Effect of Missing Physics on Tests of General Relativity with Gravitational Waves

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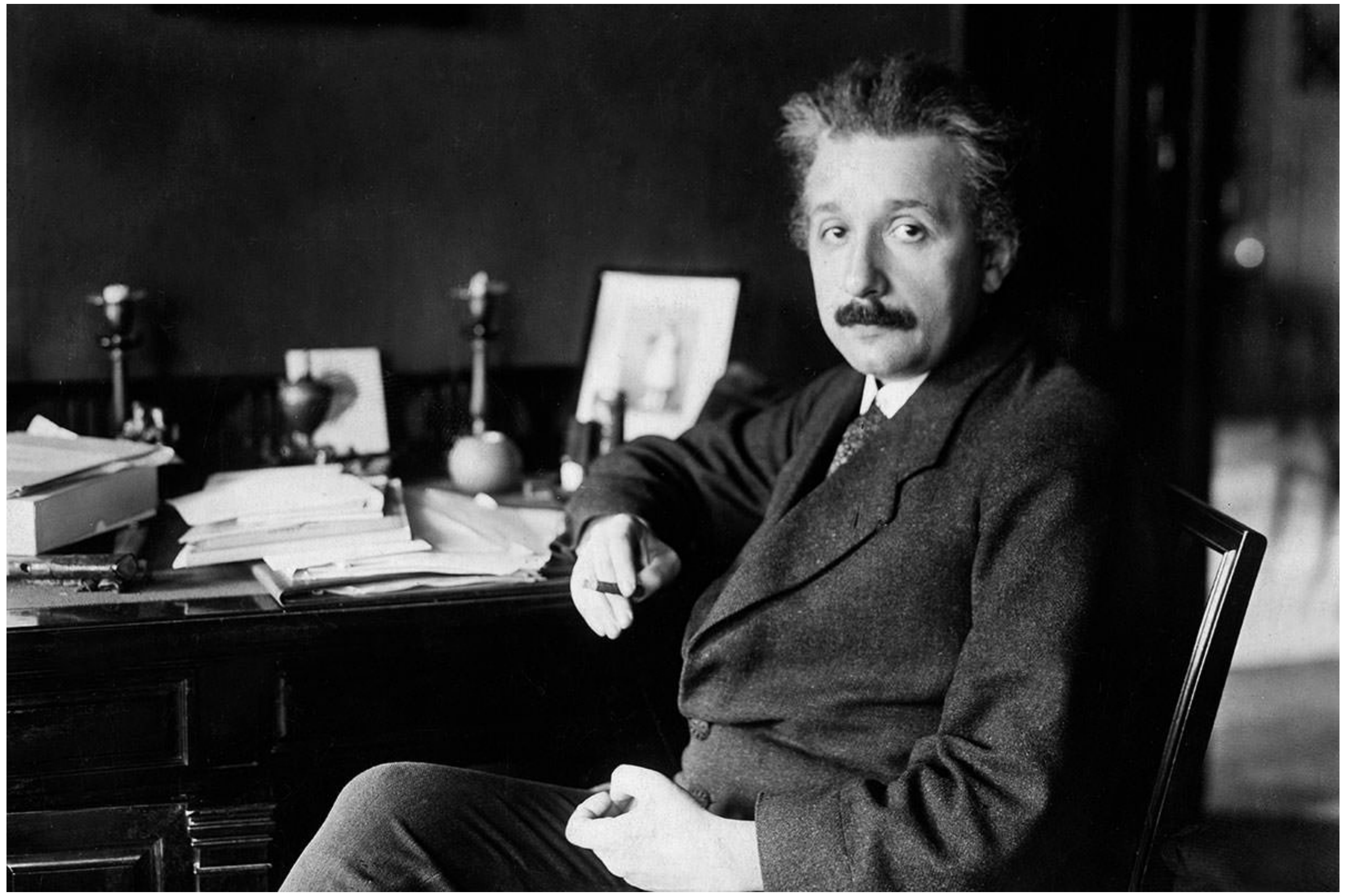
Einstein's general theory of relativity



Curvature of space

Distribution of mass/energy

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Some constants

spacetime tells matter how to move;
matter tells spacetime how to curve

1916: Gravity as a curvature of space-time rather than a force

A tremendously successful theory in explaining current astronomical observations

General consensus: GR is at best incomplete

Black Hole information loss

Spacetime Singularities

Cosmological Constant

Lack of a viable formulation of quantum gravity

Tests of General Theory of Relativity (GR)

- No failure of GR has been found for
  - Solar system tests
  - Binary pulsar tests

- These tests cannot effectively probe the *extreme gravity regime*
  - strong and dynamical gravitational field
  - large curvature of spacetime
  - comparable to the speed of light characteristic velocities

Will, LRR, 2014

Gravitational waves are excellent probes to test GR

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LVK Collaboration results on GWTC-3

arXiv > gr-qc > arXiv:2112.06861

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General Relativity and Quantum Cosmology

[Submitted on 13 Dec 2021]

Tests of General Relativity with GWTC-3

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration: R. Abbott, H. Abe, F. Acernese, K. Ackley, N. Adhikari, R. X. Adhikari, V. K. Adkins, V. B. Adya, C. Affeldt, D. Agarwal, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, T. Akutsu, P. F. de Alarcón, S. Albanesi, R. A. Alfaidi, A. Allocca, P. A. Altin, A. Amato, C. Anand, S. Anand, A. Ananyeva, S. B. Anderson, W. G. Anderson, M. Ando, T. Andrade, N. Andres, M. Andrés-Carcasona, T. Andrić, S. V. Angelova, S. Ansoldi, J. M. Antelis, S. Antier, T. Apostolatos, E. Z. Appavuravther, S. Appert, S. K. Apple, K. Arai, A. Araya, M. C. Araya, J. S. Areeda, M. Arène, N. Aritomi, N. Arnaud, M. Arogeti, S. M. Aronson, K. G. Arun, H. Asada, Y. Asali, G. Ashton, Y. Aso, M. Assiduo, S. Assis de Souza Melo, S. M. Aston, P. Astone, F. Aubin, K. AultONeal, C. Austin, S. Babak, F. Badaracco, M. K. M. Bader, C. Badger, S. Bae, Y. Bae, A. M. Baer, S. Bagnasco, Y. Bai, J. Baird, R. Bajpai, T. Baka, M. Ball, G. Ballardin, S. W. Ballmer, A. Balsamo, G. Baltus, S. Banagiri, B. Banerjee, D. Bankar, J. C. Barayoga, C. Barbieri, B. C. Barish, D. Barker, P. Barneo, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, M. A. Barton, I. Bartos, S. Basak et al. (1582 additional authors not shown)

The ever-increasing number of detections of gravitational waves (GWs) 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 (BH) mergers, the new events include GW200115_042309, a signal consistent with a neutron star--BH 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 BH constituents are consistent with those of Kerr BHs in GR. We find no evidence for dispersion of GWs, 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 BHs, 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 GW signals to calculate more precise population constraints. We find no evidence in support of physics beyond GR.

A number of tests done with GWs

Dynamics of compact binaries

Parametrized tests of PN theory

Consistency between inspiral, merger, ringdown

Constraining dipole radiation in the strong-field

Test of equivalence principle

Propagation of gravitational waves

Testing local Lorentz invariance

Testing dispersion of GWs

Bounds on graviton mass

Constraining # of space-time dimensions

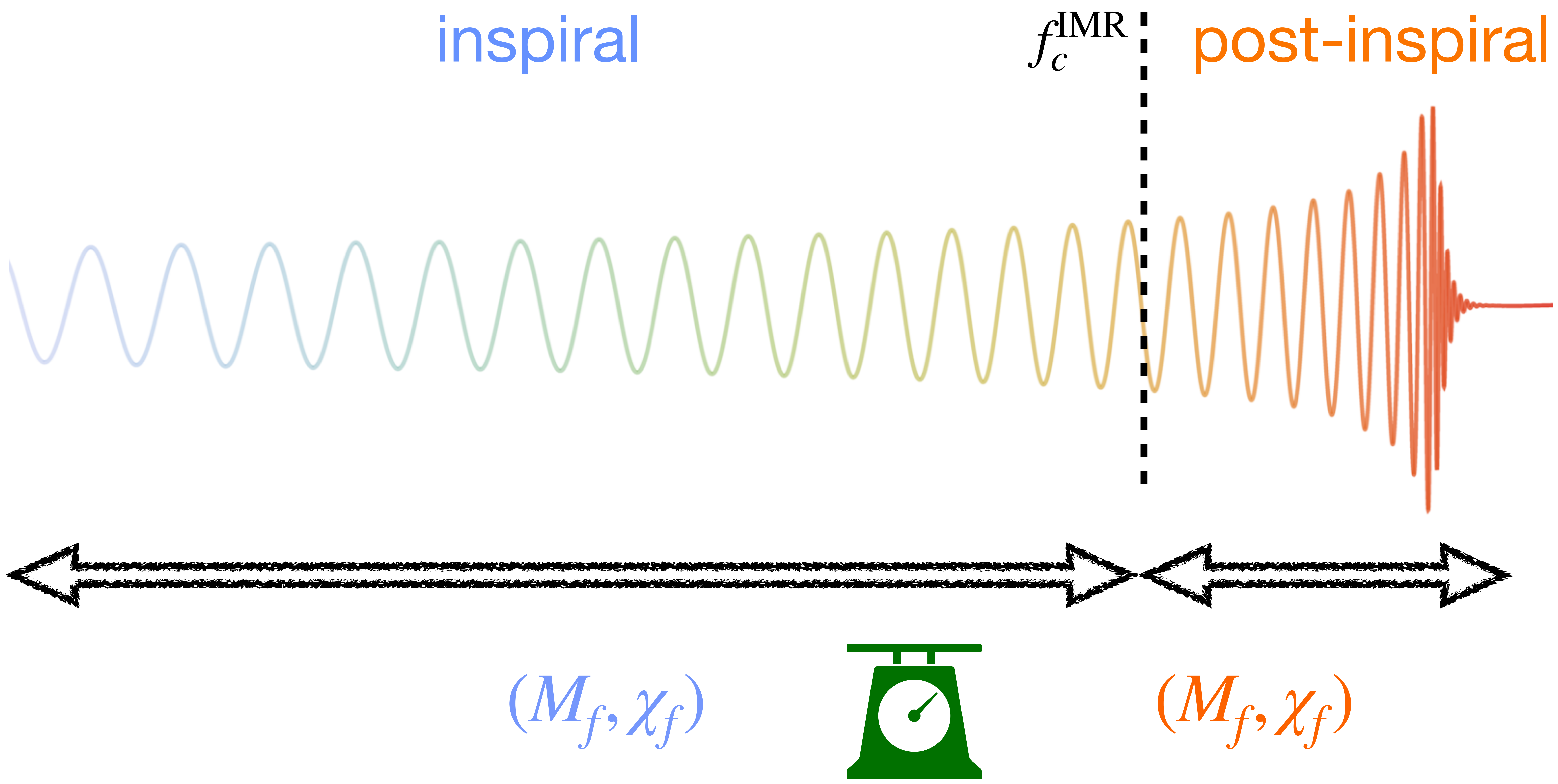
Bounds on speed of GWs

Polarization of gravitational waves

Constraining alternative polarization states

LVKC, 2016, 2017, 2018, 2019, 2021

IMR Consistency Test



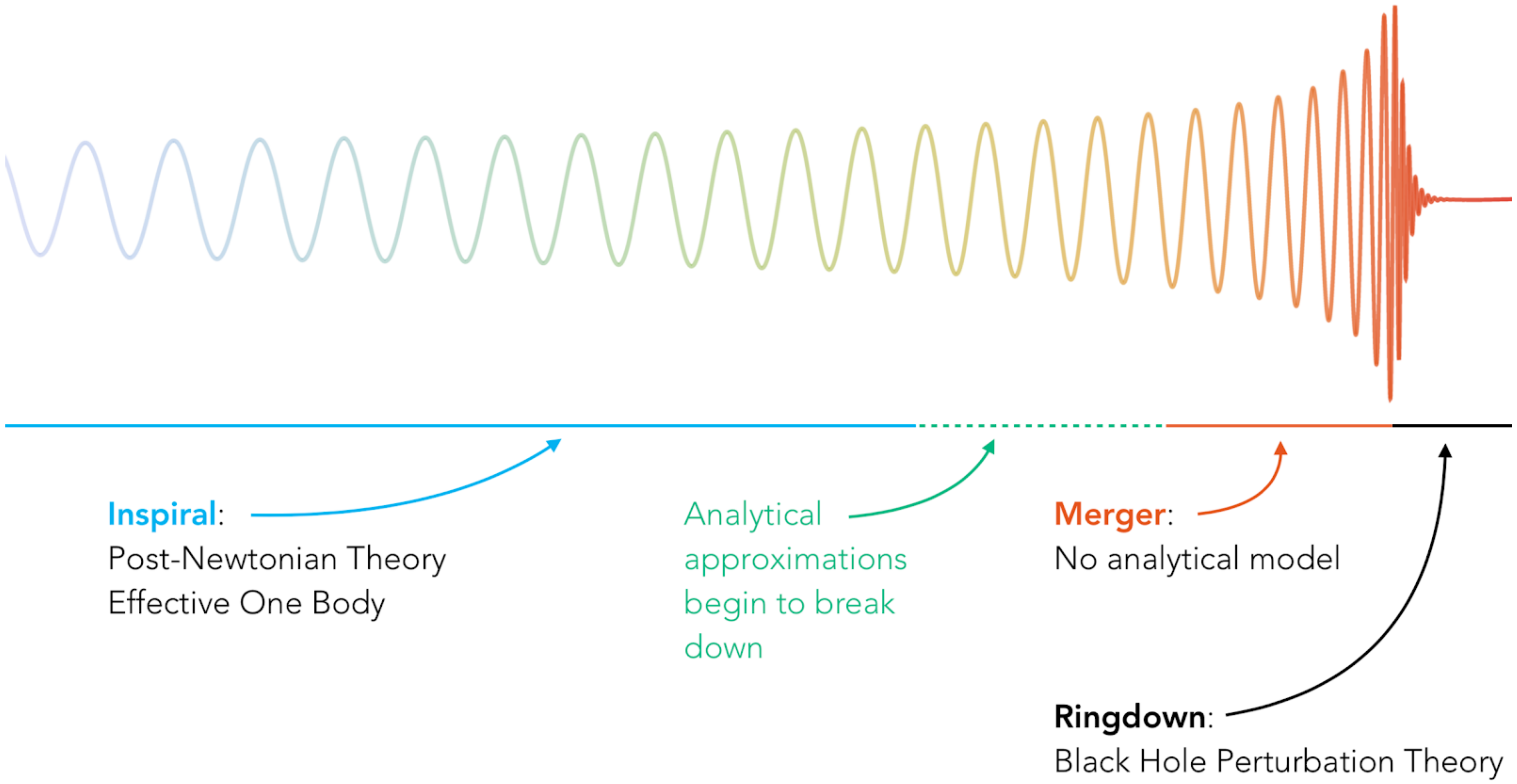
Relies on Numerical Relativity Fitting formulae that connect the initial and final BH parameters

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

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

Ghosh+, 2016

Post-Newtonian (PN) approximation of GR



$$\mathrm{v}^2 \sim 1\,\mathrm{PN}$$

PN Coefficients

$$\phi_k(m_1, m_2, \chi_1, \chi_2, \cdots)$$

$$\phi_{kl}(m_1, m_2, \chi_1, \chi_2, \cdots)$$

$$k = 0, 2, 3, 4, 6, 7$$

$$kl = 5l, 6l$$

3.5PN order

$$\tilde{h}(f) = \mathcal{A} f^{-7/6} e^{i\Phi(f)}$$

$$\Phi(f) = 2\pi f\, t_c - \phi_c + \frac{3}{128\,\eta\, v^5}\left[\sum_{k=0}^{K} \phi_k\, v^k + \sum_{kl=0}^{K} \phi_{kl}\, v^{kl} \ln v\right]$$

$$v = (\pi m f)^{1/3}$$

Figure Courtesy: Geraint Pratten

Non-linear effects in PN phasing

PN Order	Physical Effect
0PN	Quadrupolar radiation (chirp mass)
1PN	Periastron advance (component mass estimation)
1.5PN	Tails of GWs, spin-orbit interaction
2PN	Spin-spin interaction, spin-induced quadrupole
2.5PN	Black Hole horizon flux (spinning)
3PN	Tails of Tails, Tail^2
3.5PN	Spin-induced octupole
4PN	Black Hole horizon flux (non-spinning)
5PN	Tidal interactions

Slide Courtesy: K.G. Arun

Parametrized PN test

- One or more of these physical effects will be qualitatively and/or quantitatively different in modified theories of gravity

$$\phi_a \to \phi_a^{\rm GR}\left(1 + \frac{\delta\phi_a}{\phi_a^{\rm GR}}\right)$$

$$\phi_a \to \phi_a^{\rm GR}\left(1 + \delta\hat{\phi}_a\right)$$

In GR, $\delta\hat{\phi}_a = 0$

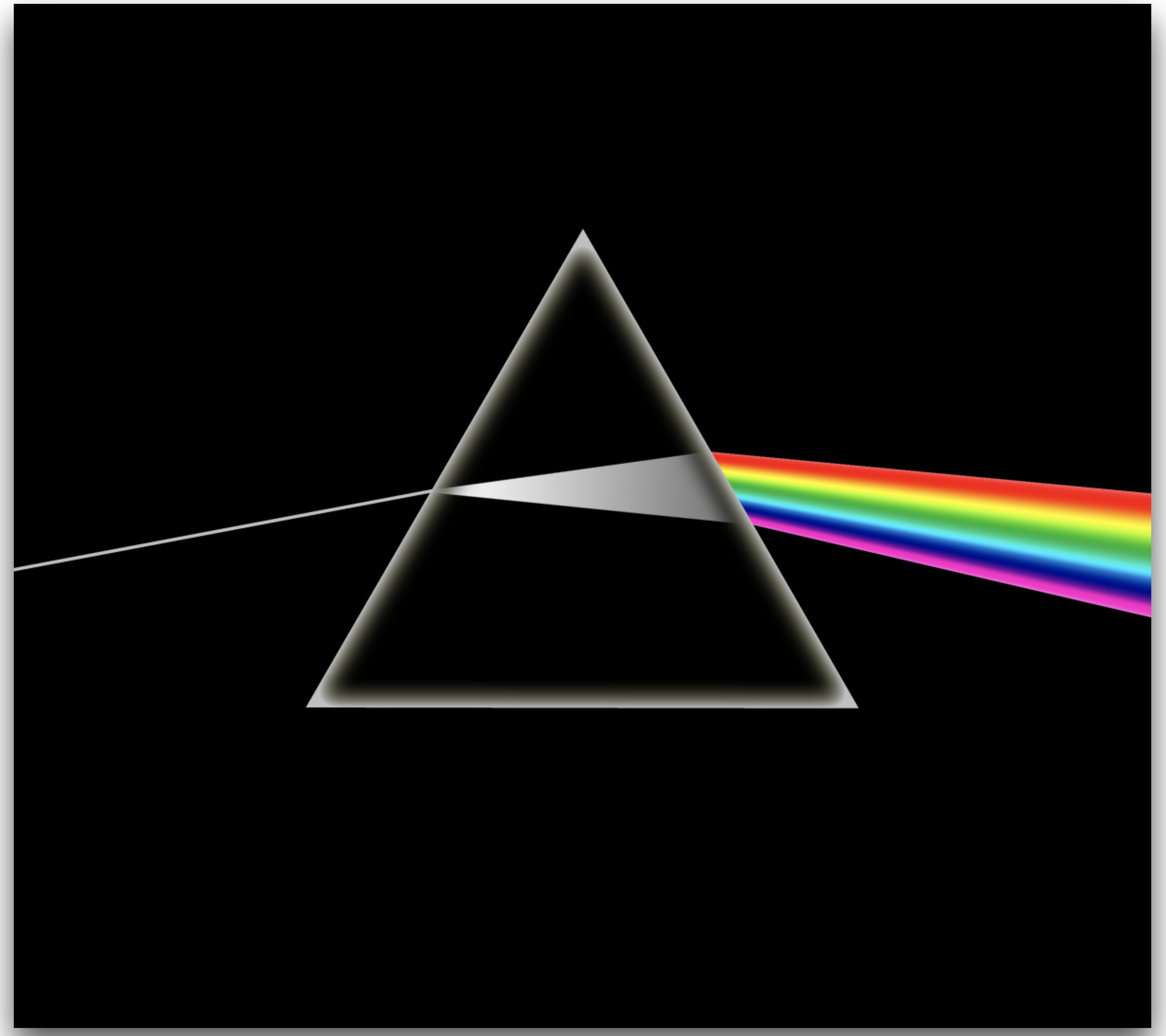
where, $a = k, kl$

Blanchet and Sathyaprakash, 1994, 1995
Arun, Iyer+, 2006
Yunes and Pretorius, 2009
Mishra, Arun+, 2010
Li+, 2012

Generalized Dispersion Relation

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

$E =$ energy
$p =$ momentum
$c =$ speed of light
$A_\alpha, \alpha =$ phenomenological parameters



Dispersion of light

GR	Extensions of GR
$A_\alpha = 0$, for all α	Massive Graviton Theory
$m_g = 0$	$\alpha = 0, A_\alpha > 0, m_g = A_0^{1/2} c^{-2}$

$m_g =$ graviton mass

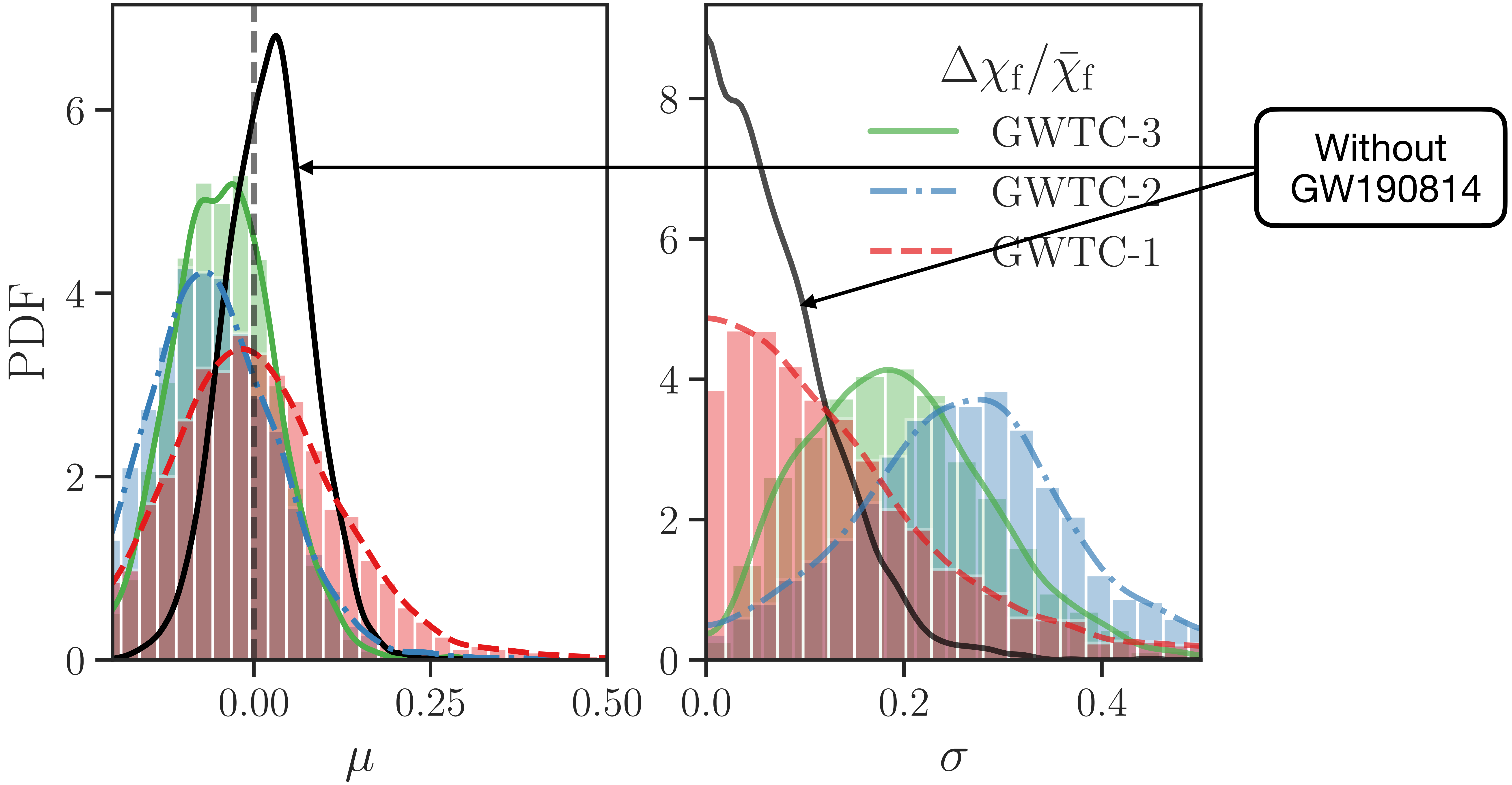
No GR deviation has been reported by LVK Collaboration so far…

But!

IMRCT Bounds from GWTC-3 events

$\mu = 0$: GR

$\sigma = 0$: same deviation for all events

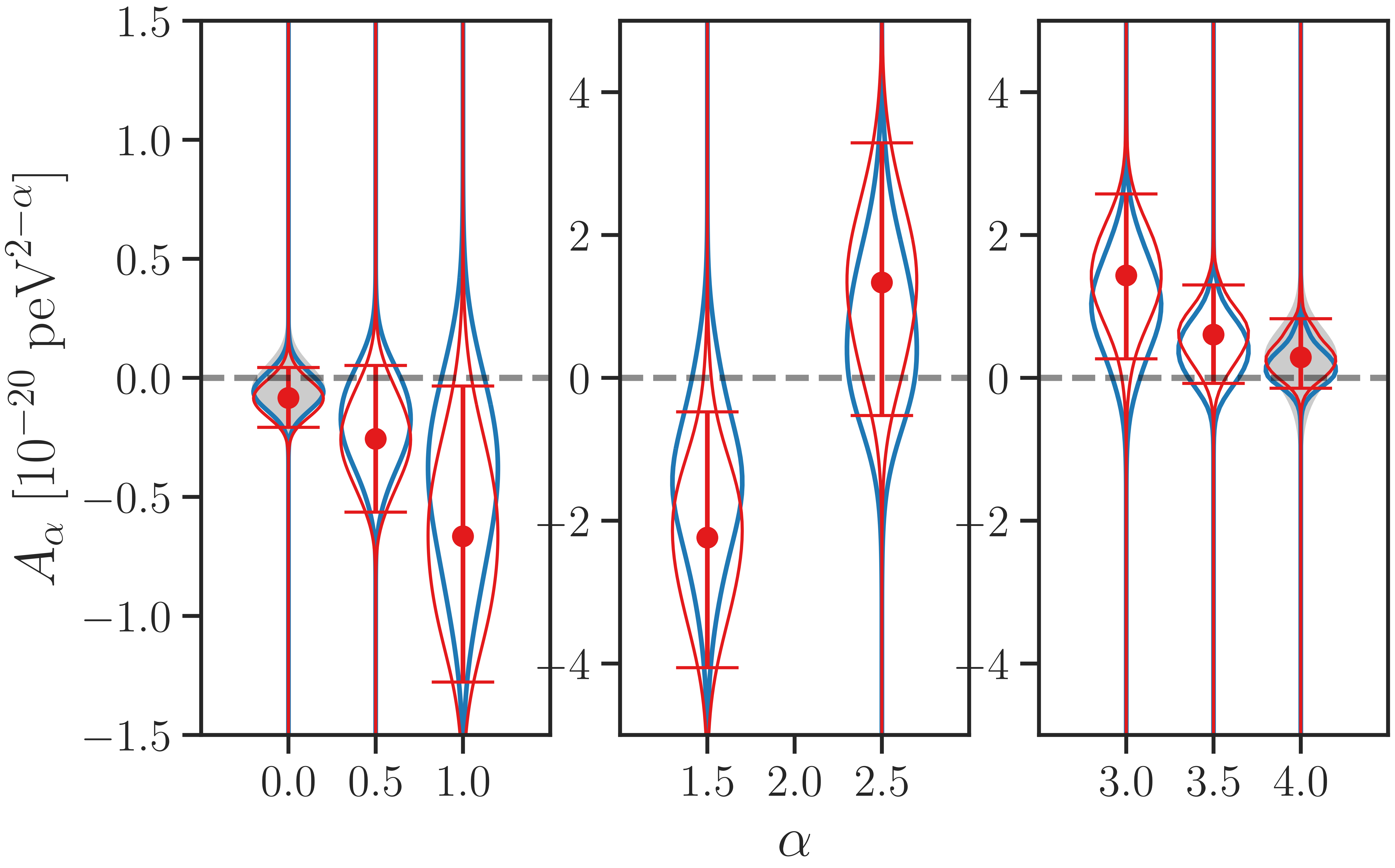


Combining results assuming the deviation from events follow a Gaussian distribution

MDR Bounds from GWTC-3 events

Blue: exclude GW200219_094415, GW200225_060421

Gray: GWTC-2



"These events require detailed analysis to understand the reasons for the observed deviations, which we leave for follow-up work." — LVKC, 2021

How to perform precision tests of GR in strong gravity?

First, access false causes of GR violation

- Detector Noise
- Waveform Systematics
- Missing Physics
- Environmental Effects
- Overlapping Signals
- Unknown

Detector Noise

Waveform Systematics

Missing Physics

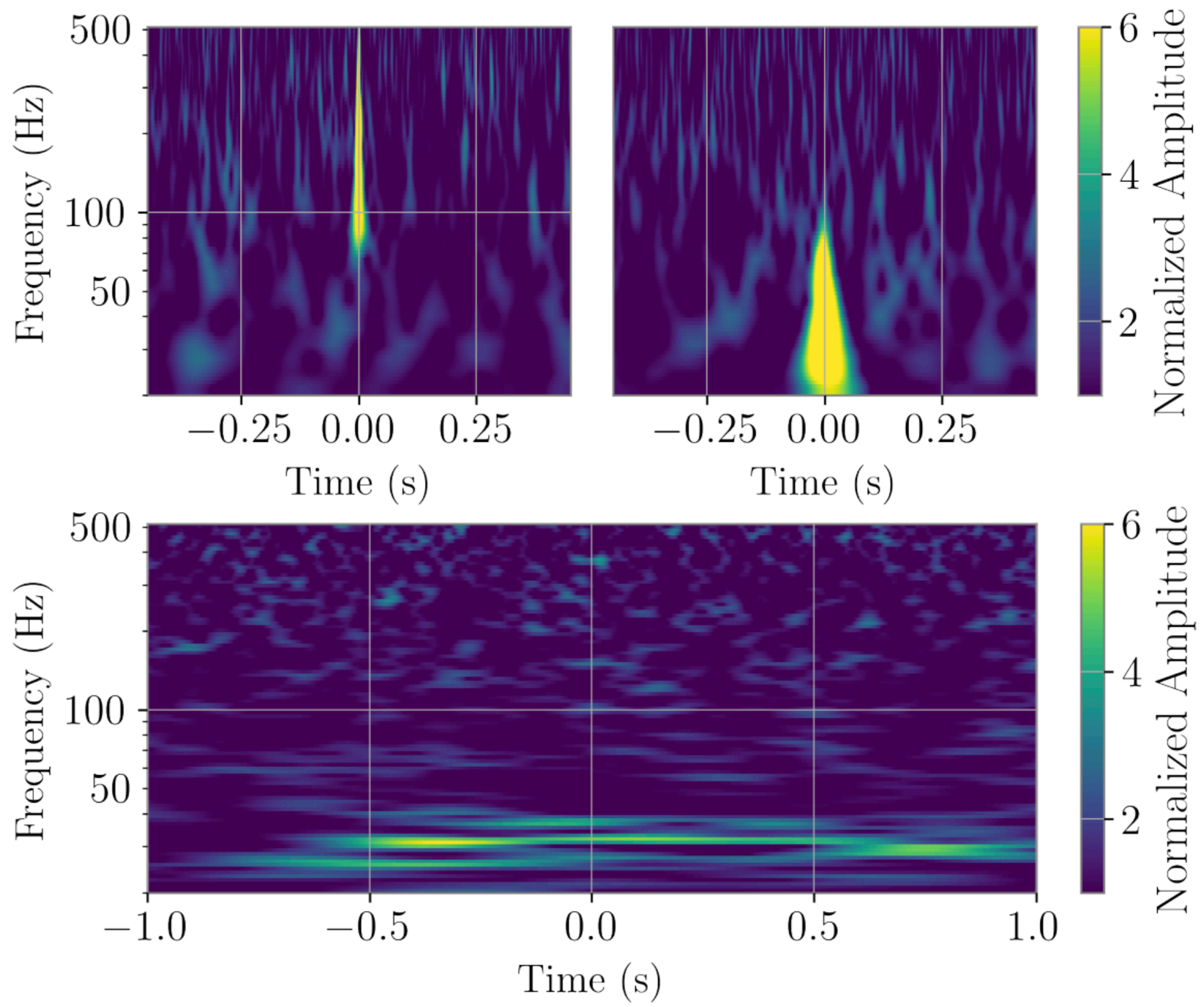
Environmental Effects

Overlapping Signals

Unknown

Noise Systematics

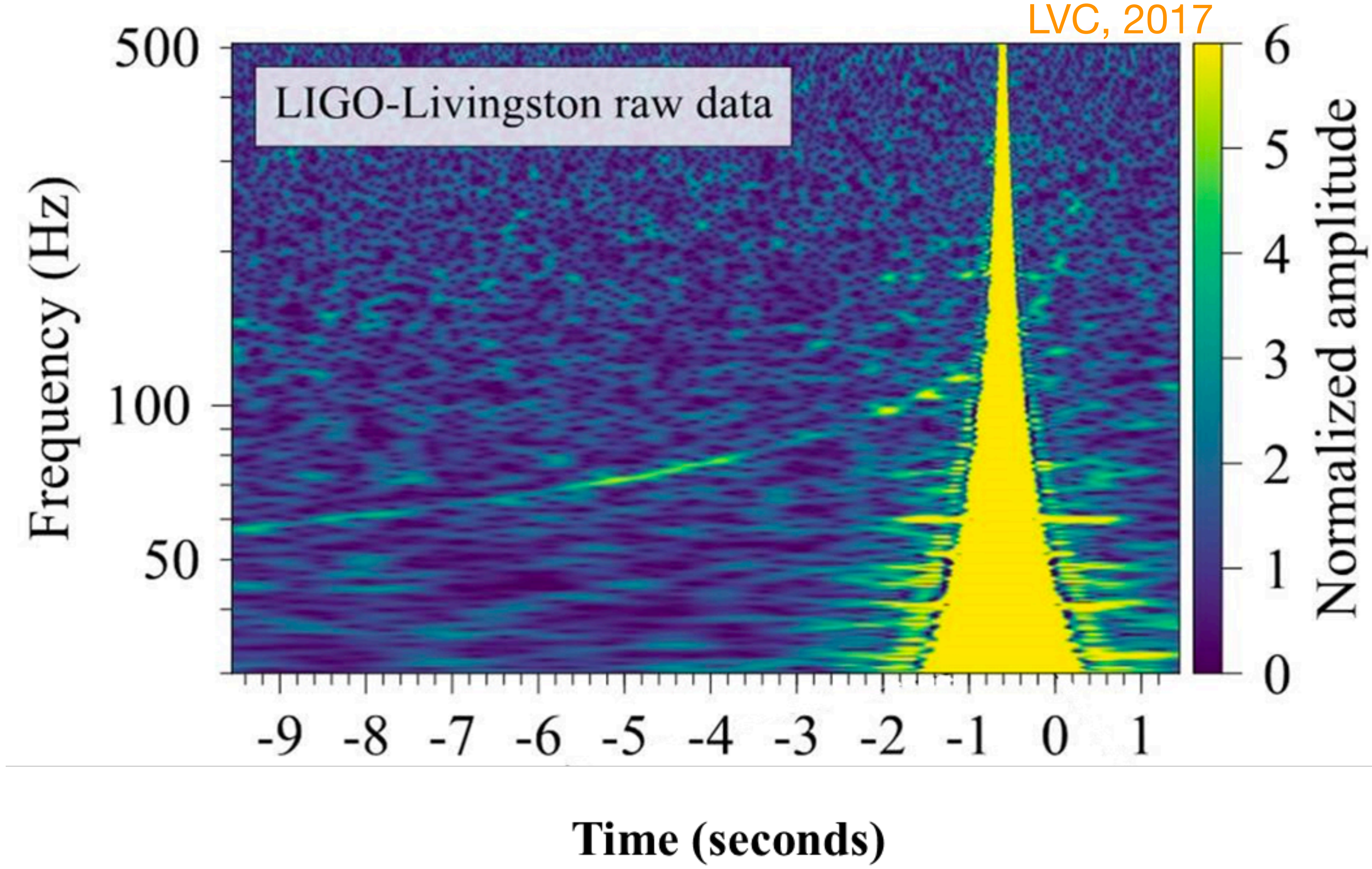
- Non-stationary noise (varies over short timescale)
- Non-Gaussian noise (glitches)
- Overdoing noise cleaning



Kwok+, 2022

Some of the commonly occurring glitches in GW data

LVC, 2017

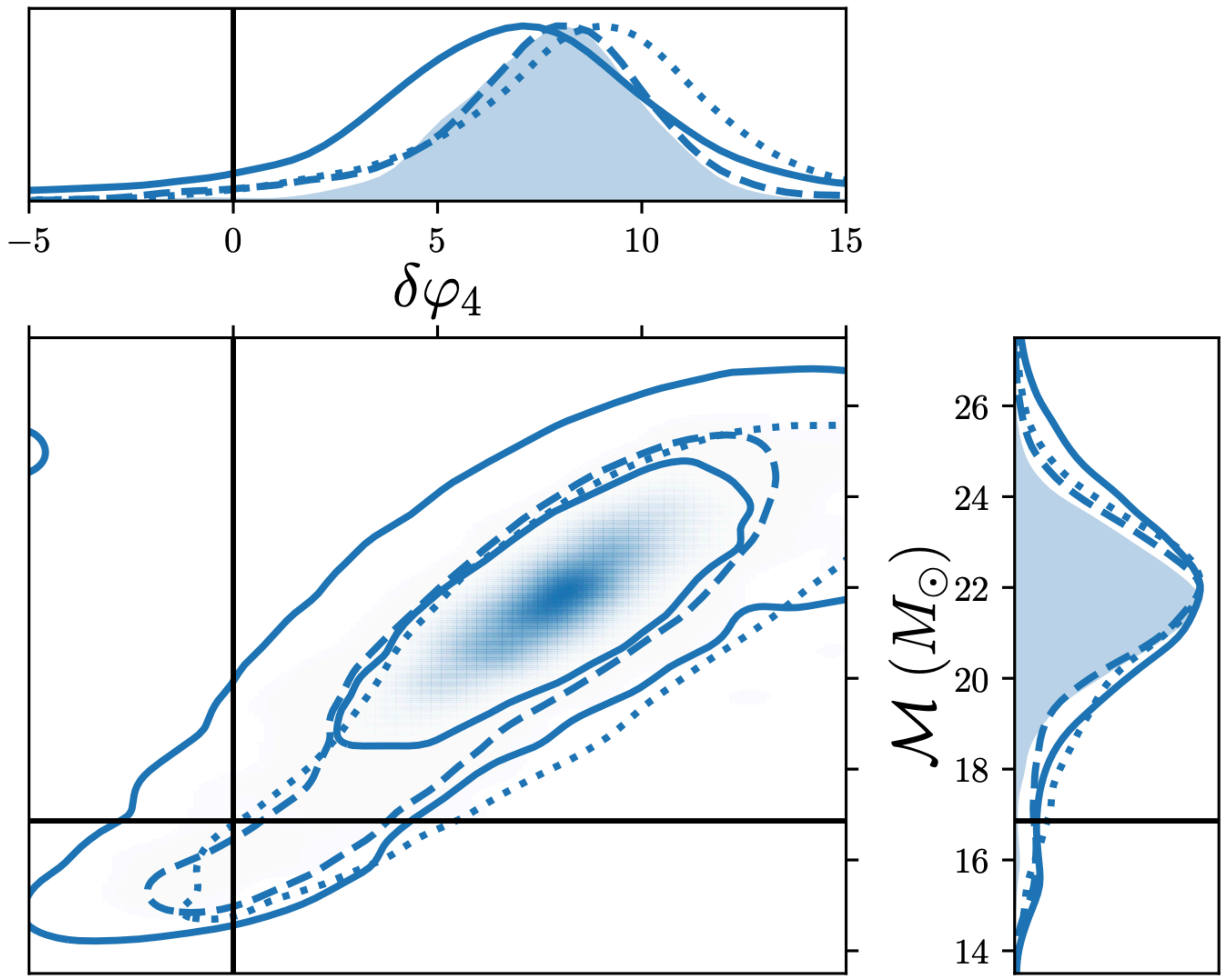


A huge glitch during the time of GW170817

Noise Systematics

- Presence of non-Stationary and non-Gaussian artifacts could affect
  - Searches (Canton+, 2013; Cabero+, 2019; and others)
  - Parameter Estimation (Chatziioannou+, 2019; Edy+, 2022)
  - Astrophysical Population Inference (Heinzel+, 2023)
  - Measurement of cosmological parameters (Mozzon+, 2021)
  - Tests of GR (Kwok+, 2022)

Effect of glitches on Tests of GR



Kwok+, 2022

Signal overlaps with a blip glitch

Shaded— Unmitigated

Solid — band passed cleaning

Dotted — glitch-subtracted

Dashed— inpainted

Detector Noise

Waveform Systematics

Missing Physics

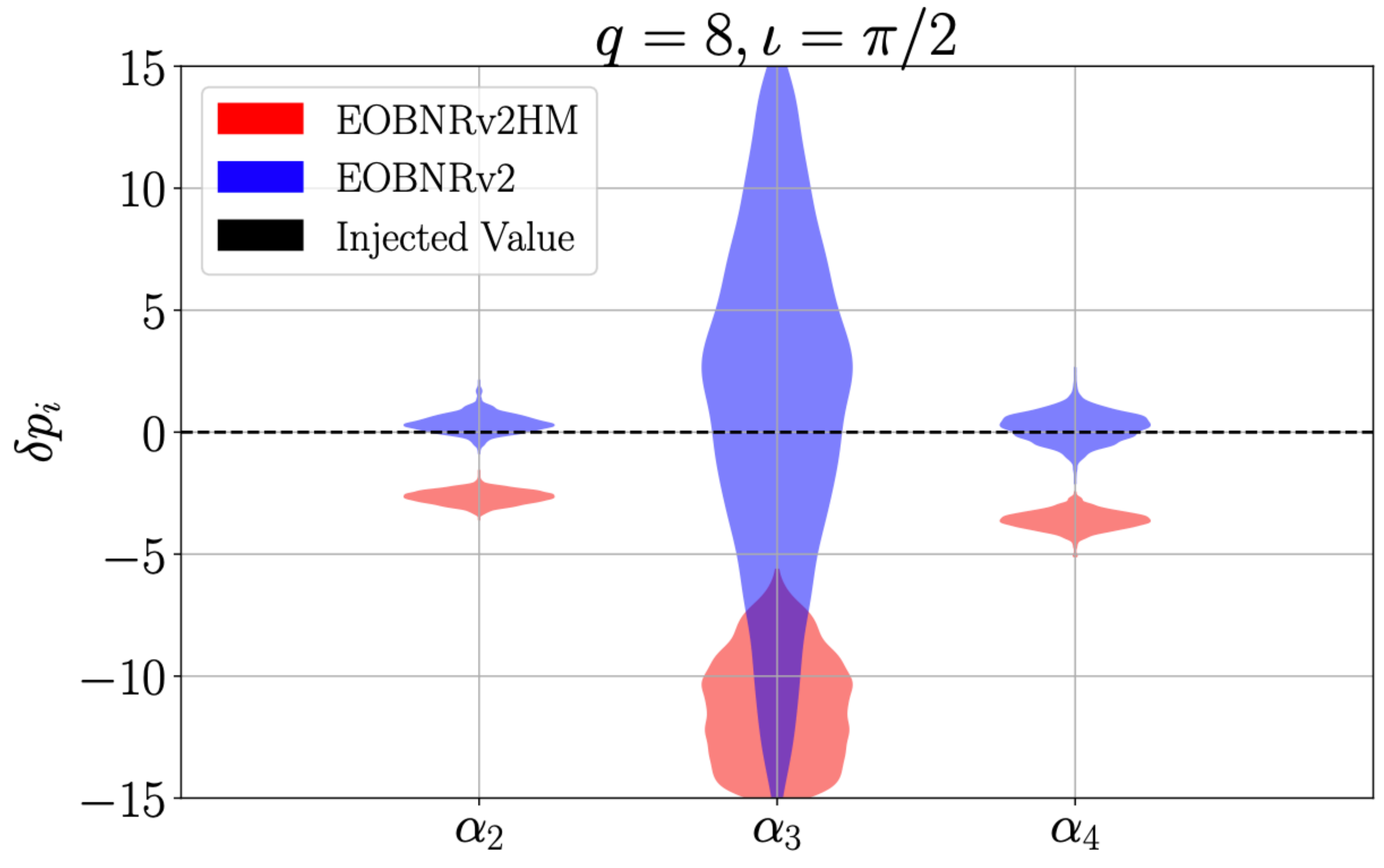
Environmental Effects

Overlapping Signals

Unknown

Effect of Waveform Systematics

- Phenomenological waveform family
- Effective-one-body waveform family
- All based on 'some' approximation
- Heavily calibrated with NR simulation
- NR simulations themselves have numerical errors
- Do not have all spherical harmonic modes



Pang+, 2018

See also Hu and Veitch, 2023

Detector Noise

Waveform Systematics

Missing Physics

Environmental Effects

Overlapping Signals

Unknown

Effect of Missing Physics

- Eccentricity (Saini+, 2022; Bhat+, 2022; Narayan+, 2023)
- Gravitational lensing (Vijaykumar+, 2022)
- Tidal effects (static tides, dynamical tides, NR simulations)
- Overtones and Mirror modes
- Others

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PhD Candidate
University of Mississippi

NR waveforms as mock signals

ID	mass ratio	eccentricity
SXS:BBH:1155	1	$< 10^{-4}$
SXS:BBH:1355	1	0.053
SXS:BBH:1357	1	0.097
SXS:BBH:1222	2	$< 10^{-4}$
SXS:BBH:1364	2	0.044
SXS:BBH:1368	2	0.097
SXS:BBH:2265	3	$< 10^{-4}$
SXS:BBH:1371	3	0.055
SXS:BBH:1373	3	0.093

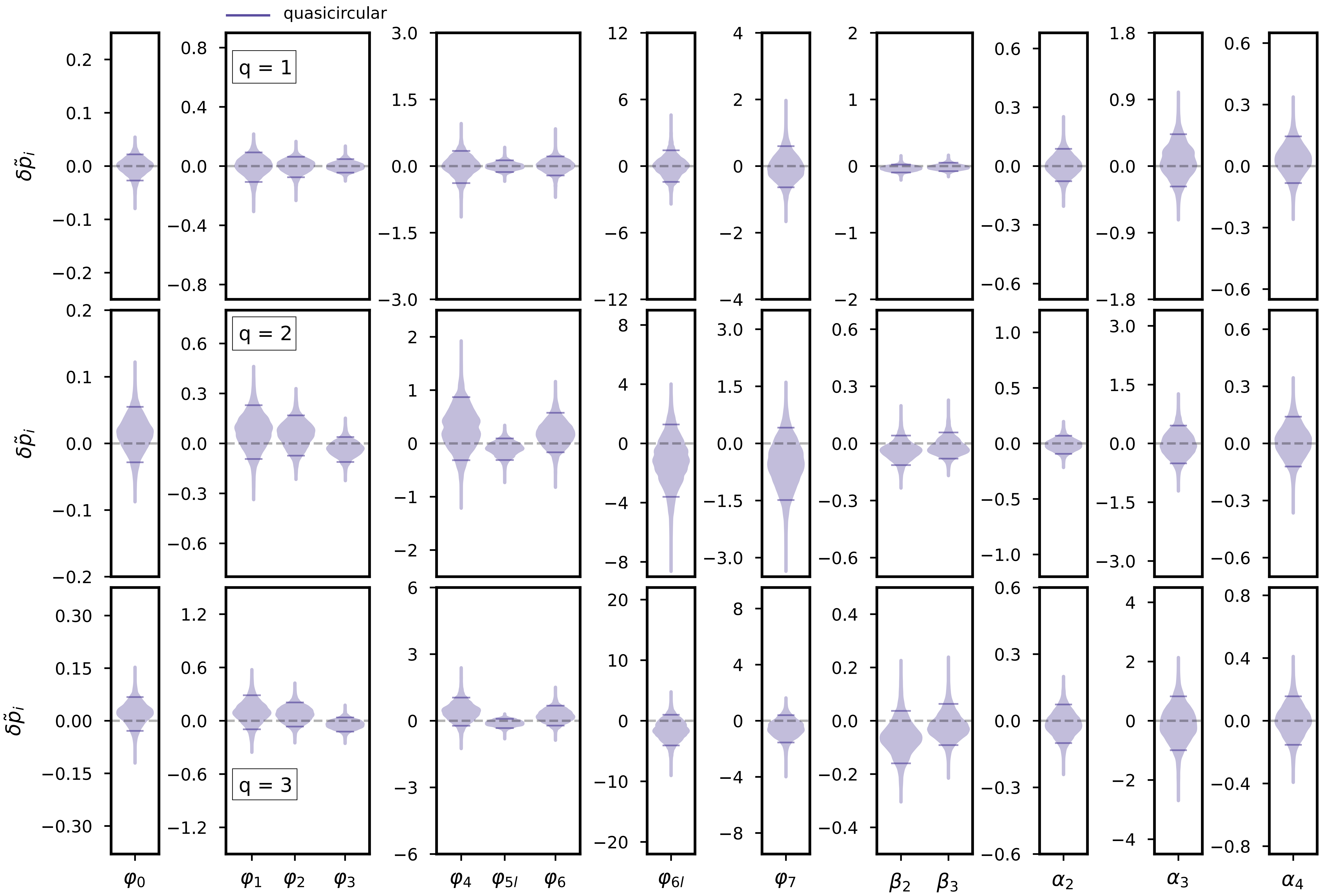
eccentricity@17 Hz

Total Mass = 80 $M_{\odot}$

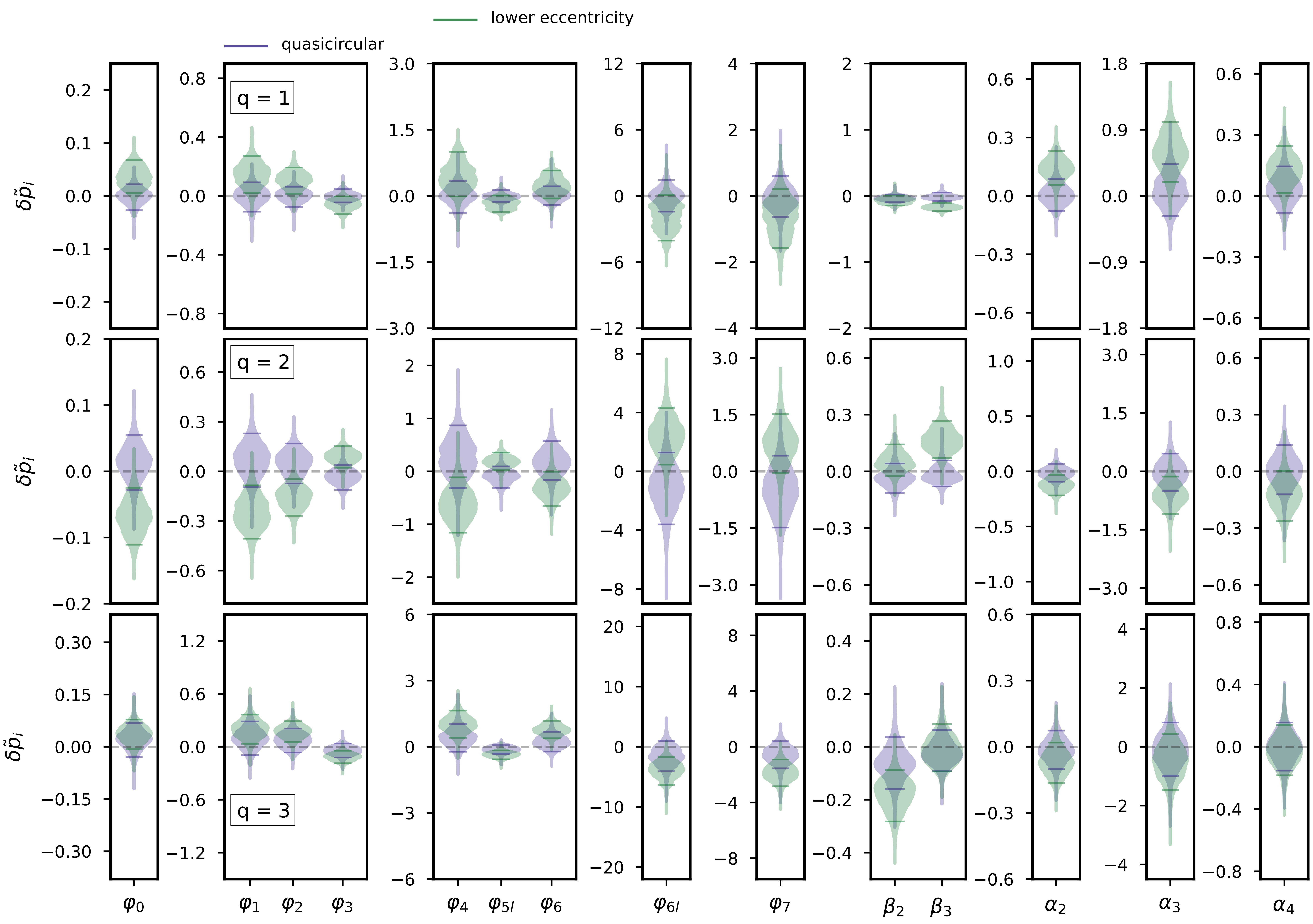
Distance = 400 Mpc

Narayan+, PRD, 2023

Parametrized Test on quasi-circular BBHs



Narayan+, PRD, 2023

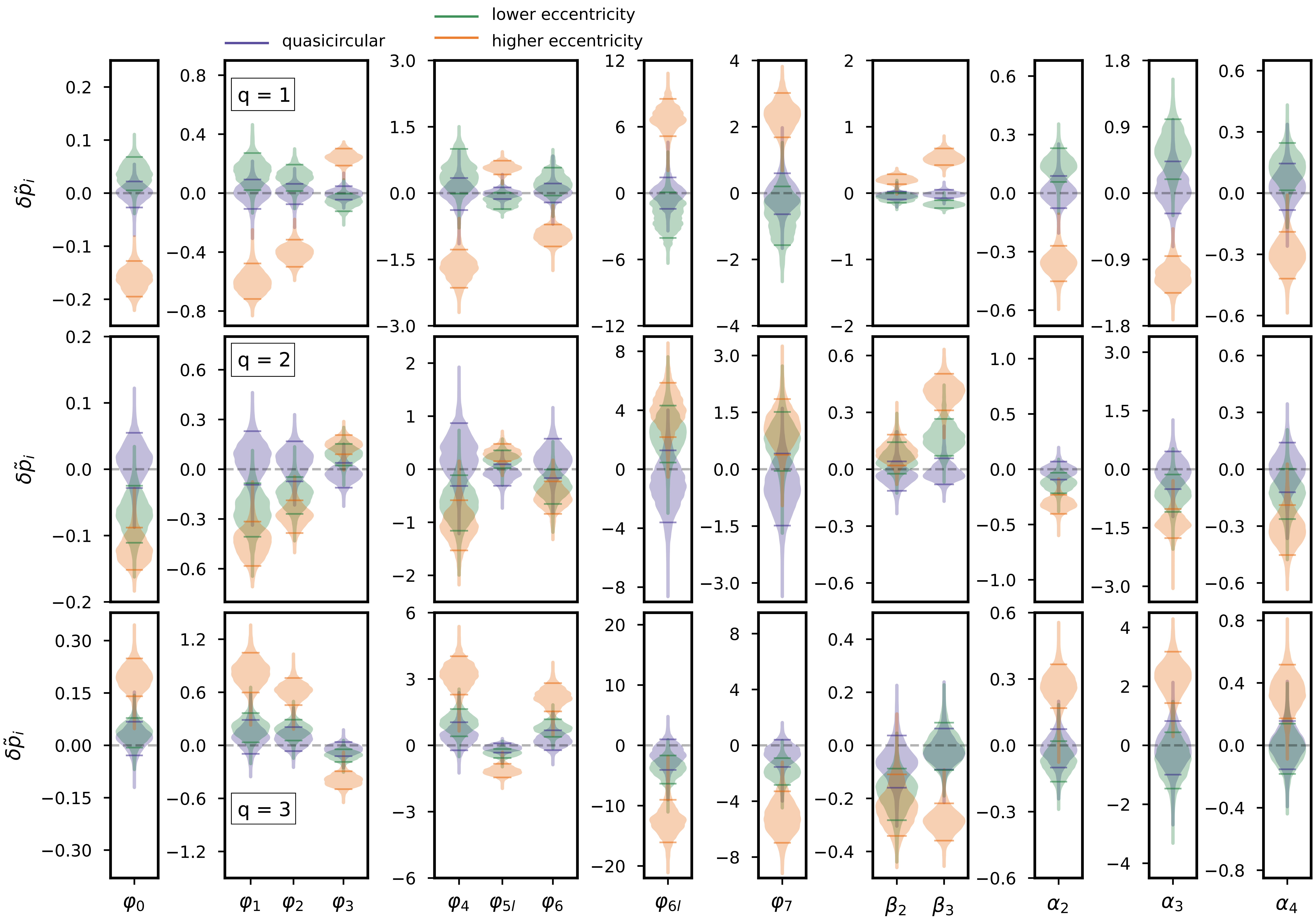


Parametrized Test on quasi-circular BBHs

+

e~0.05@17 Hz

Narayan+, PRD, 2023



Parametrized Test on quasi-circular BBHs

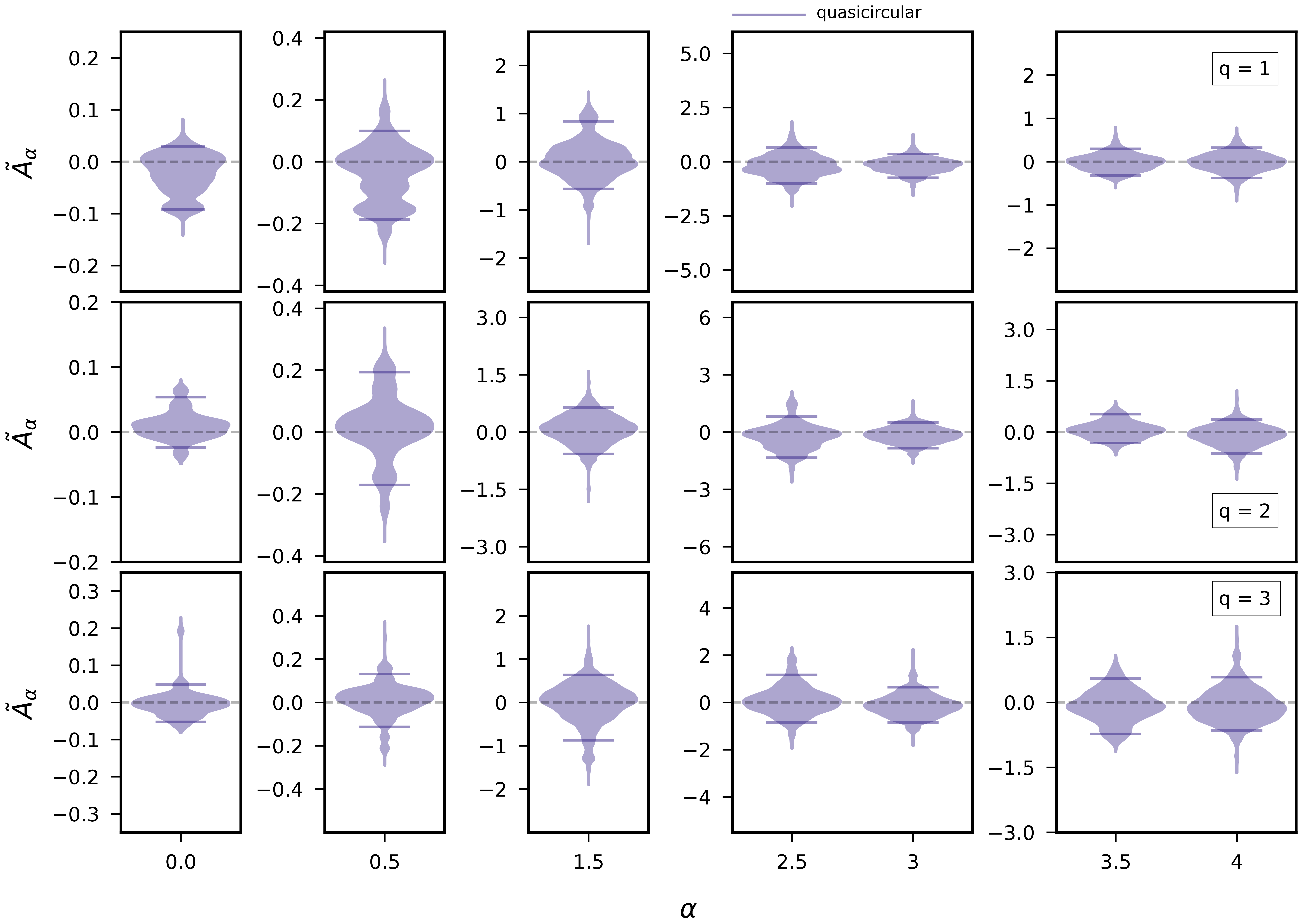
+

e~0.05@17 Hz

+

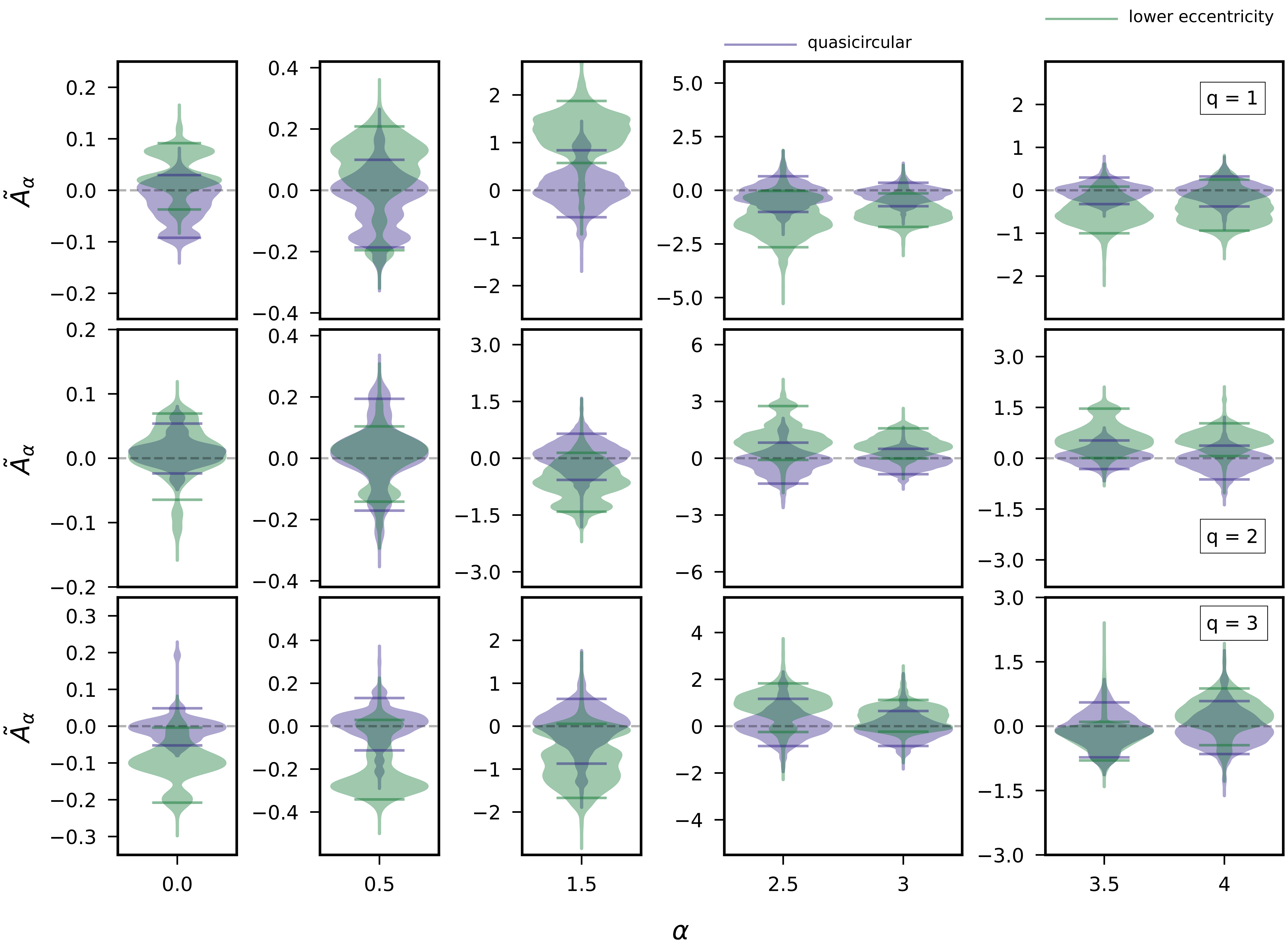
e~0.1@17 Hz

Narayan+, PRD, 2023



Modified dispersion relation test on quasi-circular BBHs

Narayan+, PRD, 2023

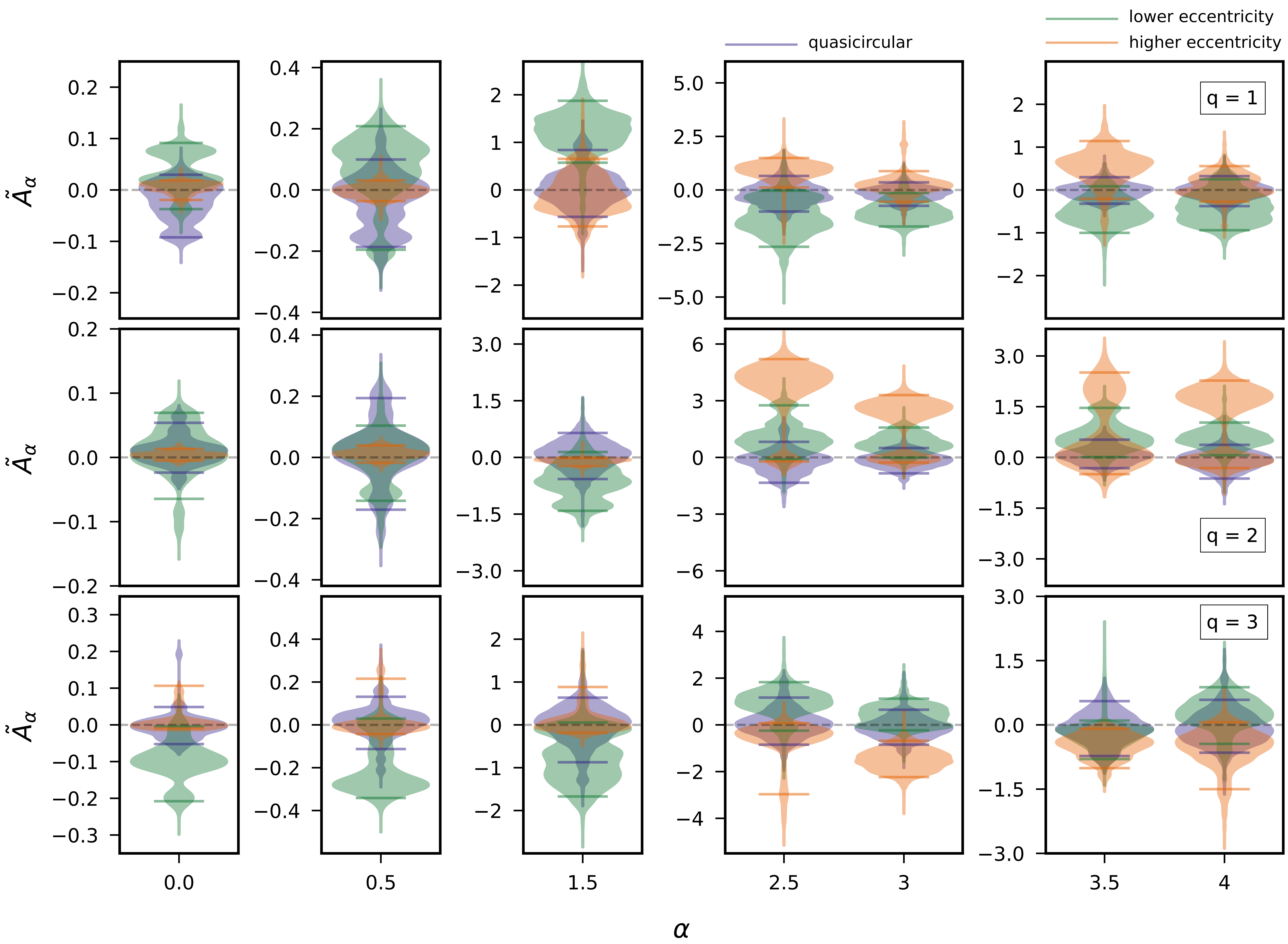


Modified dispersion relation test on quasi-circular BBHs

+

e~0.05@17 Hz

Narayan+, PRD, 2023



Modified dispersion relation test on quasi-circular BBHs

+

e~0.05@17 Hz

+

e~0.1@17 Hz

Narayan+, PRD, 2023

Detector Noise

Waveform Systematics

Missing Physics

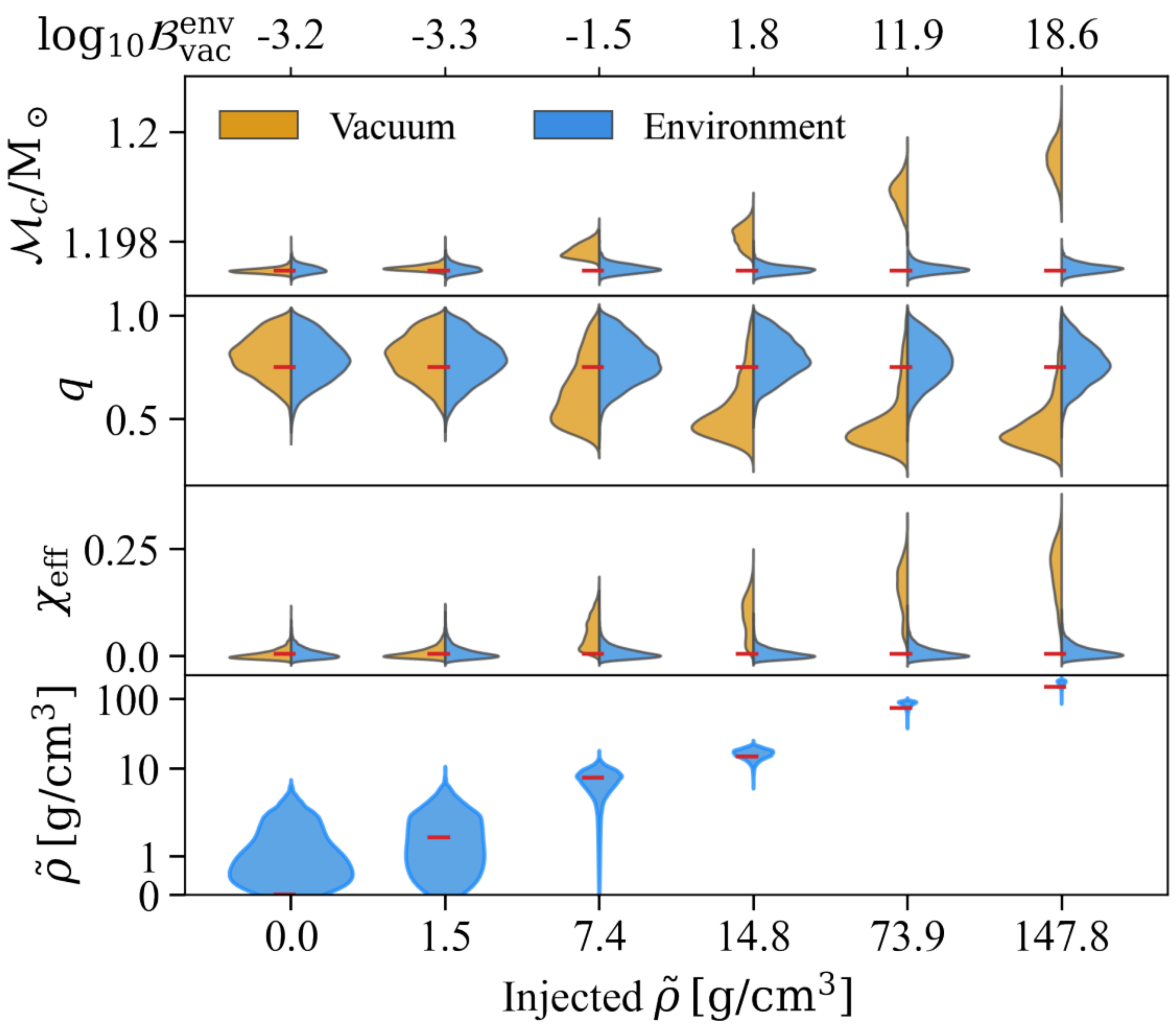
Environmental Effects

Overlapping Signals

Unknown

Environmental Effects

- Gaseous environment
  - common envelopes
  - dense cores of massive stars
  - accretion disks of active galactic nuclei
- Dark matter halo
- Time-varying Doppler shift (Vijaykumar+, 2023)
- Hierarchical triples
- Expansion of the universe



Santoro+, 2023

Detector Noise

Waveform Systematics

Missing Physics

Environmental Effects

Overlapping Signals

Unknown

Overlapping Signals

- One can identify two overlapping signals in LVK's O4 sensitivity
- Parameter Estimation is not a serious problem for O4 and O5
- The background of unresolved quiet overlapping signal could be problematic
- Foreground subtraction could also be problematic
- Especially when combining multiple events

For effect on parameter estimation, see:
Pizzati+, 2022
Samajdar+, 2021
Relton+, 2021
Himemoto+, 2021

For effect on test of GR, see:
Reali+, 2022
Hu and Veitch, 2023

Detector Noise

Waveform Systematics

Missing Physics

Environmental Effects

Overlapping Signals

Unknown

Mistaken Source Class

- Black Hole mimickers (boson stars, neutron stars)
- Parabolic or hyperbolic encounters
- Head-on Collision

Summary

- The current waveform models used in the test of GR are not perfect
- Can lead to false GR violation in many scenarios
- Eccentricity can definitely lead to false GR violation
- Other causes need to be accessed
- We need to make our waveform models and/or tests more robust

The way forward

- Compile a list of possible false causes of GR violations
    - We are writing a White Paper!
- Develop Framework for quantifying the effect of these causes
- Build community-wide consensus on the list and the framework

Thank You!