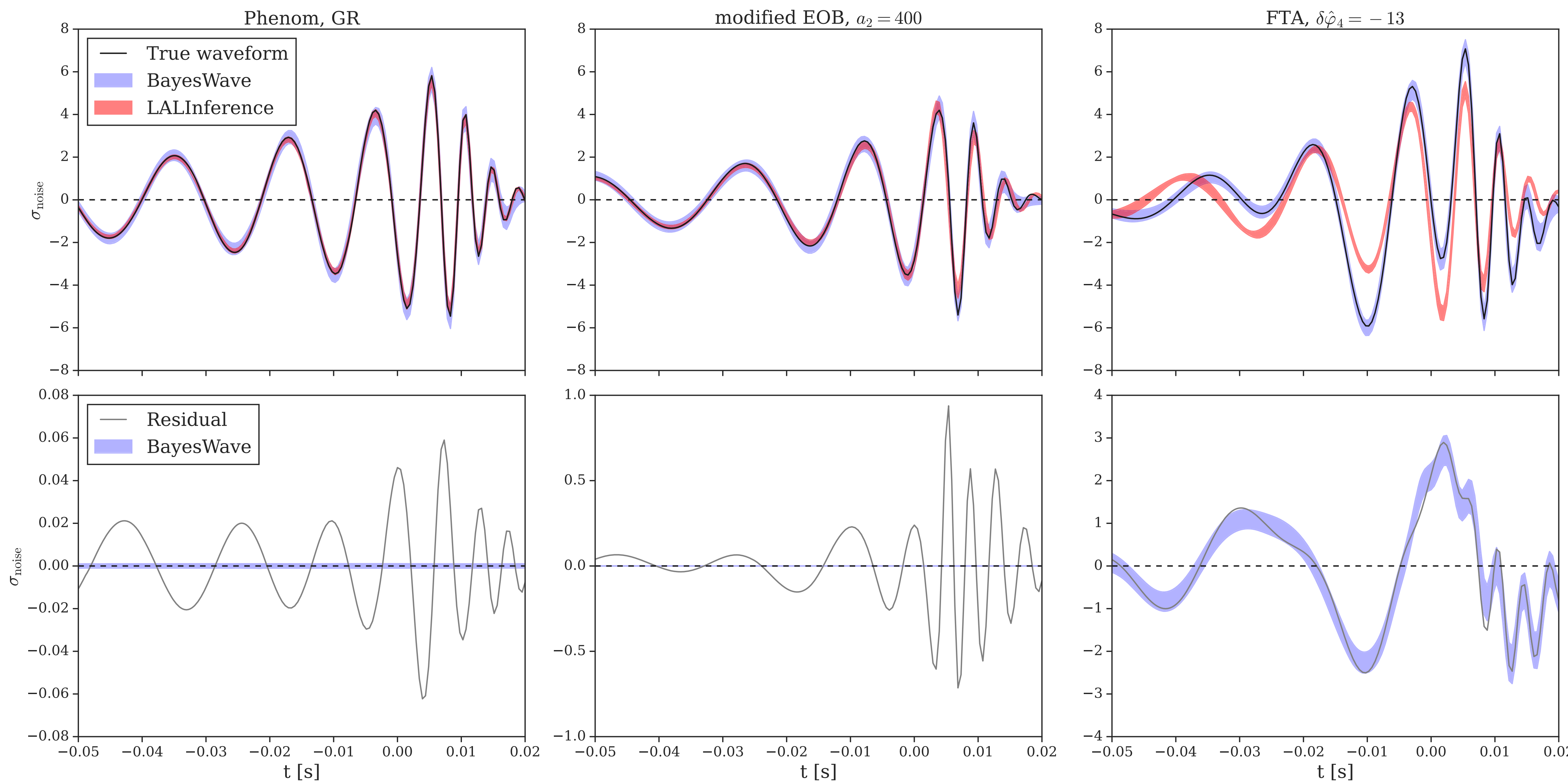
SIGNIFICANT SELECTION EFFECTS FAVORING GR?

- <u>Ghosh, NKJ-M, et al. (CQG, 2018)</u> found that a non-GR signal with a fairly significant GR deviation (~50% deviation in the 2PN coefficient + higher-order and post-merger modifications) had no signal consistency penalty and would likely be detected by the matched filter searches.



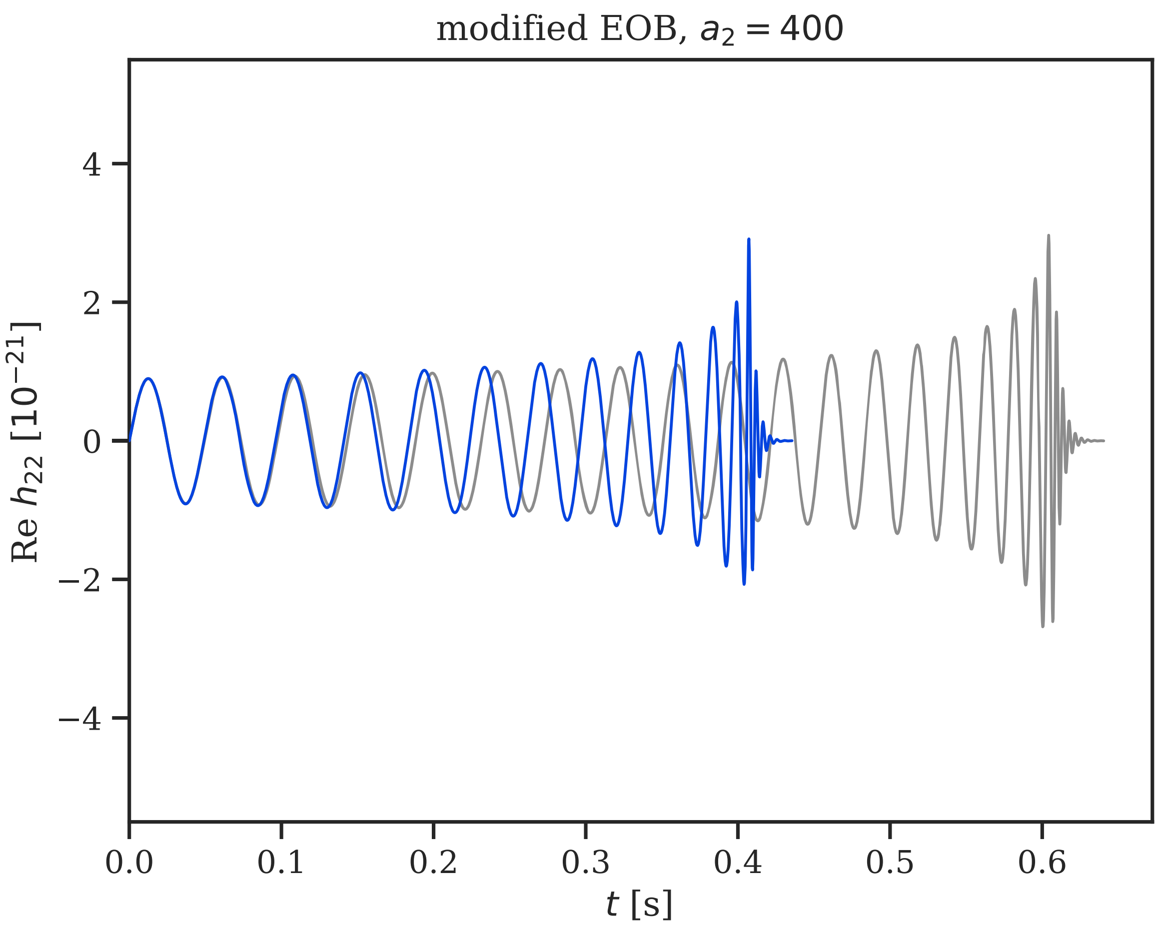


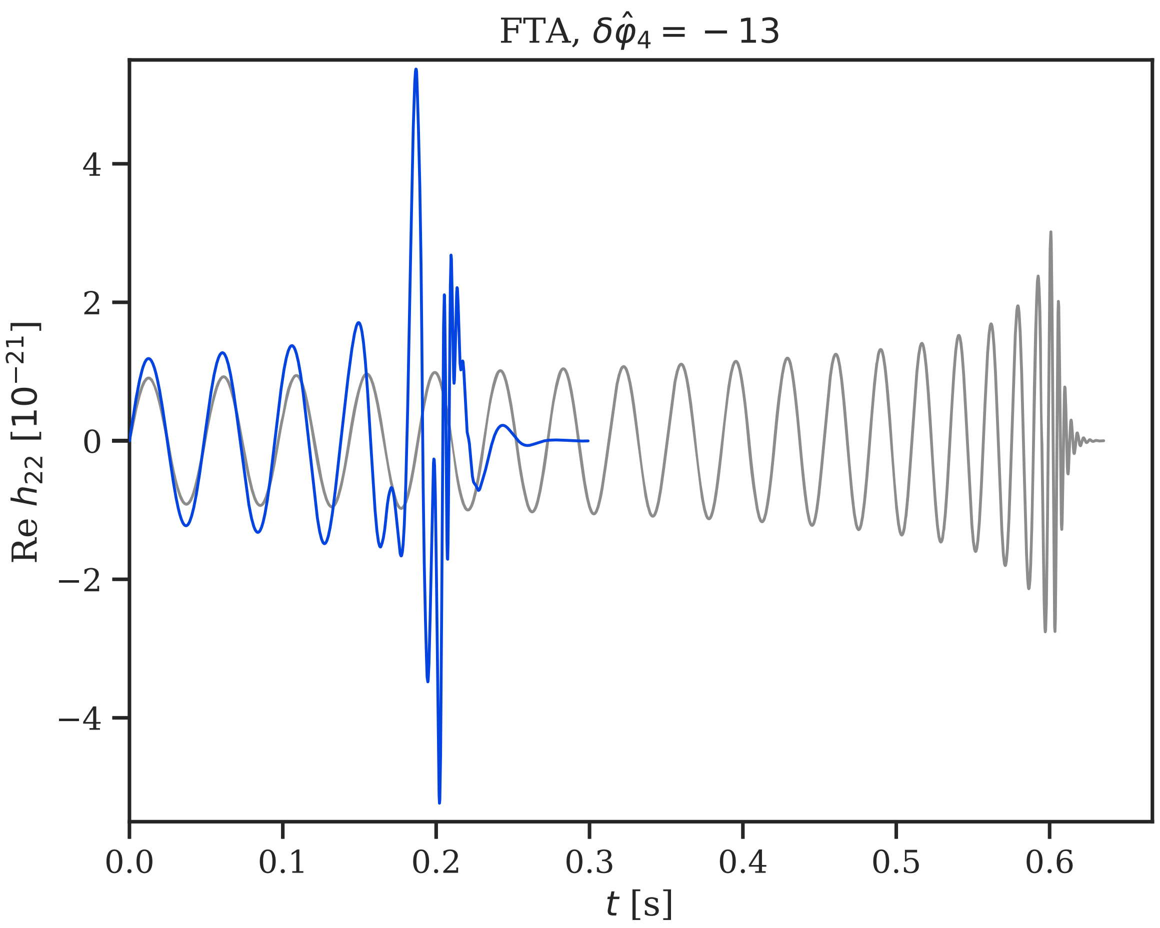
RESIDUALS AND RECONSTRUCTIONS OF NON-GR WAVEFORMS: PHENOMENOLOGICAL CASE



From NKJ-M et al. (PRD, 2022)
SNR ~50

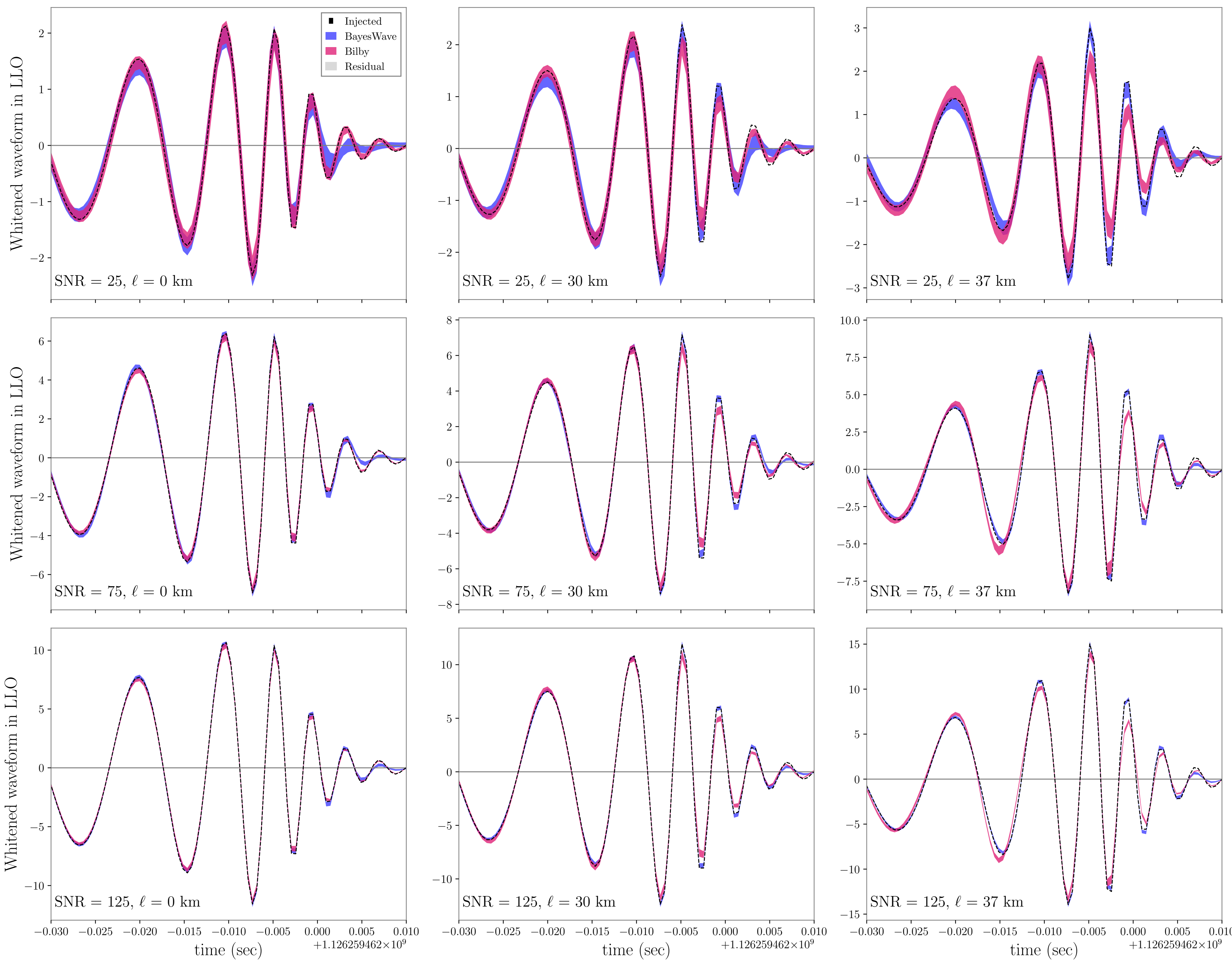
PHENOMENOLOGICAL WAVEFORMS WITH GR DEVIATION





From NKJ-M et al. (PRD, 2022)

RESIDUALS AND RECONSTRUCTIONS OF NON-GR WAVEFORMS: DYNAMICAL CHERN-SIMONS CASE

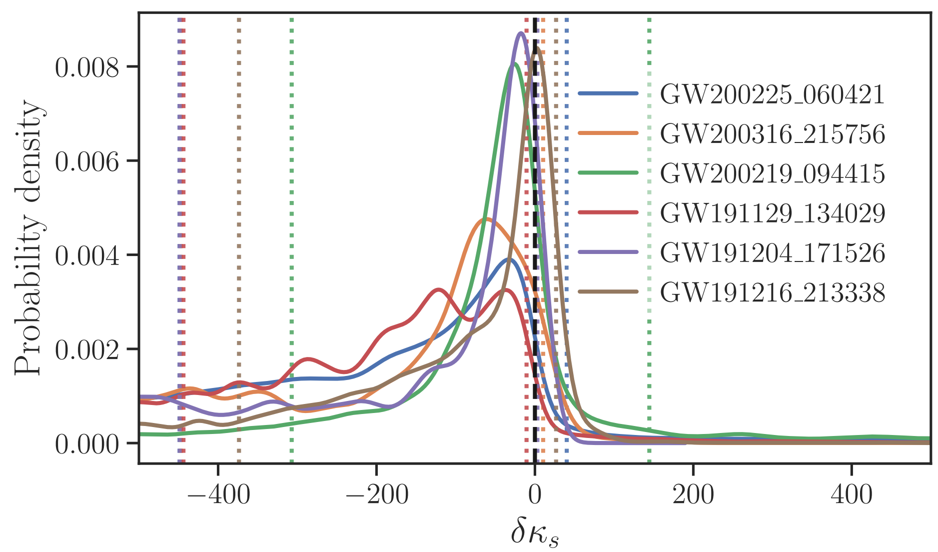


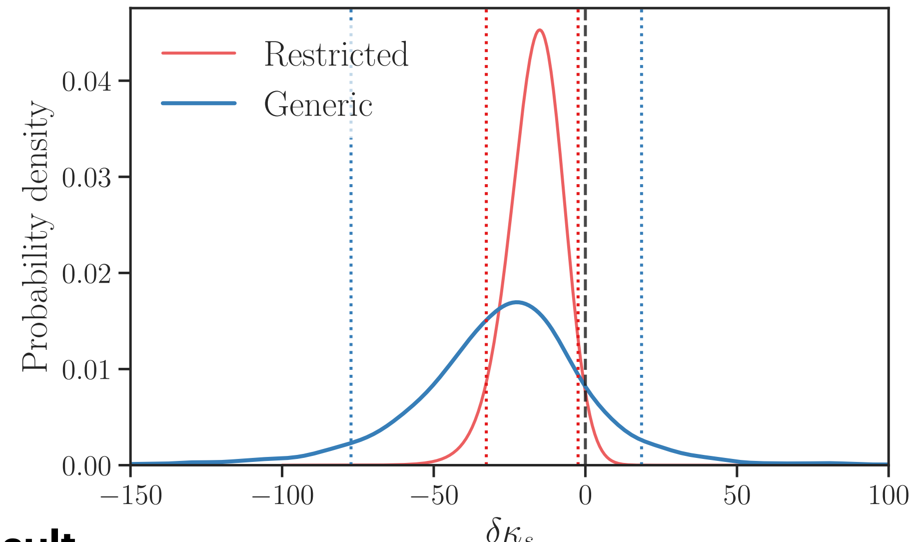
From
Okounkova et al. (PRD, 2023)

PARAMETERIZED TESTS: SPIN-INDUCED QUADRUPOLE MOMENT

- **Like TIGER, except allows for non-BBH values of the spin-induced quadrupole moment terms at 2PN through 3.5PN to give a null test of BBH nature of objects in binary—see Krishnendu et al. PRL (2017) and Krishnendu et al. PRD (2019). These are parameterized by $\kappa_{1,2}$, where the quadrupole moments are** $Q_{1,2} = -\kappa_{1,2}\chi_{1,2}^2 m_{1,2}^3$.
- **Due to degeneracies, samples on the symmetric combination of quadrupole moment parameters, $\kappa_s := (\kappa_1 + \kappa_2)/2$, setting the antisymmetric version to zero, so assuming $\kappa_1 = \kappa_2$.**

Tighter bounds obtained by assuming $\kappa_s > 0$; best bound from GW191216_213338 of $\kappa_s < 10.65$ (90% credibility).

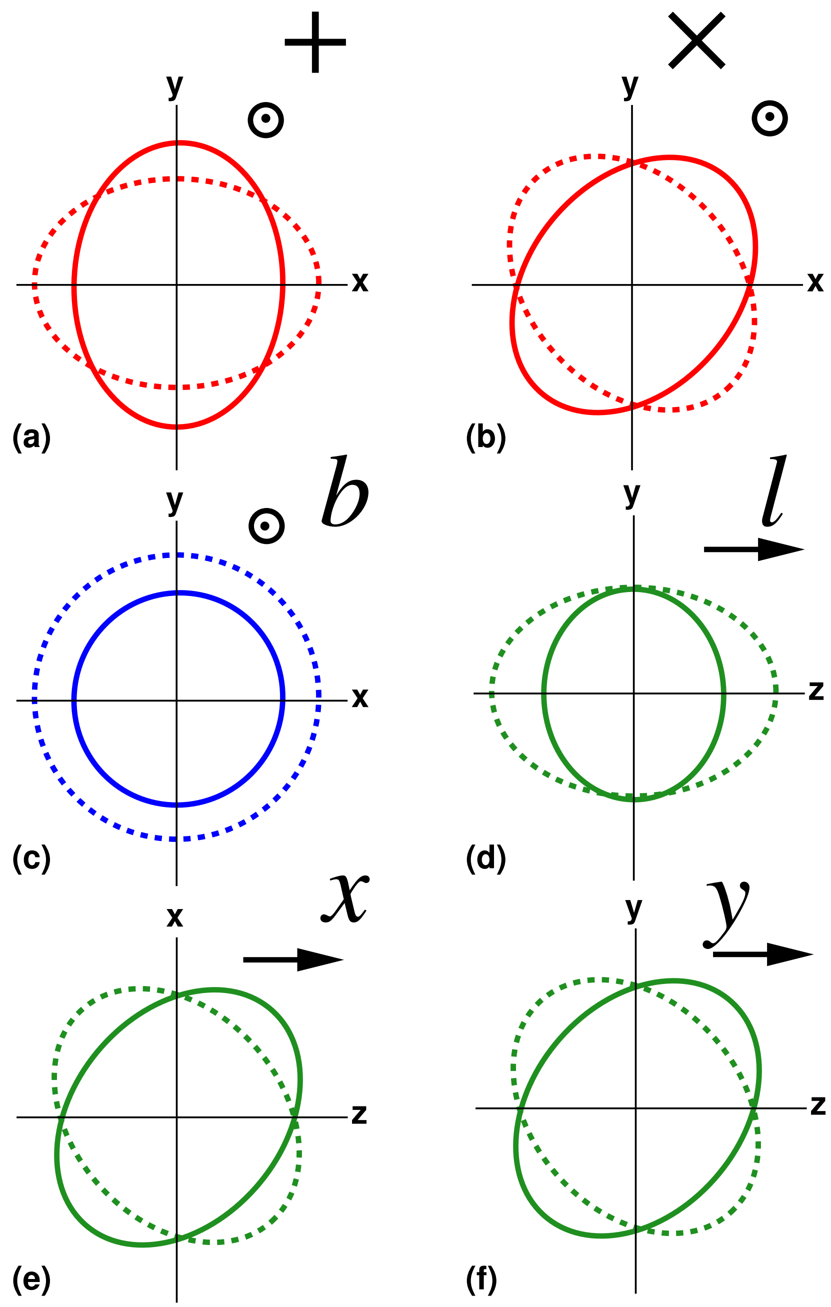




GWTC-3 result (LVK, arXiv 2021)

POLARIZATION TEST

- Uses the null stream method and projects onto a basis of polarization vectors to allow it to constrain polarization content with even 2 detectors—see I. C. F. Wong et al., arXiv (2021).
- Computes the power in the null stream in the time-frequency domain.
- Considers both a single basis mode (more constraining, and allows for only two detectors) and two basis modes (includes more polarization modes and requires two detectors).



Will, LRR (2014)

POLARIZATION TEST: SETUP

Hypothesis	Description	# of basis modes	Mode(s)	Basis mode(s)	Free parameters
$\mathcal{H}_{\mathrm{T},1}$	Pure tensorial	1	$+, \times$	$+$	5
$\mathcal{H}_{\mathrm{V},1}$	Pure vectorial	1	x, y	x	5
$\mathcal{H}_{\mathrm{S},1}$	Pure scalar	1	b	b	2
$\mathcal{H}_{\mathrm{TS},1}$	Tensor–scalar	1	$+, \times, b, l$	$+$	9
$\mathcal{H}_{\mathrm{TV},1}$	Tensor–vector	1	$+, \times, x, y$	$+$	9
$\mathcal{H}_{\mathrm{VS},1}$	Vector–scalar	1	x, y, b, l	x	9
$\mathcal{H}_{\mathrm{TVS},1}$	Tensor–vector–scalar	1	$+, \times, b, l, x, y$	$+$	13
$\mathcal{H}_{\mathrm{T},2}$	Pure tensorial	2	$+, \times$	$+, \times$	2
$\mathcal{H}_{\mathrm{V},2}$	Pure vectorial	2	x, y	x, y	2
$\mathcal{H}_{\mathrm{TS},2}$	Tensor–scalar	2	$+, \times, b, l$	$+, b$	11
$\mathcal{H}_{\mathrm{TV},2}$	Tensor–vector	2	$+, \times, x, y$	$+, x$	11
$\mathcal{H}_{\mathrm{VS},2}$	Vector–scalar	2	x, y, b, l	x, b	11
$\mathcal{H}_{\mathrm{TVS},2}$	Tensor–vector–scalar	2	$+, \times, b, l, x, y$	$+, b$	19

GWTC-3 settings
(LVK, arXiv 2021)

POLARIZATION TEST: RESULTS

One basis mode (2-detector and 3-detector events)

Events	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{S}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{V}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TS}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TV}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{VS}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TVS}}$
O1	-0.04 ± 0.07	0.09 ± 0.07	0.04 ± 0.07	0.09 ± 0.07	0.09 ± 0.07	0.07 ± 0.07
O2	-0.42 ± 0.12	0.04 ± 0.12	0.08 ± 0.12	0.22 ± 0.12	0.09 ± 0.12	0.35 ± 0.12
O3a	-1.85 ± 0.21	-1.04 ± 0.20	0.25 ± 0.20	0.07 ± 0.20	-1.05 ± 0.20	-0.18 ± 0.20
O3b	-1.93 ± 0.17	-0.79 ± 0.17	-0.17 ± 0.17	-0.07 ± 0.17	-0.86 ± 0.17	-0.32 ± 0.17
Combined	-4.24 ± 0.30	-1.70 ± 0.30	0.20 ± 0.30	0.31 ± 0.30	-1.73 ± 0.30	-0.08 ± 0.30

Two basis modes (only 3-detector events)

Events	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{V}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TS}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TV}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{VS}}$	$\log_{10} \mathcal{B}_{\mathrm{T}}^{\mathrm{TVS}}$
O1	–	–	–	–	–
O2	0.05 ± 0.03	0.01 ± 0.03	-0.02 ± 0.03	0.06 ± 0.03	0.01 ± 0.03
O3a	-0.37 ± 0.12	-0.77 ± 0.12	-0.72 ± 0.12	-0.73 ± 0.12	-0.91 ± 0.12
O3b	-0.09 ± 0.10	-0.22 ± 0.10	-0.35 ± 0.10	-0.38 ± 0.10	-0.38 ± 0.10
Combined	-0.41 ± 0.16	-0.98 ± 0.16	-1.09 ± 0.16	-1.05 ± 0.16	-1.29 ± 0.16

Negative numbers indicate that the tensor hypothesis is favored

GWTC-3 result
(LVK, arXiv 2021)

RINGDOWN TESTS: pyRING FLAVOURS

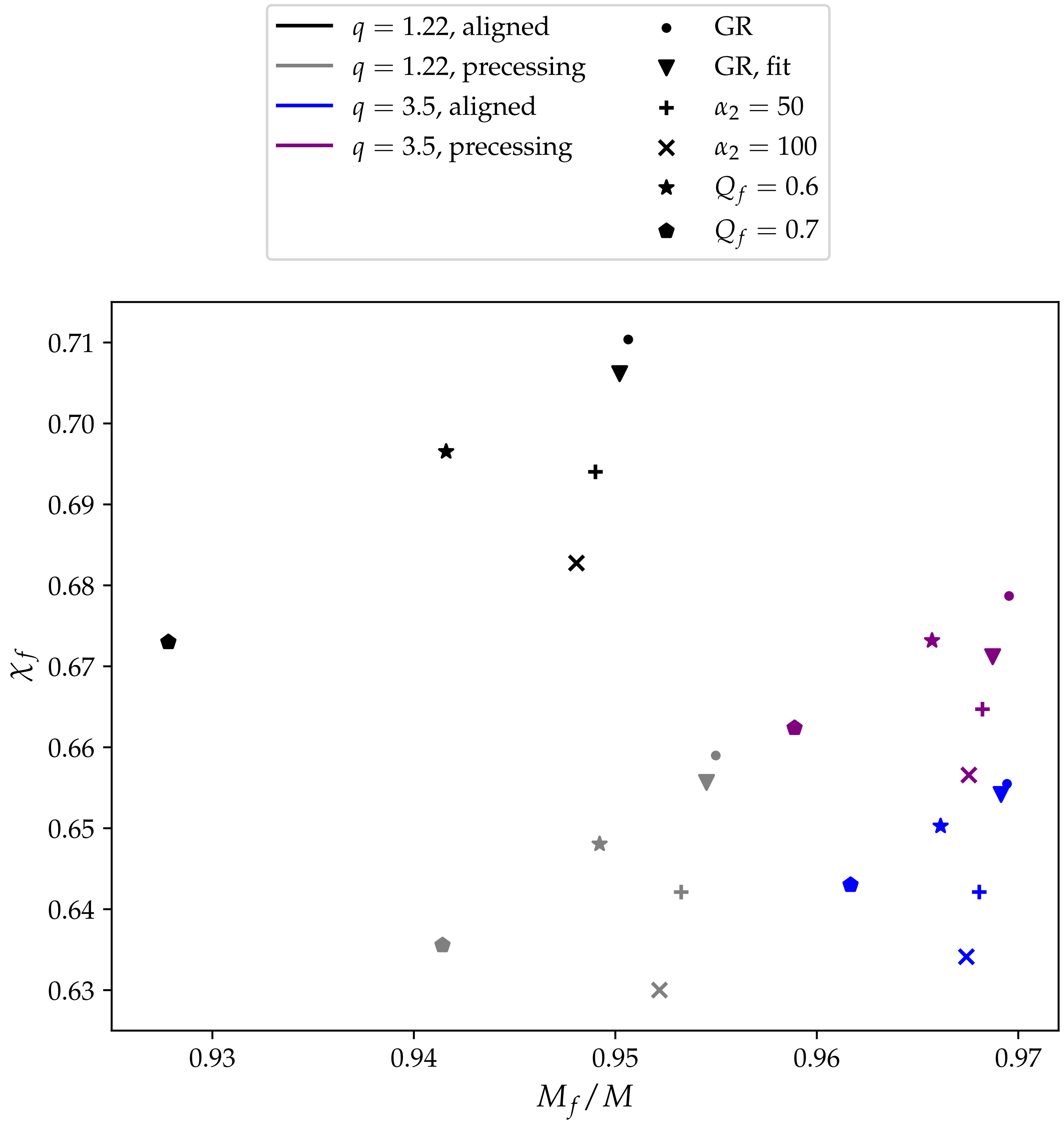
- **Kerr$_{220}$: Just includes the 220 QNM with free final mass and spin as well as free amplitude, phase, frequency, and damping time, starting at 10M$_z$ after the peak of the waveform.**

- **Kerr$_{221}$: Also includes the 221 QNM (first overtone) and starts at the peak of the waveform. Modifies the 221 frequency and damping time to test GR.**

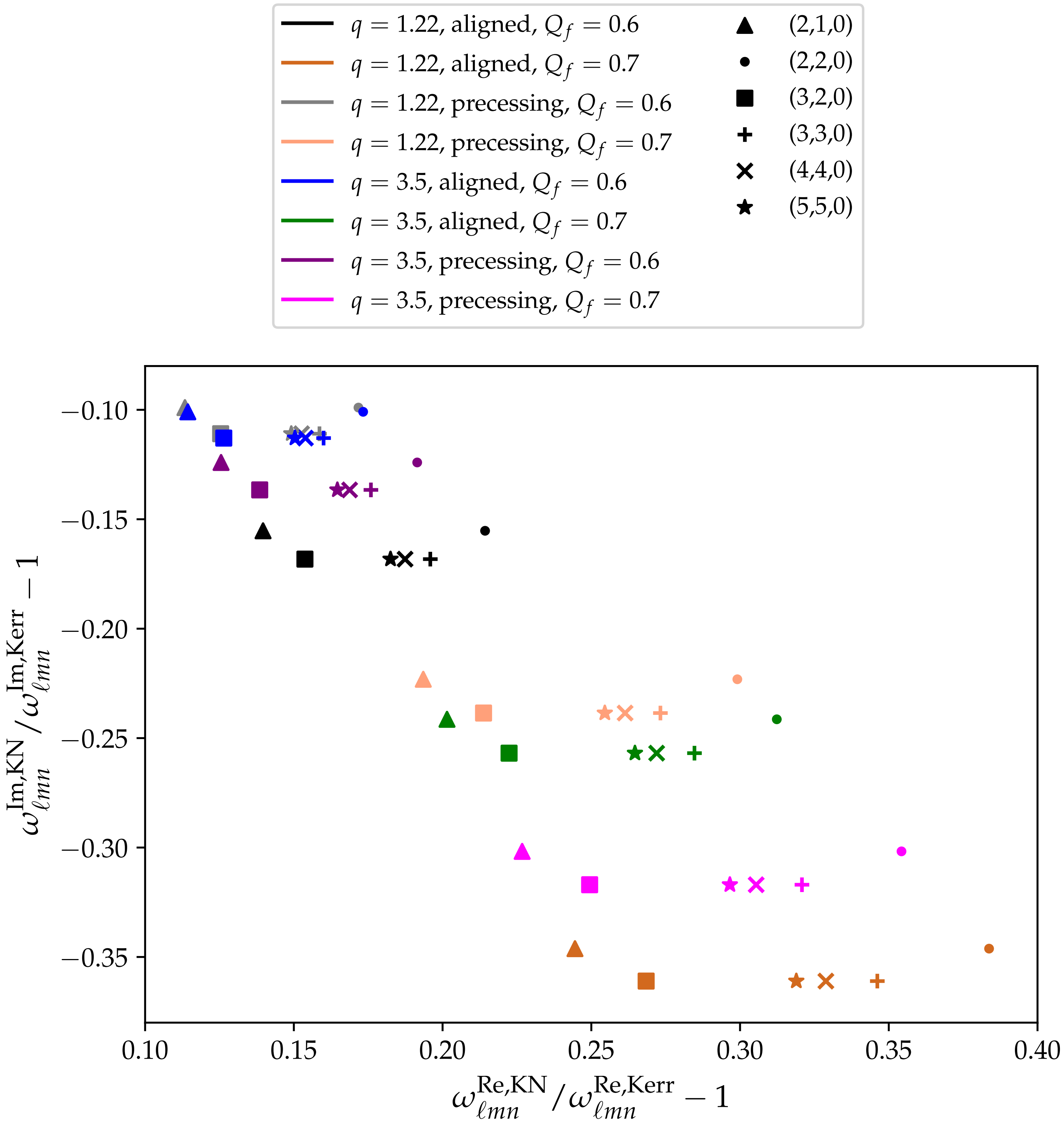
- **Kerr$_{HM}$: Uses the amplitudes and phases for n = 0 QNMs with $\ell \leq 4$ from a fit to aligned-spin NR simulations (L. London, PRD 2020); starts at 15M$_z$ after the peak of the waveform.**

- **Also just fit a damped sinusoid to the data, as a check.**

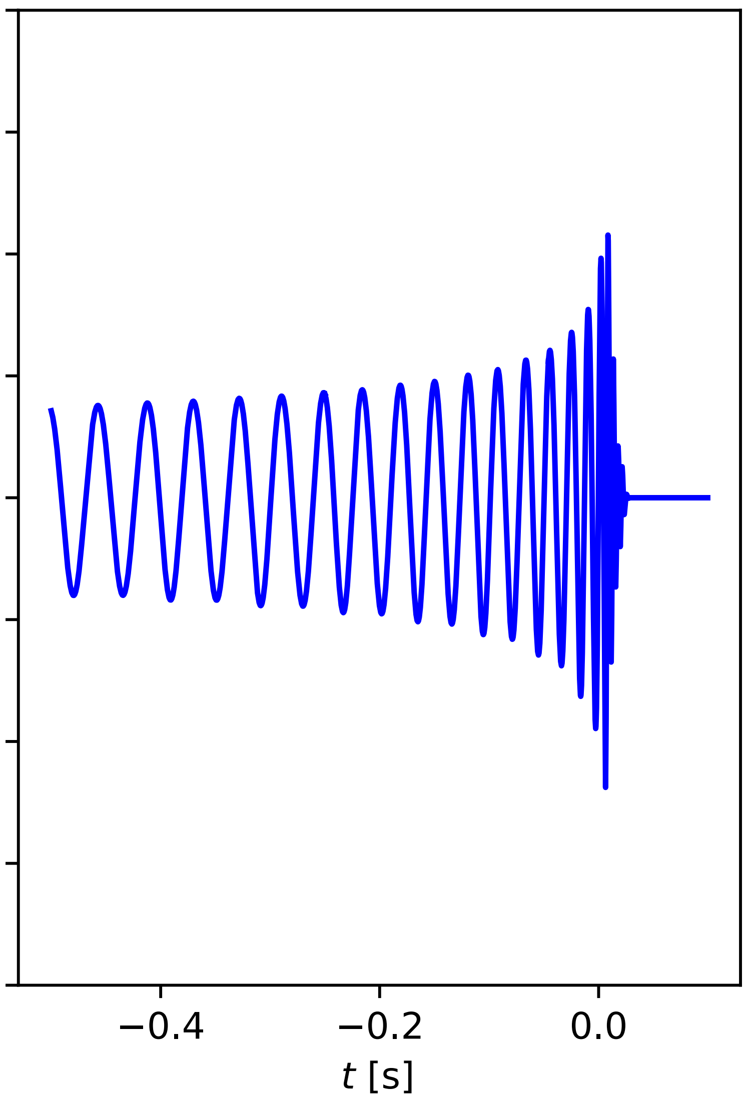
FINAL MASS AND SPIN IN MODIFIED EOB WAVEFORMS

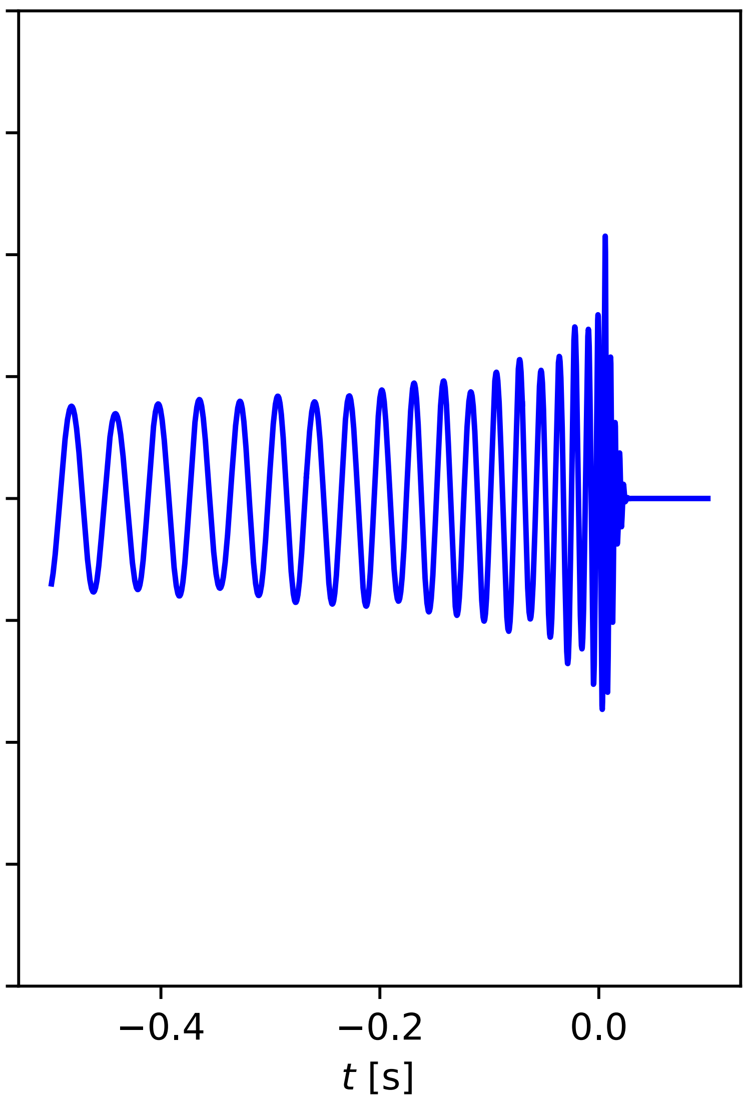


MODIFICATION TO QNM SPECTRUM



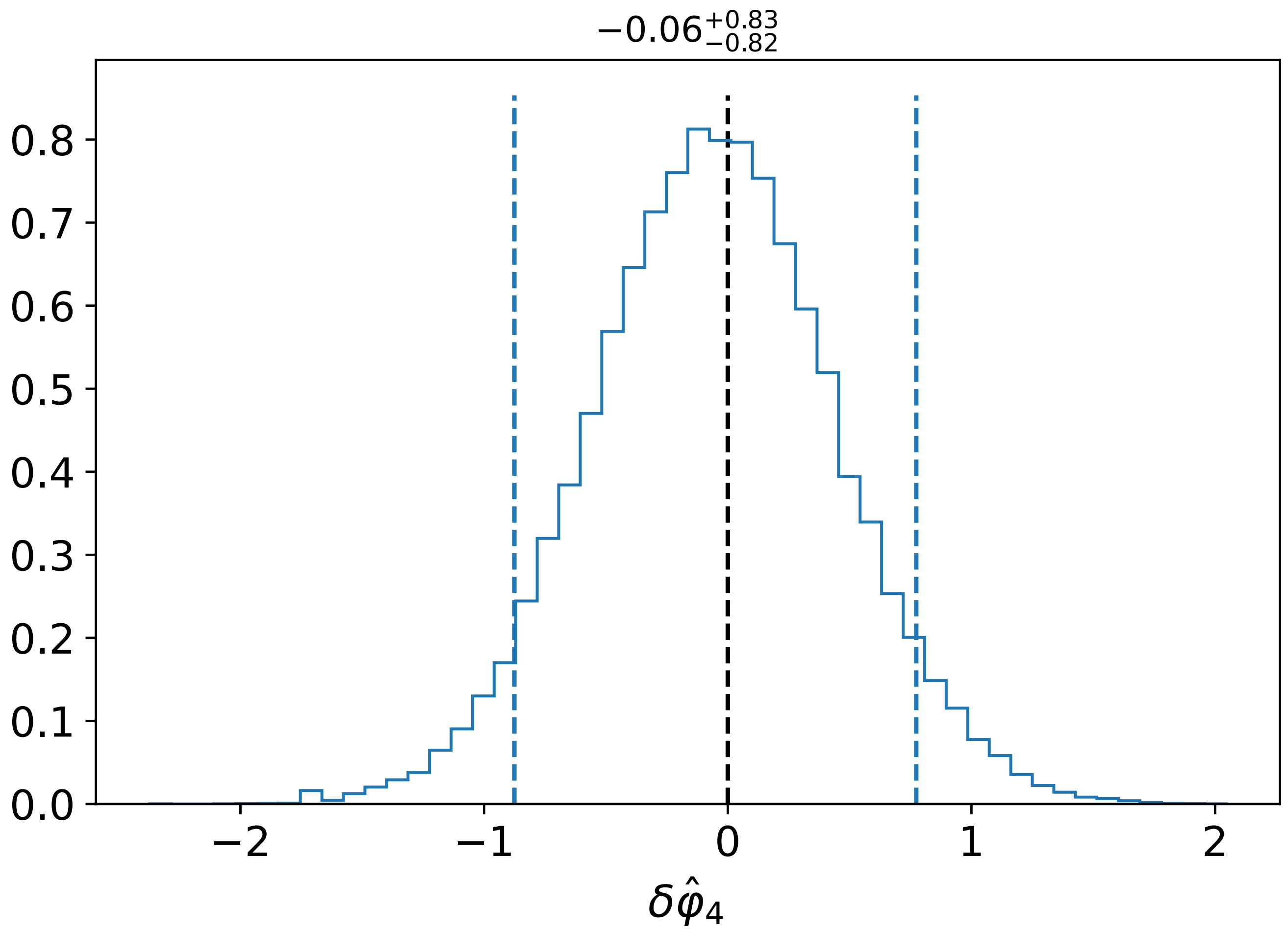
NON-GR SIGNALS:
GW150914-LIKE MASSIVE GRAVITON DISPERSION





NON-GR SIGNALS: GW150914-LIKE MODIFIED ENERGY FLUX

TIGER, 2PN



Thanks to Soumen Roy

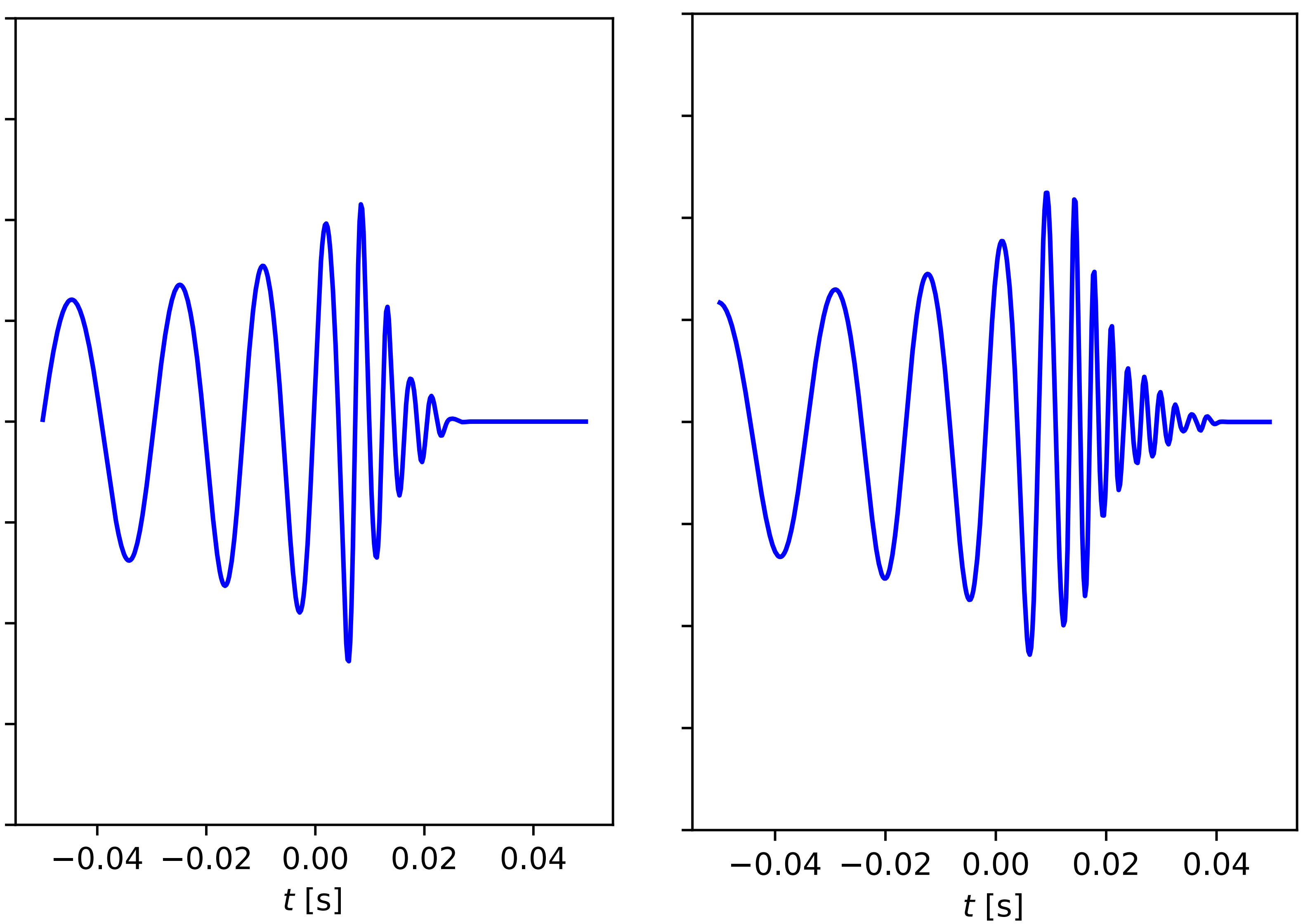
Aligned-spin, factor 10 multiplying modes, extra energy goes into a field that doesn't couple to GW detectors

Injected $\delta\hat{\varphi}_4 \simeq -4.3$ excluded at very high credibility by TIGER

NON-GR SIGNALS: GW150914-LIKE MODIFIED QNM SPECTRUM

GR

non-GR



Zoomed in on ringdown

Aligned-spin, $Q_f = 0.7$

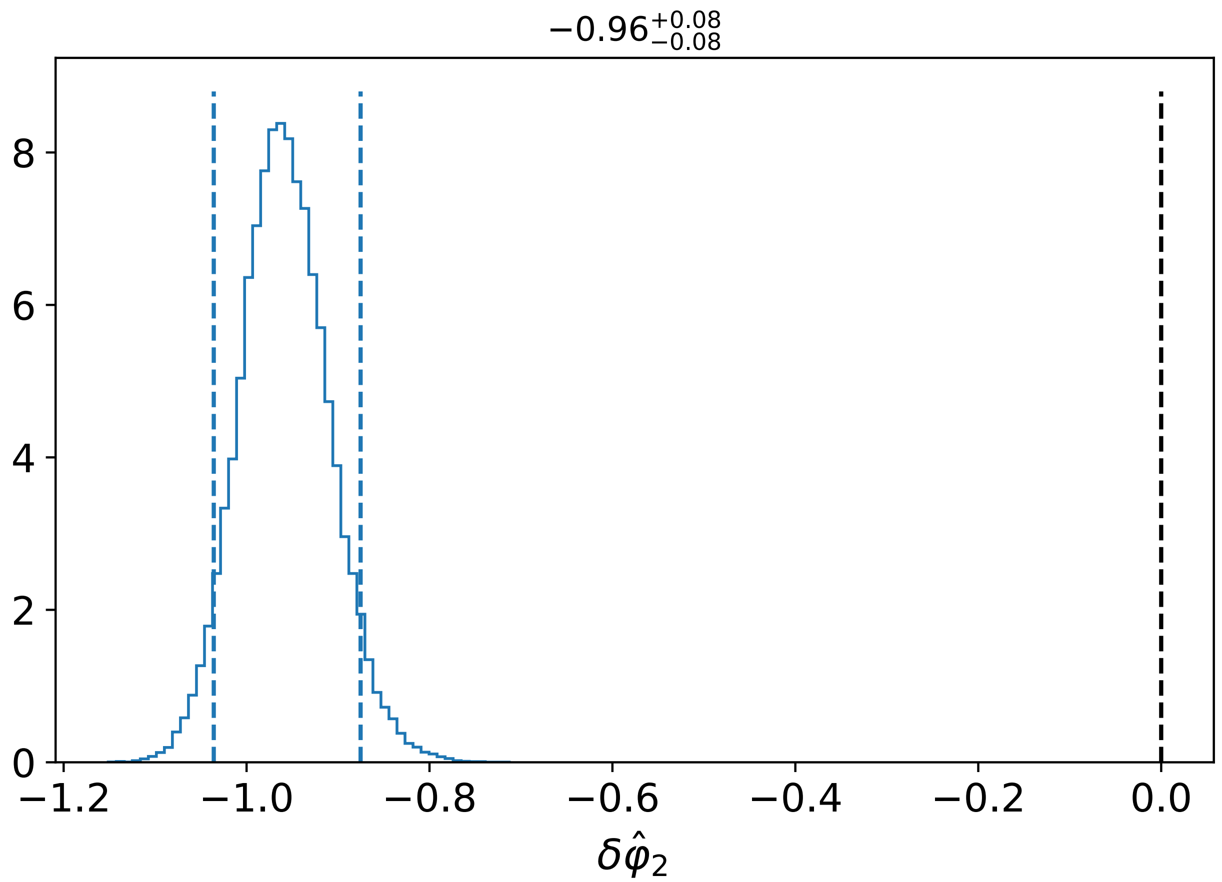
QNM frequencies and damping times increased by ~20-40% and ~40-50% compared to their uncharged values (for the same mass and spin)

Final mass and spin decrease by ~2% and ~5%, respectively, compared to GR

NON-GR SIGNALS: GW150914-LIKE MODIFIED QNM SPECTRUM

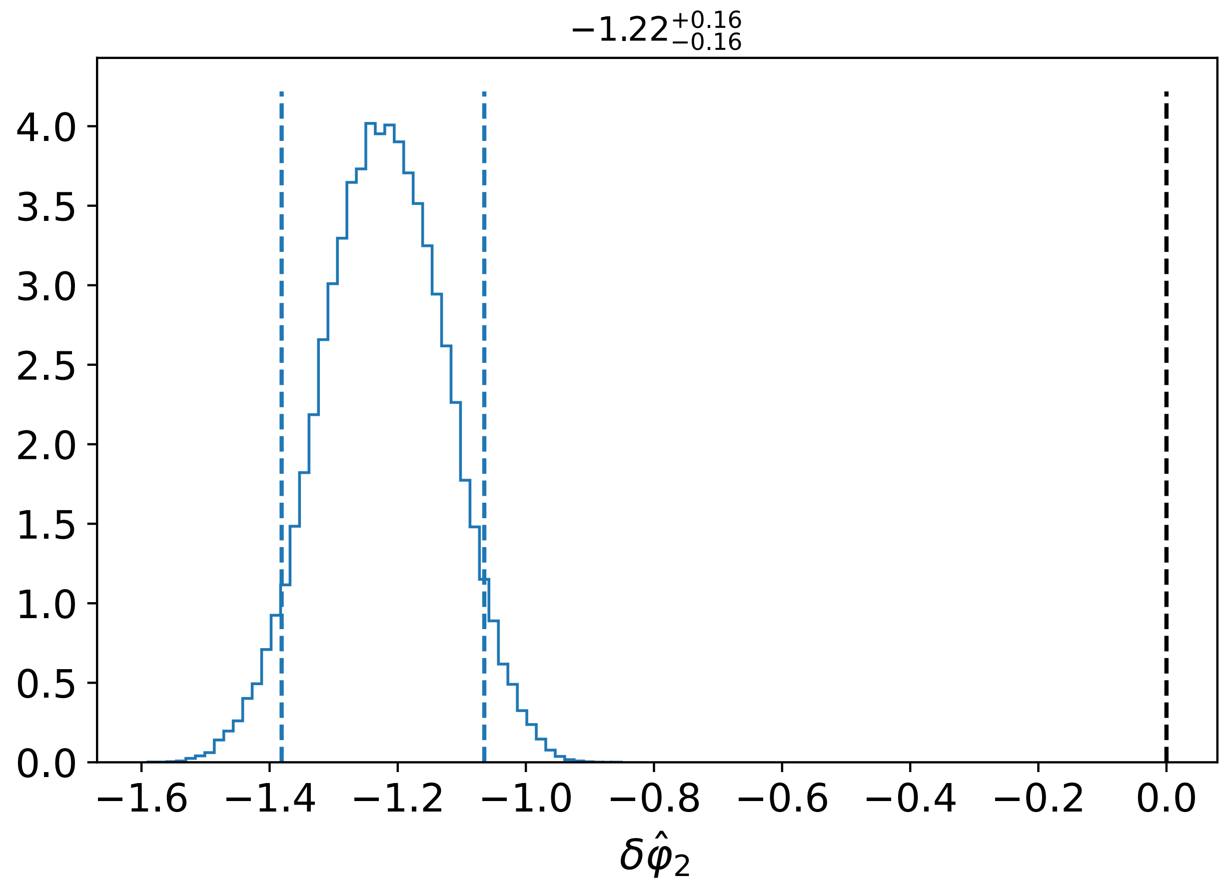
Aligned-spin, $Q_f = 0.7$

TIGER, 1PN



Thanks to Soumen Roy

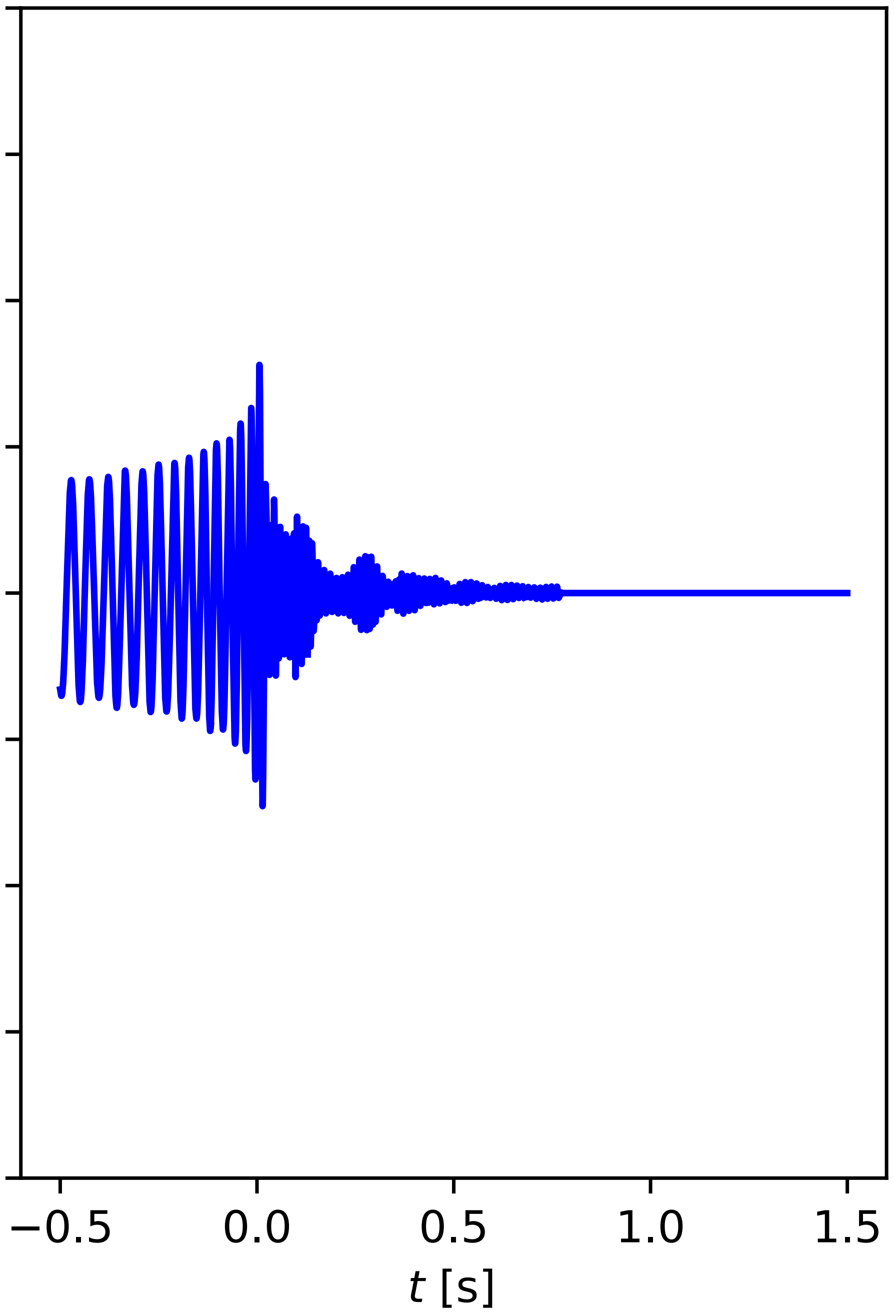
FTI, 1PN



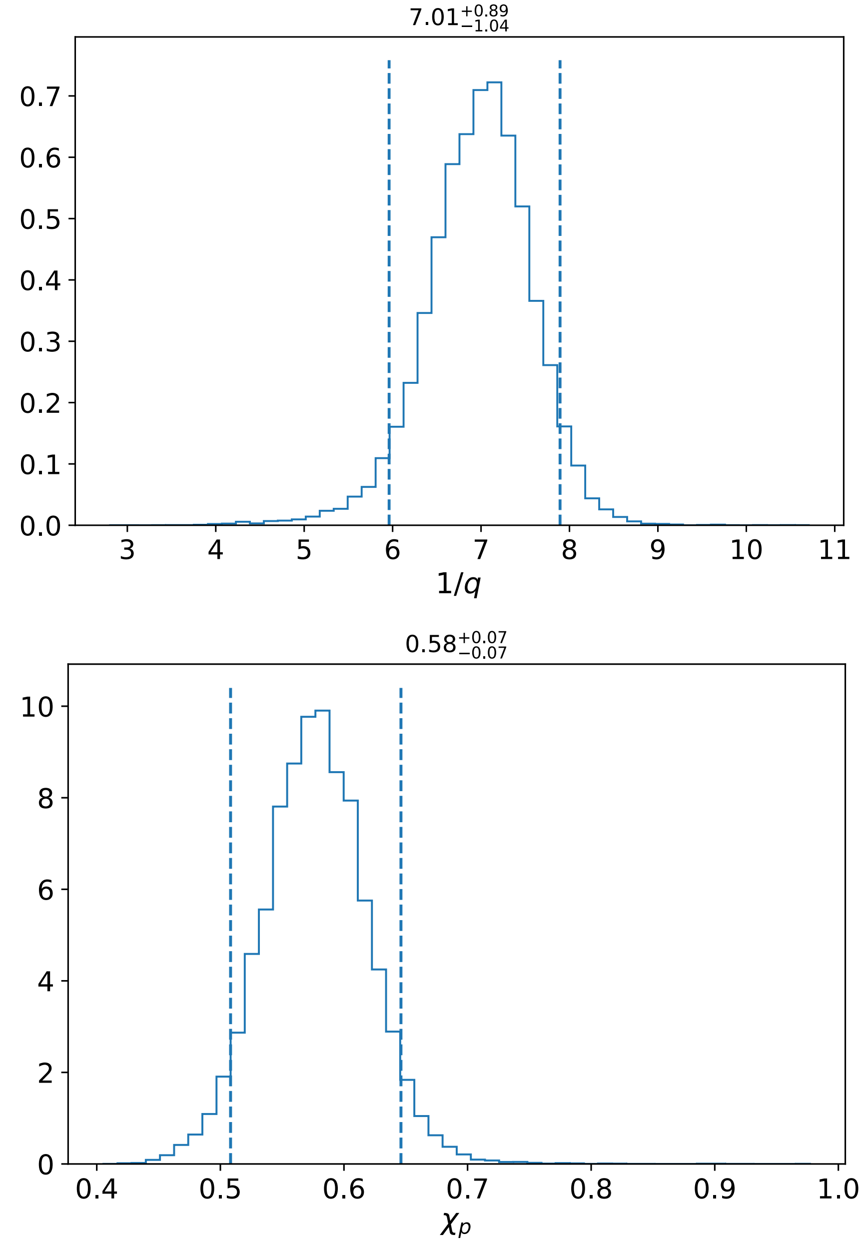
Thanks to Elise Sänger

NON-GR SIGNALS: GW150914-LIKE SCALED BNS

q = 1.5 $[(1.65 + 1.1)M_{\odot}]$ **SLy**
TEOBResumS + BAM hybrid from Calderón Bustillo et al., ApJL (2021)

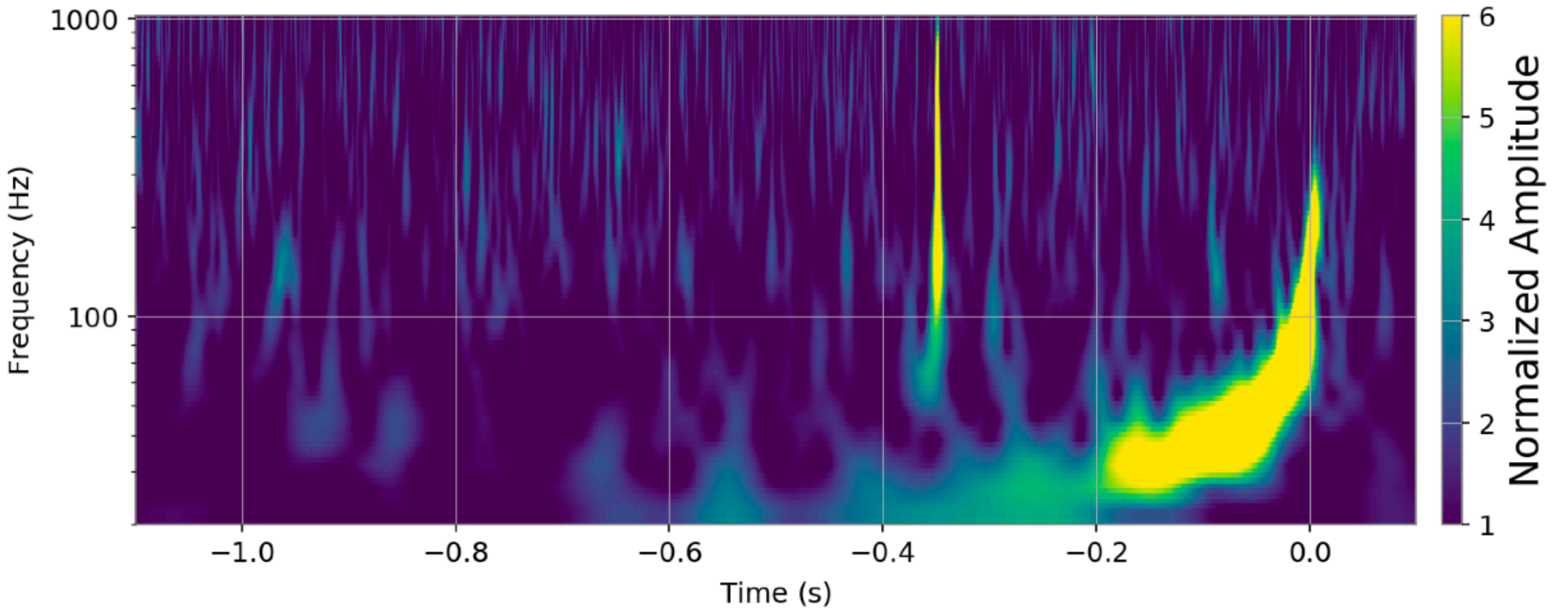


GR recovery with IMRPhenomXPHM gives a $q \simeq 7\ [\sim(100+16)M_{\odot}]$ **highly spinning, significantly precessing binary [injected total mass is** $72.2M_{\odot}$**]**

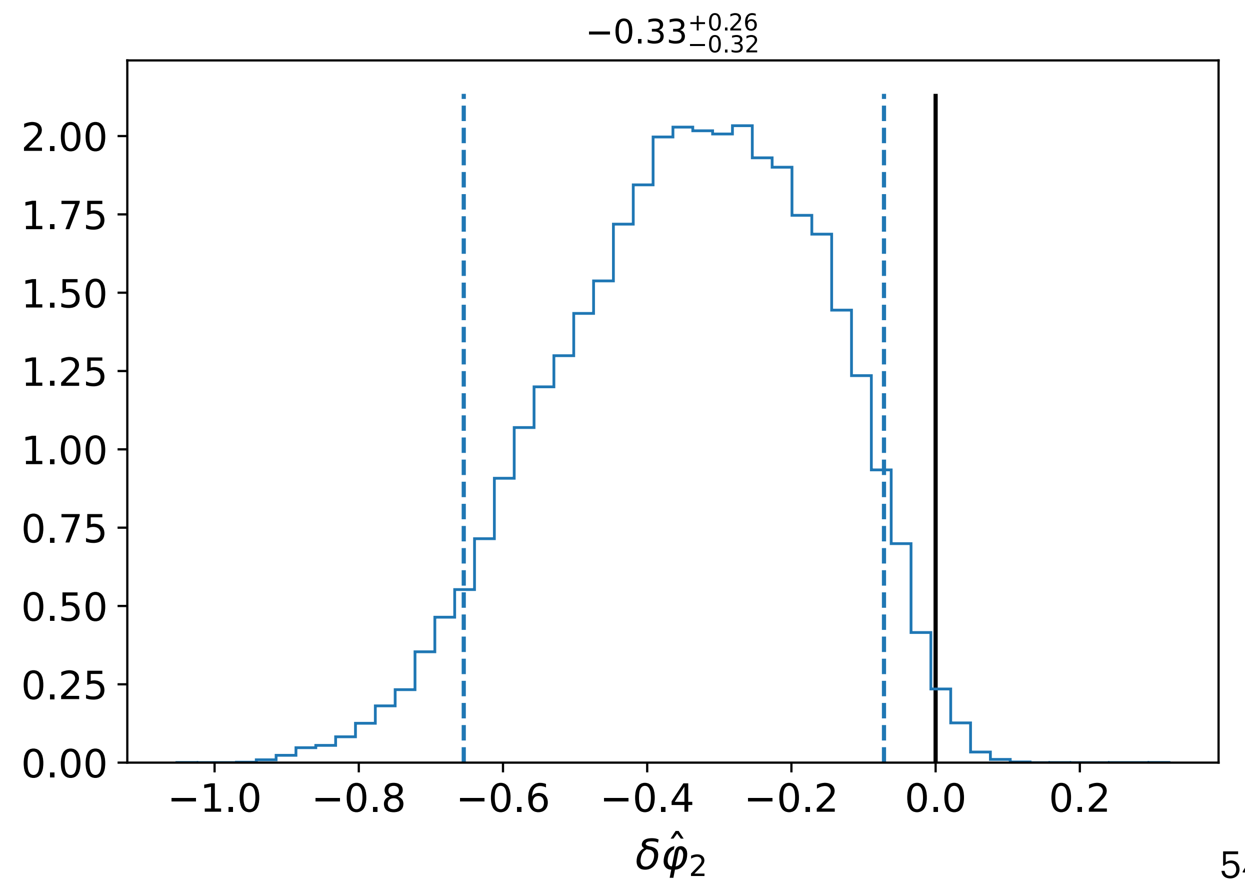


Recovers SNR of ~27.3; 30.9 injected

GLITCH CASE:
GW150914-LIKE WITH BLIP GLITCH

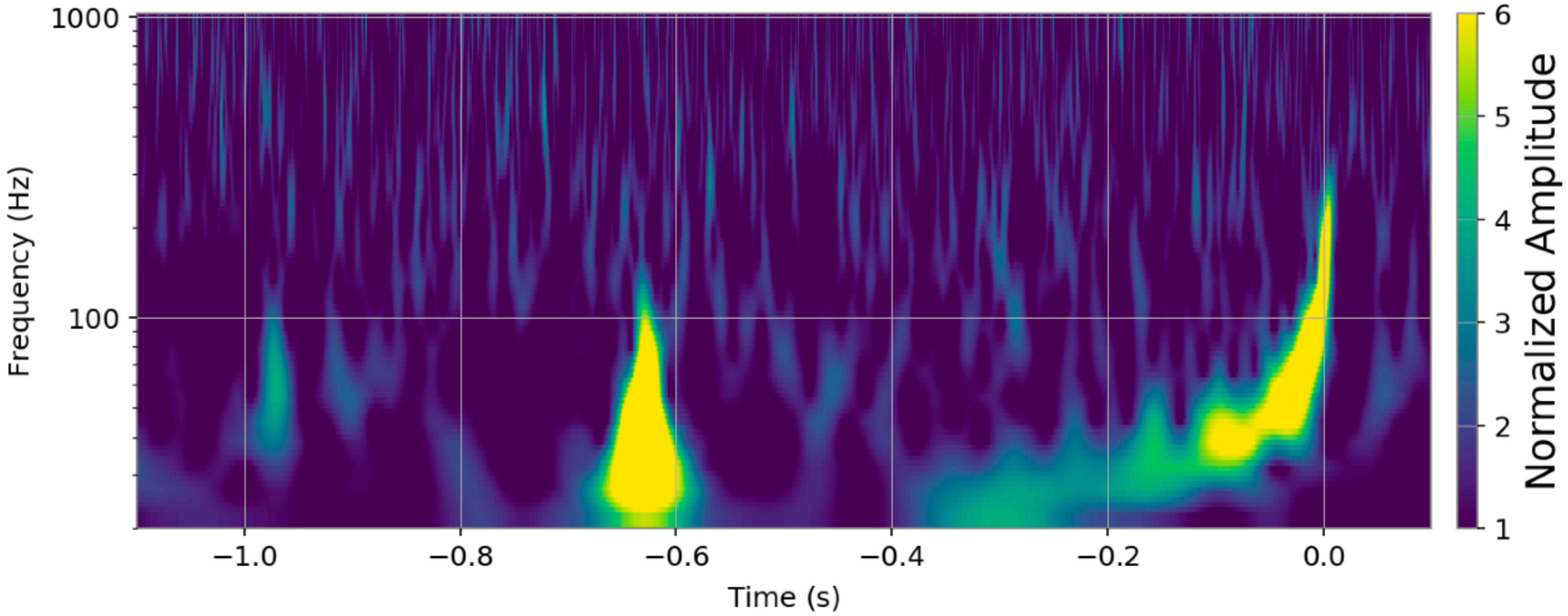


FTI, 1PN

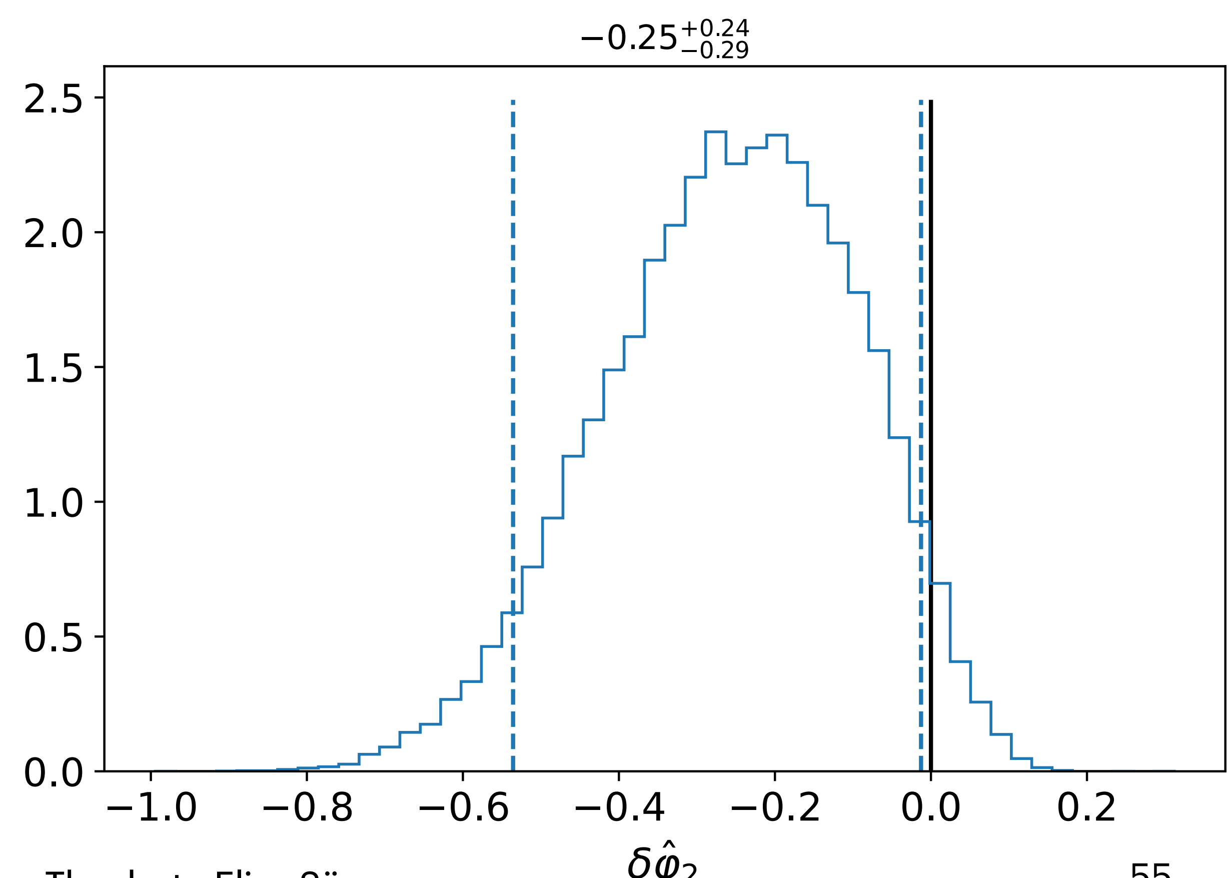


Thanks to Elise Sänger

GLITCH CASE:
GW150914-LIKE WITH TOMTE GLITCH

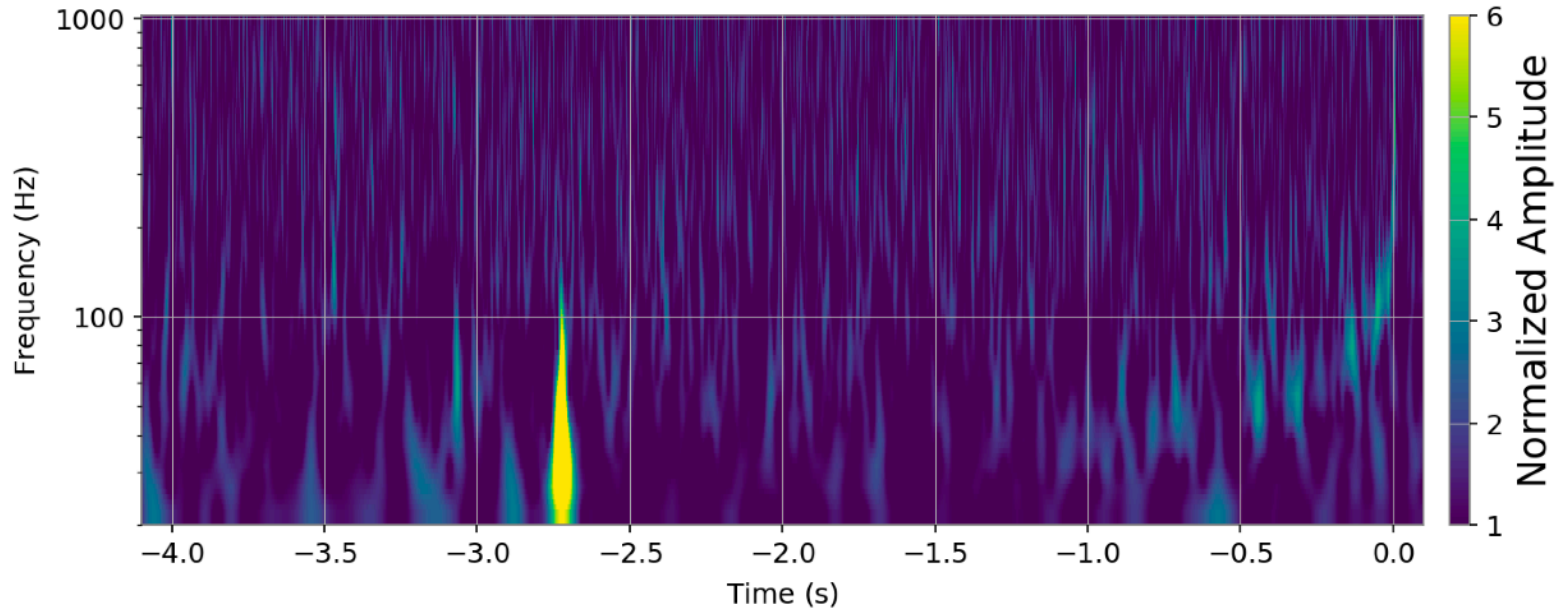


FTI, 1PN

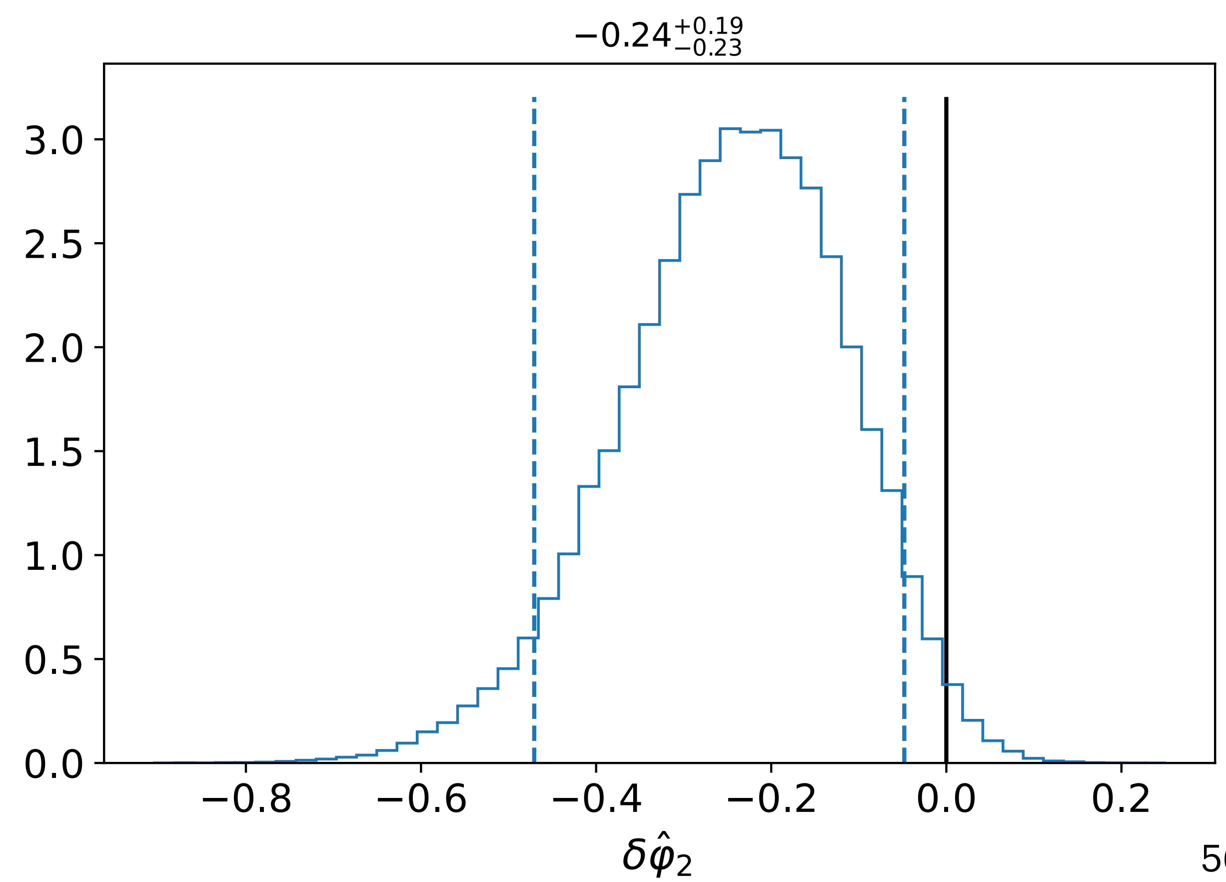


Thanks to Elise Sänger

GLITCH CASE: GW170608-LIKE WITH TOMTE GLITCH



FTI, 1PN



Thanks to Elise Sänger

RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS

[Narayan, NKJ-M, Gupta, arXiv 2023]

- Check how IMR consistency, TIGER, FTI, and modified dispersion test respond to eccentric binary black hole signals, modeled using SXS simulations: The simulations are nonspinning with mass ratios 1, 2, and 3, and with eccentricities of 0.1 and 0.05 at x = 0.075 [from Hinder et al., PRD (2018)], as well as corresponding quasicircular simulations.

- Consider total mass of $80M_{\odot}$ and face-on signals (so only m = 2 modes contribute), so the numerical waveforms are long enough to start the analysis from 20 Hz. With this total mass the eccentricities are given at ~17 Hz.

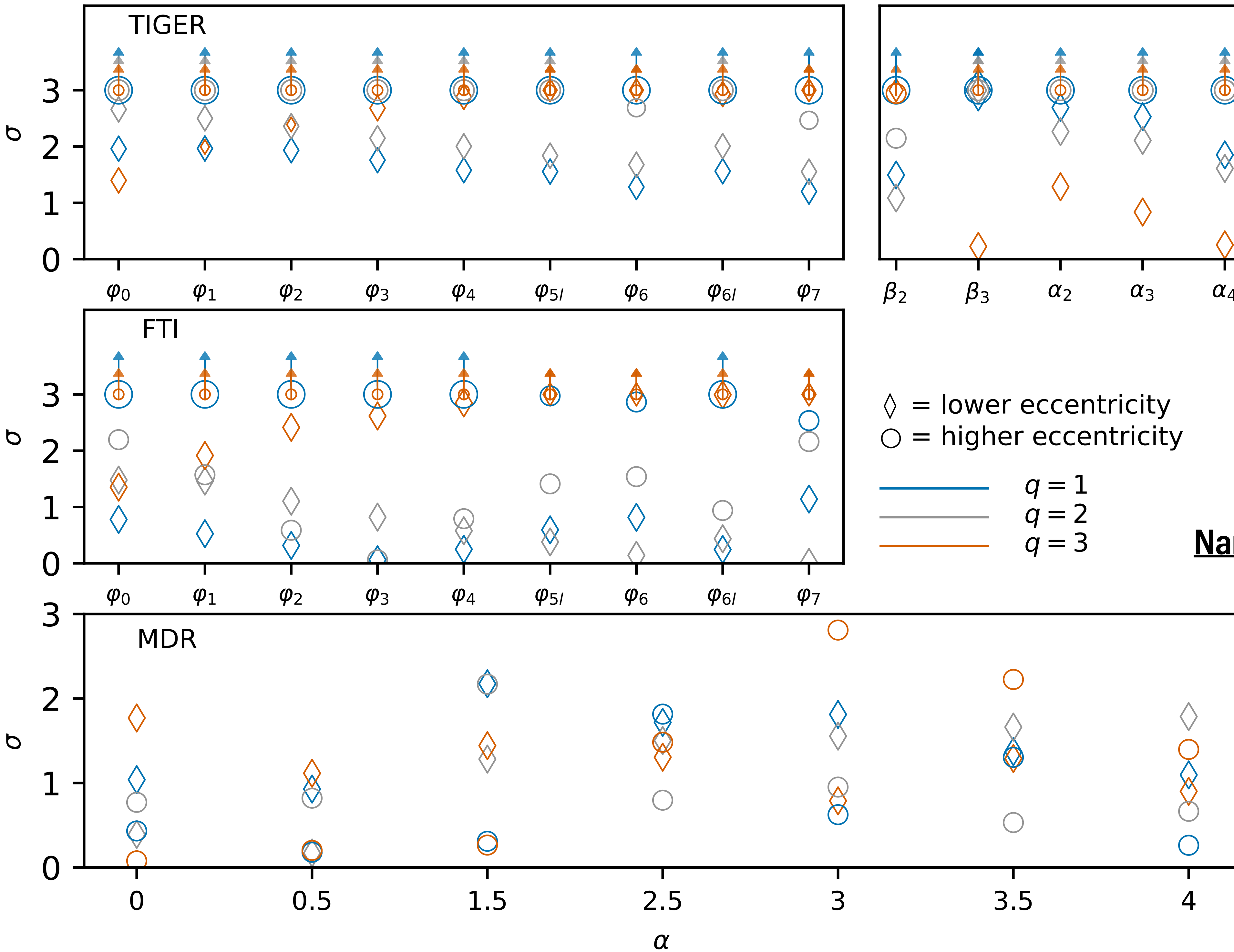
- Use the forecast O4 sensitivity and no noise, with a luminosity distance of 400 Mpc, so SNRs of ca. 120, 105, and 90 for mass ratios of 1, 2, and 3.

- TIGER and FTI find significant deviations from GR ($> 3\sigma$) for most higher-eccentricity cases and some lower-eccentricity cases, with GR excluded at > 90% credibility at almost 2 Gpc for TIGER and > 1 Gpc for FTI.

- MDR finds smaller deviations, all $< 3\sigma$ and only a few $> 2\sigma$.

- Find a bias due to higher-order modes for IMR consistency test applied to quasicircular signals—being investigated by the analysts.

RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: SUMMARY

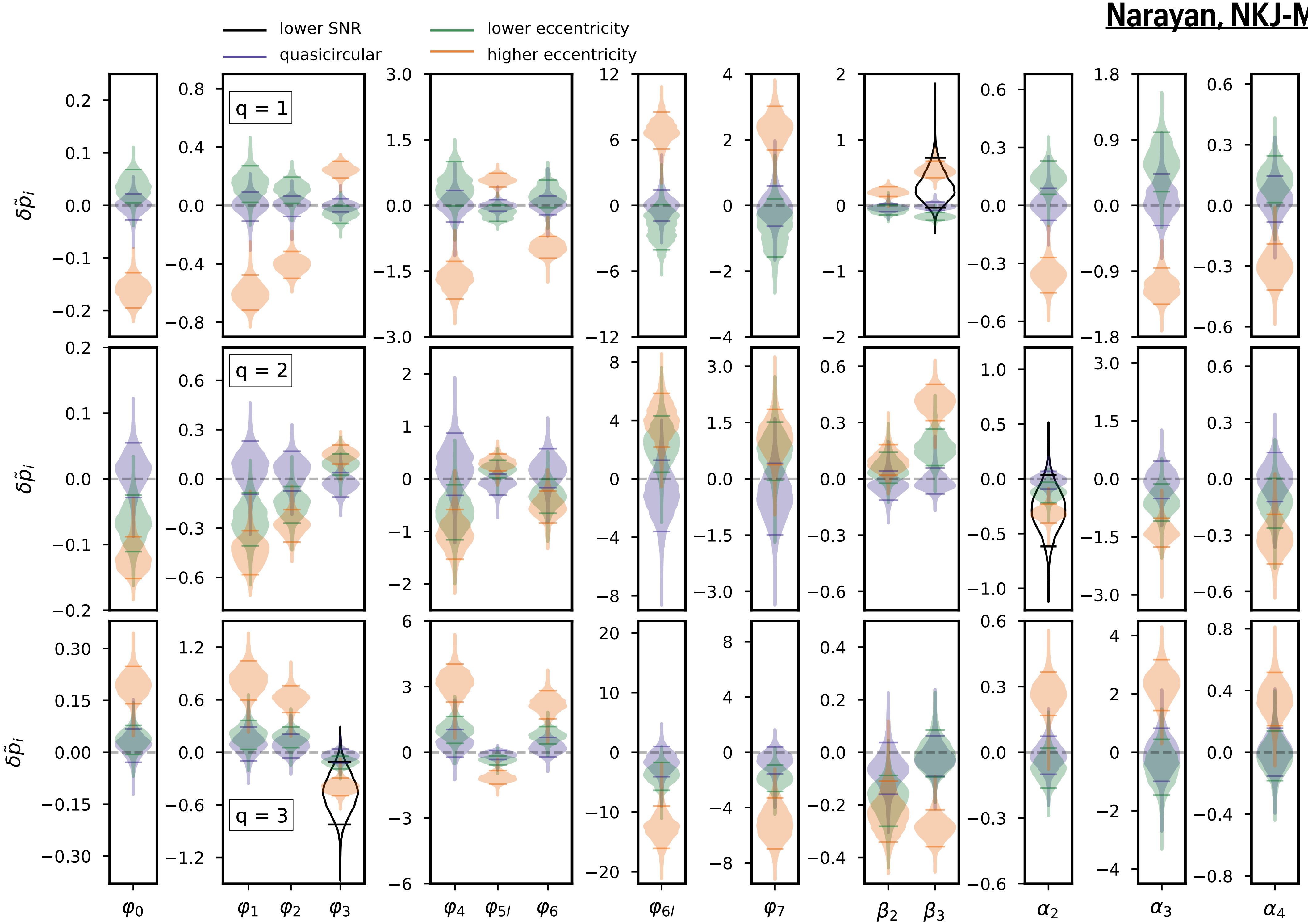


Narayan, NKJ-M, Gupta (arXiv, 2023)

Lower bound on significance comes from the finite number of samples ($\sim 10^4$)

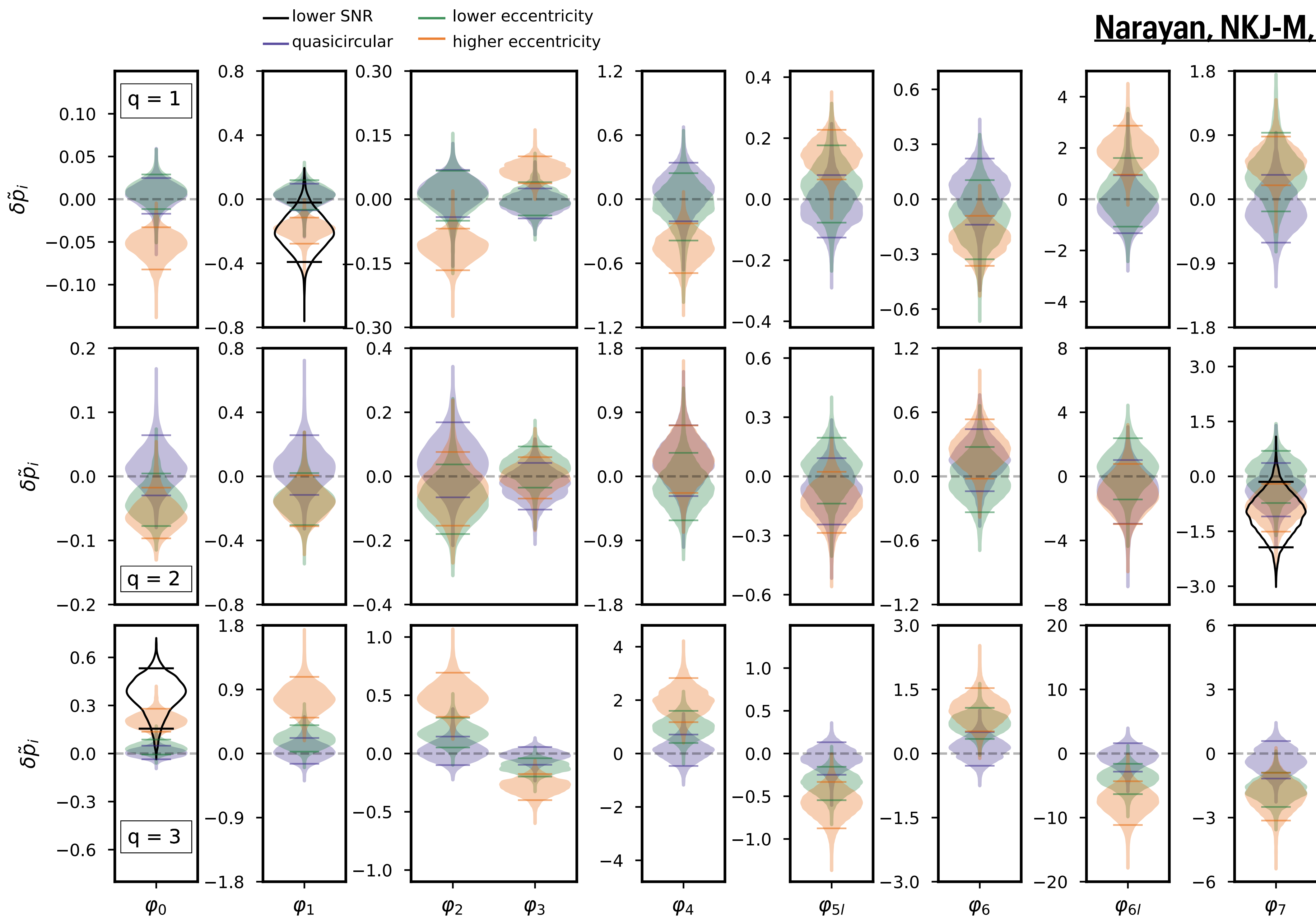
RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: TIGER

Narayan, NKJ-M, Gupta (arXiv, 2023)



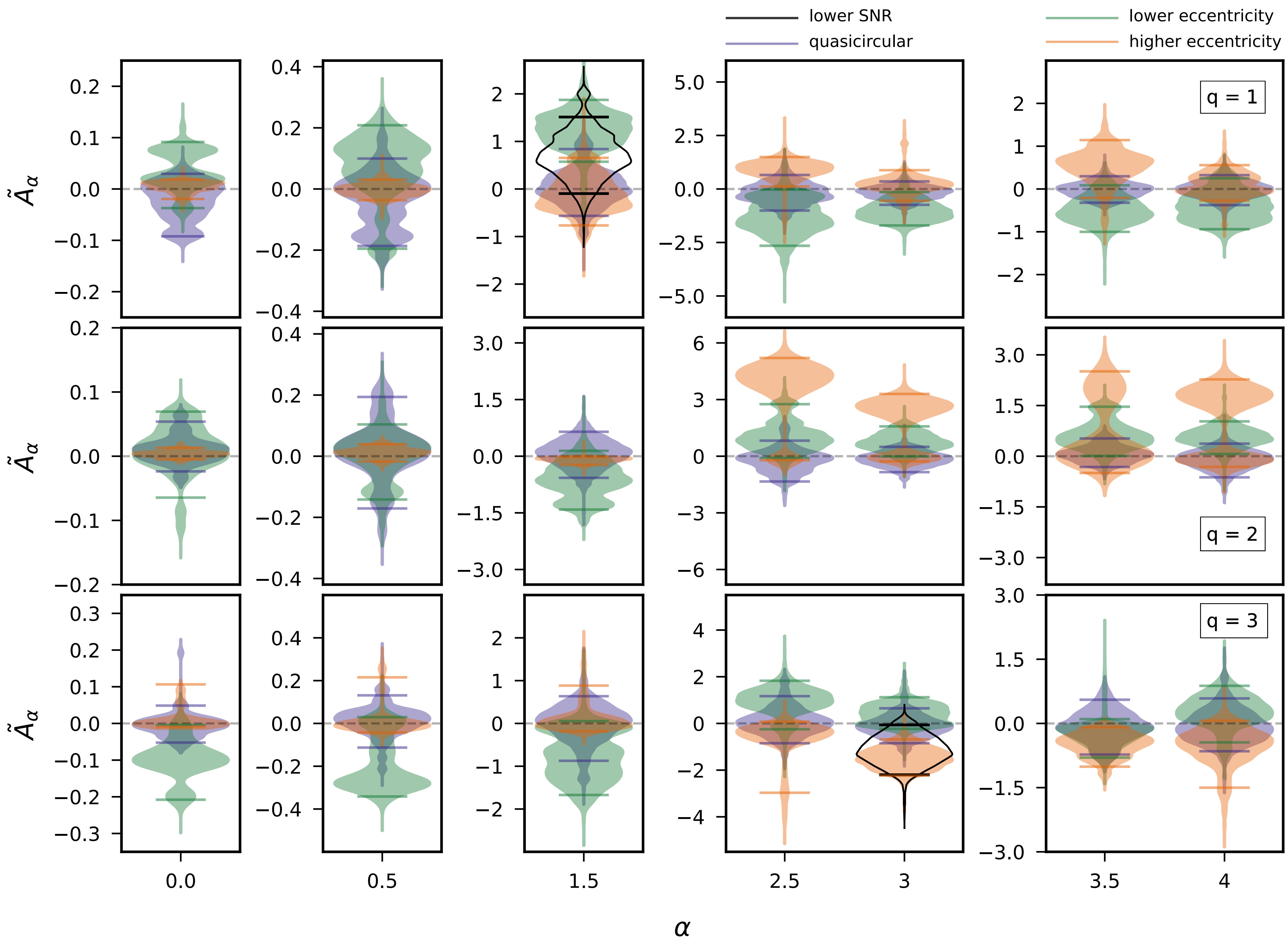
RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: FTI

Narayan, NKJ-M, Gupta (arXiv, 2023)

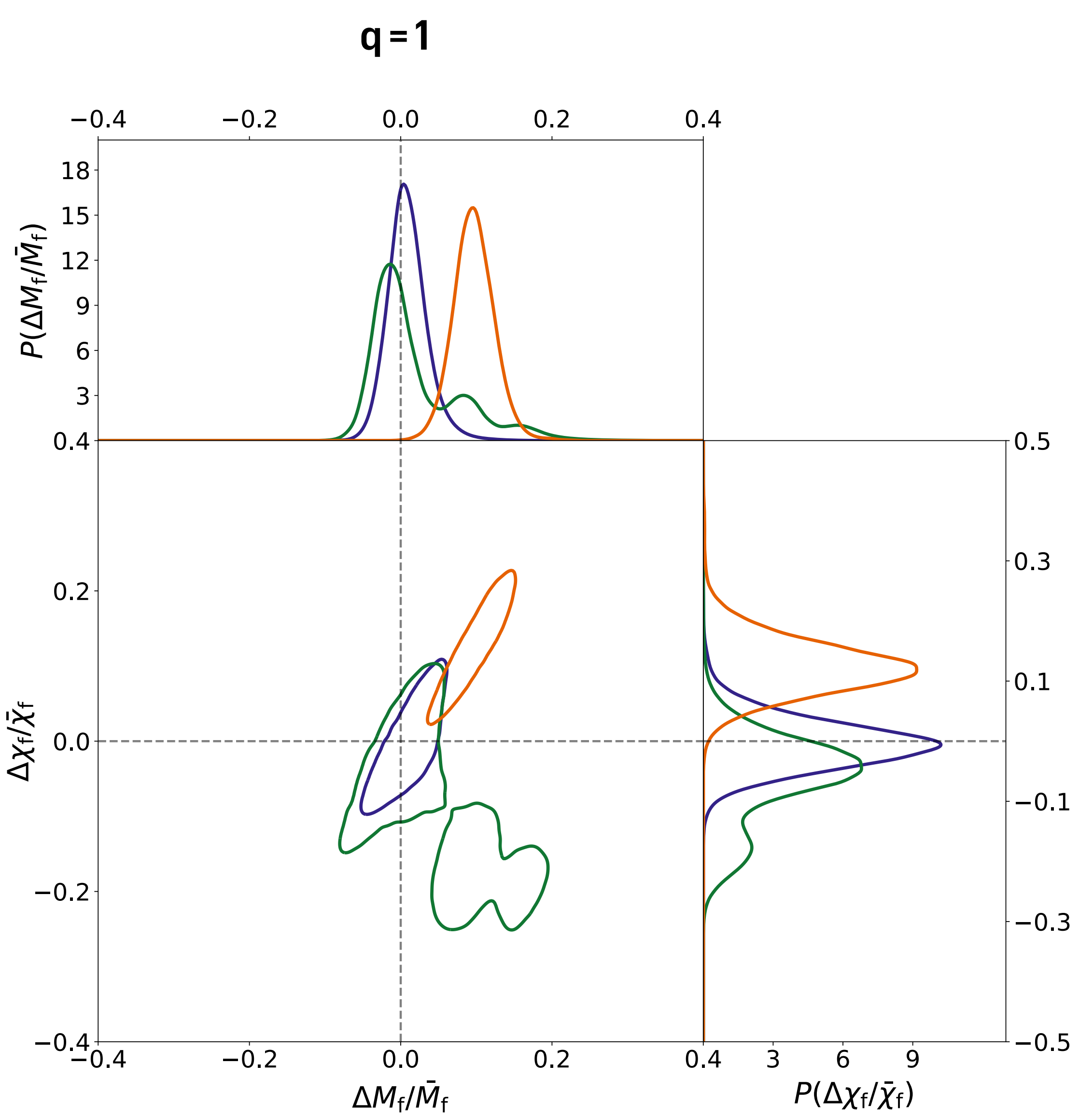


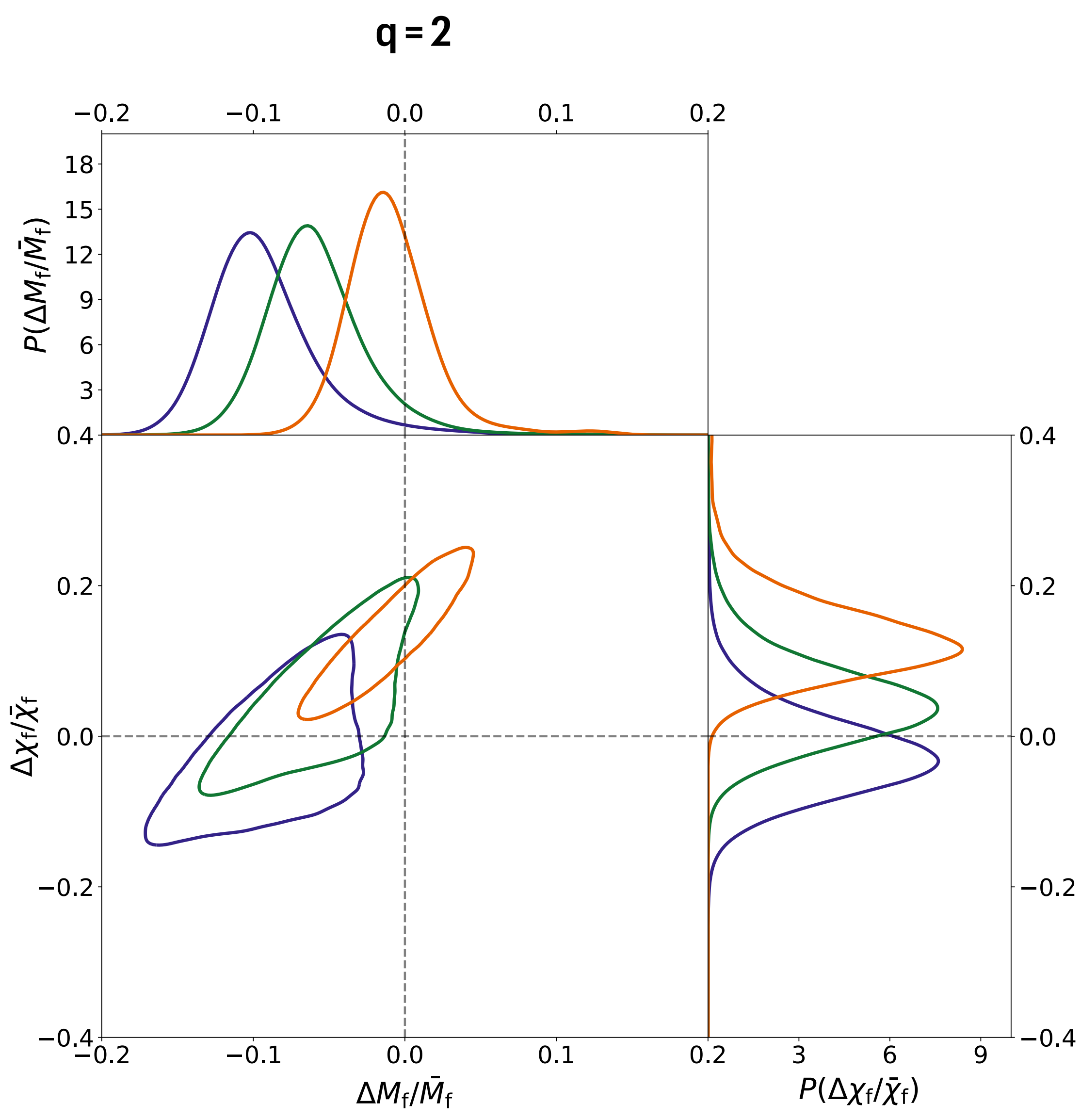
RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: MDR

Narayan, NKJ-M, Gupta (arXiv, 2023)



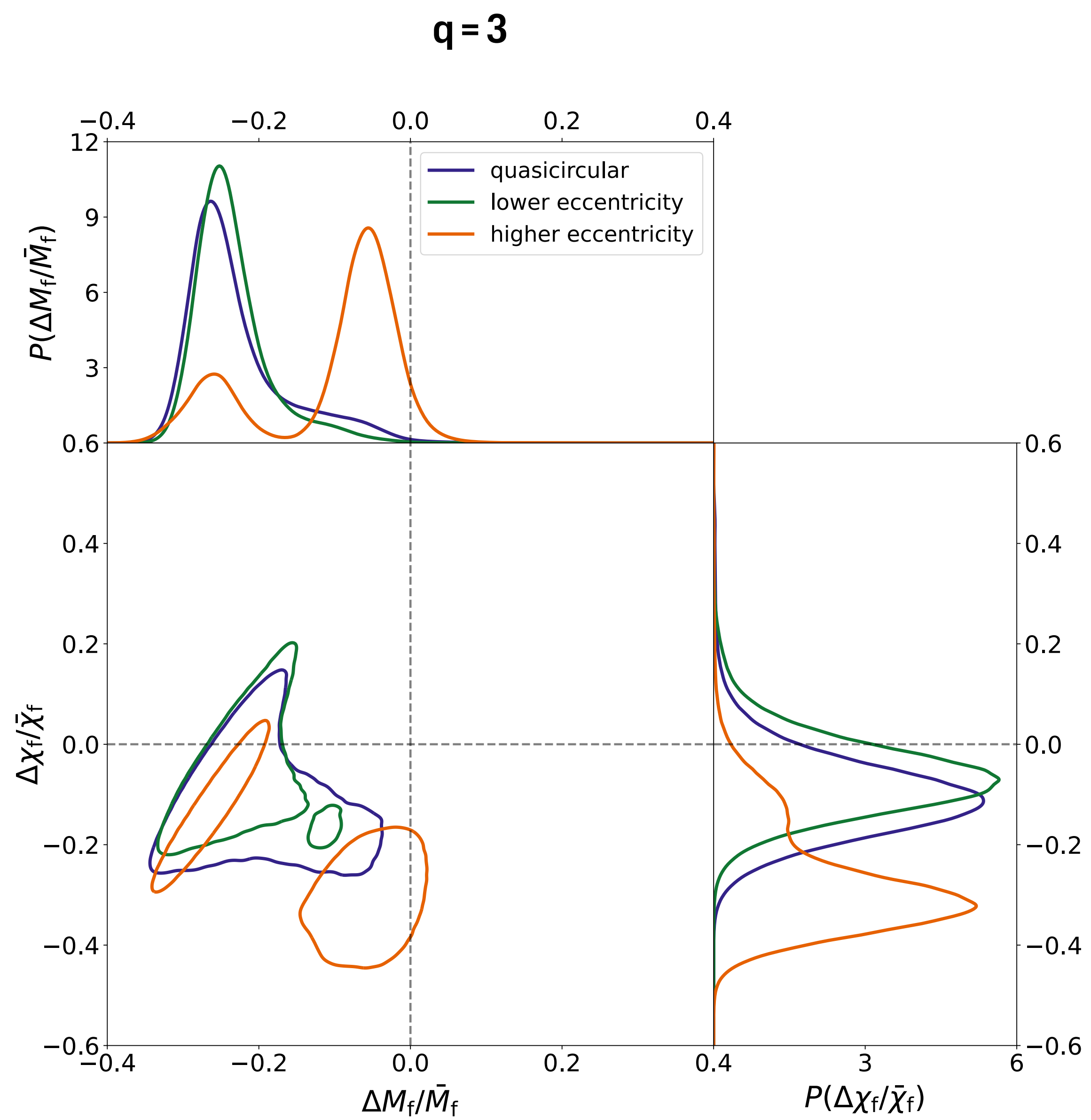
RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: IMR CONSISTENCY





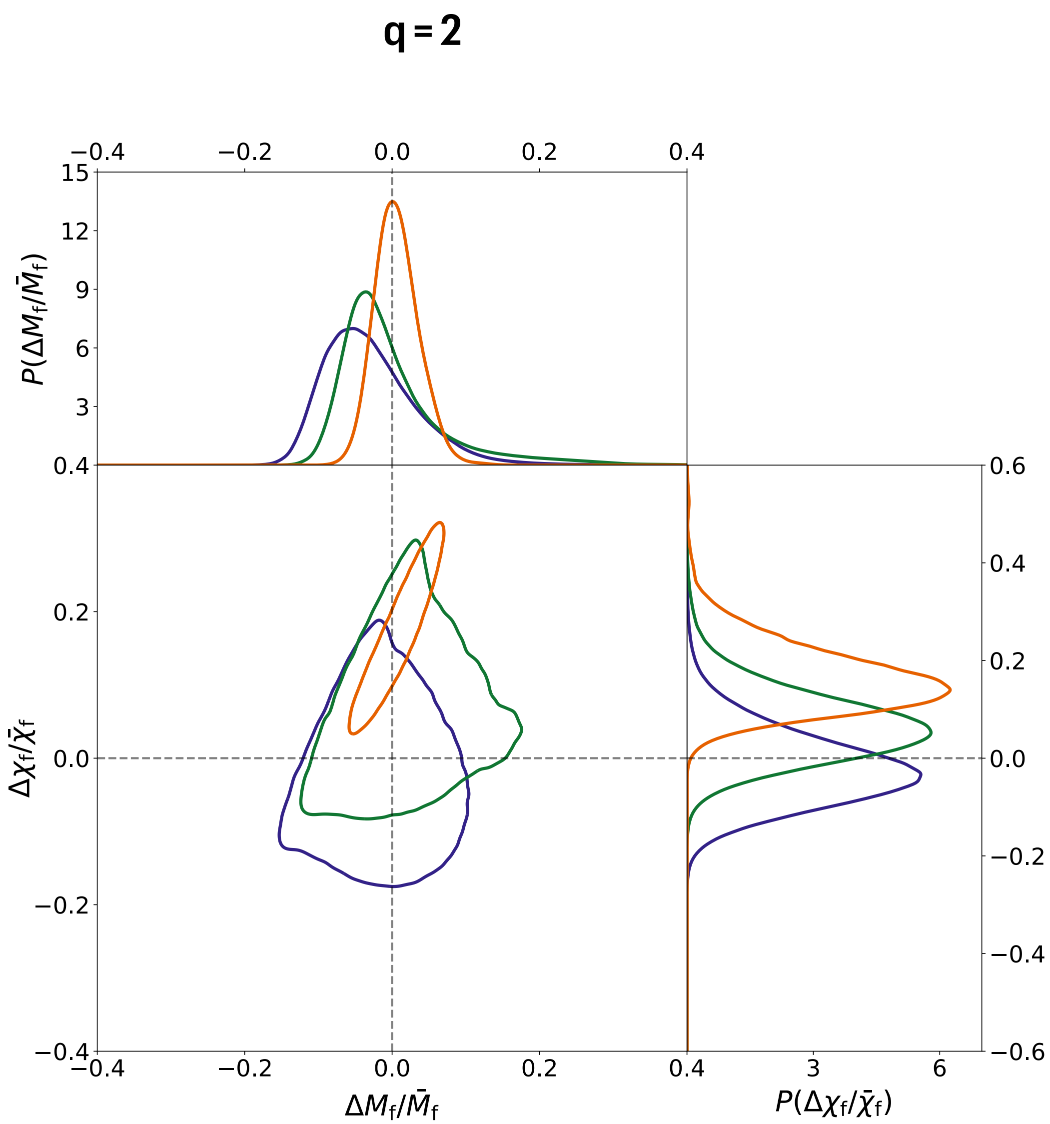
Narayan, NKJ-M, Gupta (arXiv, 2023)

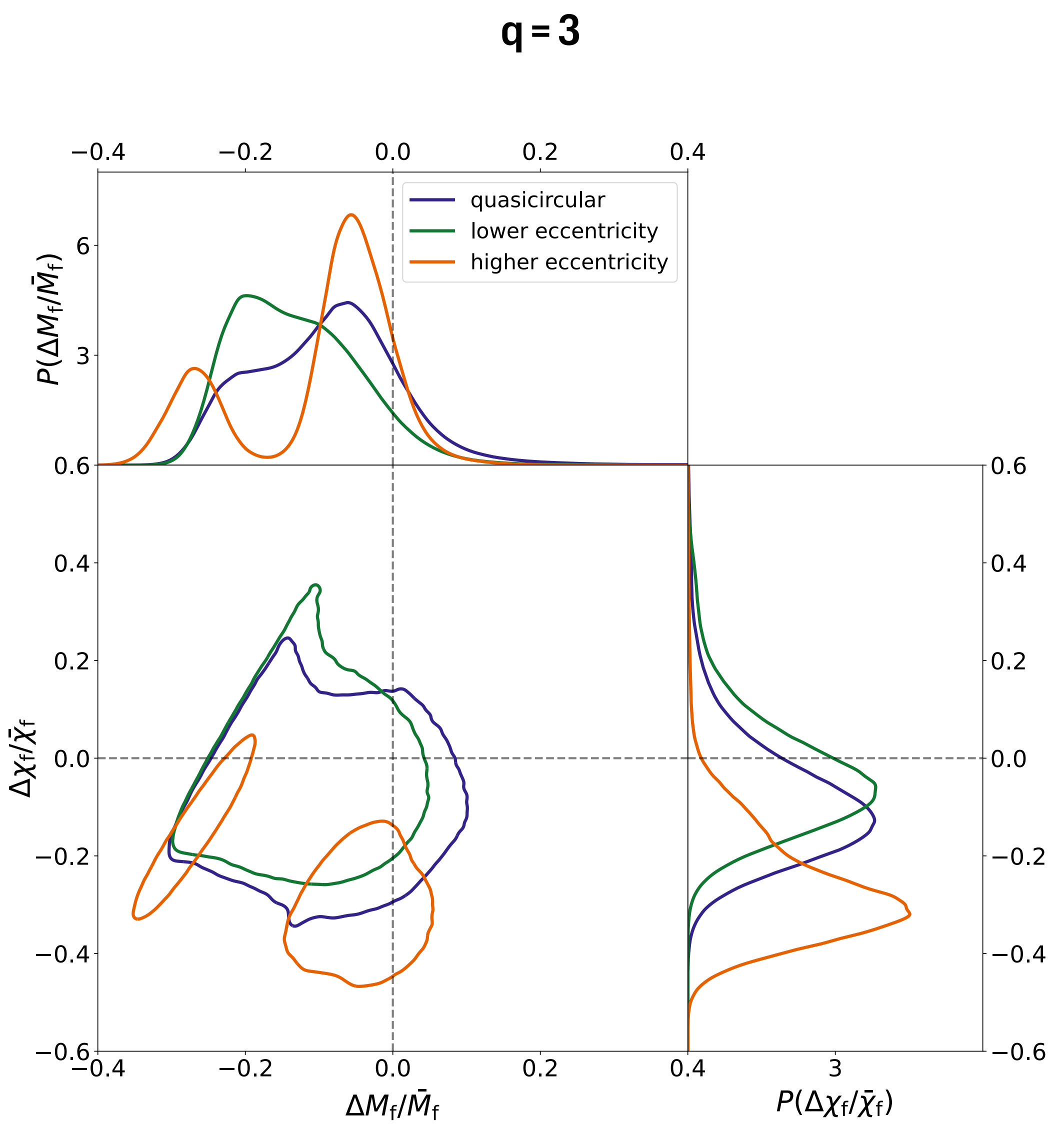
RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: IMR CONSISTENCY



Narayan, NKJ-M, Gupta (arXiv, 2023)

RESPONSE OF TESTS OF GR TO ECCENTRIC SIGNALS: IMR CONSISTENCY WITH JUST $(2, \pm 2)$ MODES





Narayan, NKJ-M, Gupta (arXiv, 2023)