Tests of GR with GWs from compact binary coalescences

12th Iberian Gravitational Waves meeting

6th June 2022

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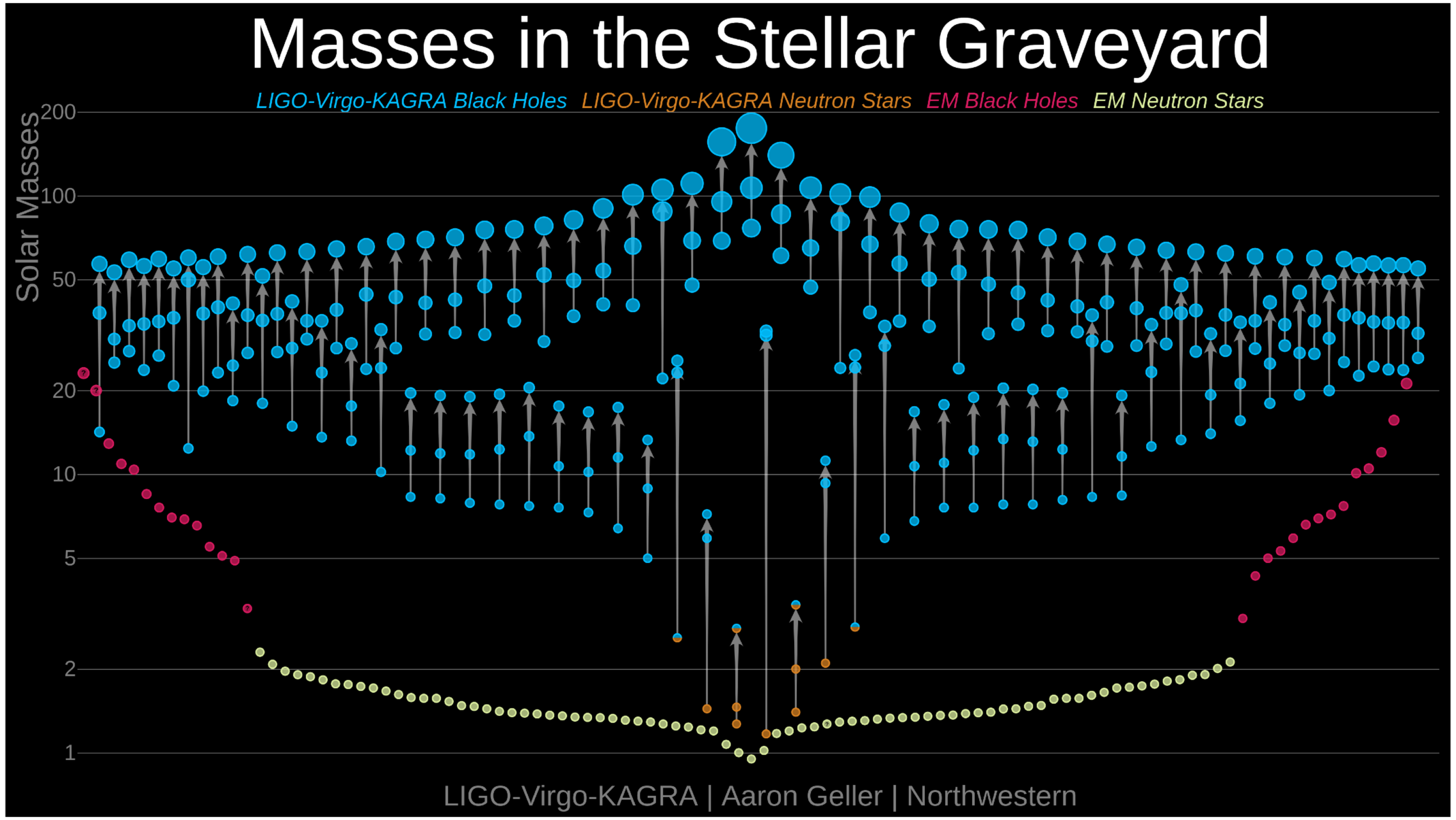
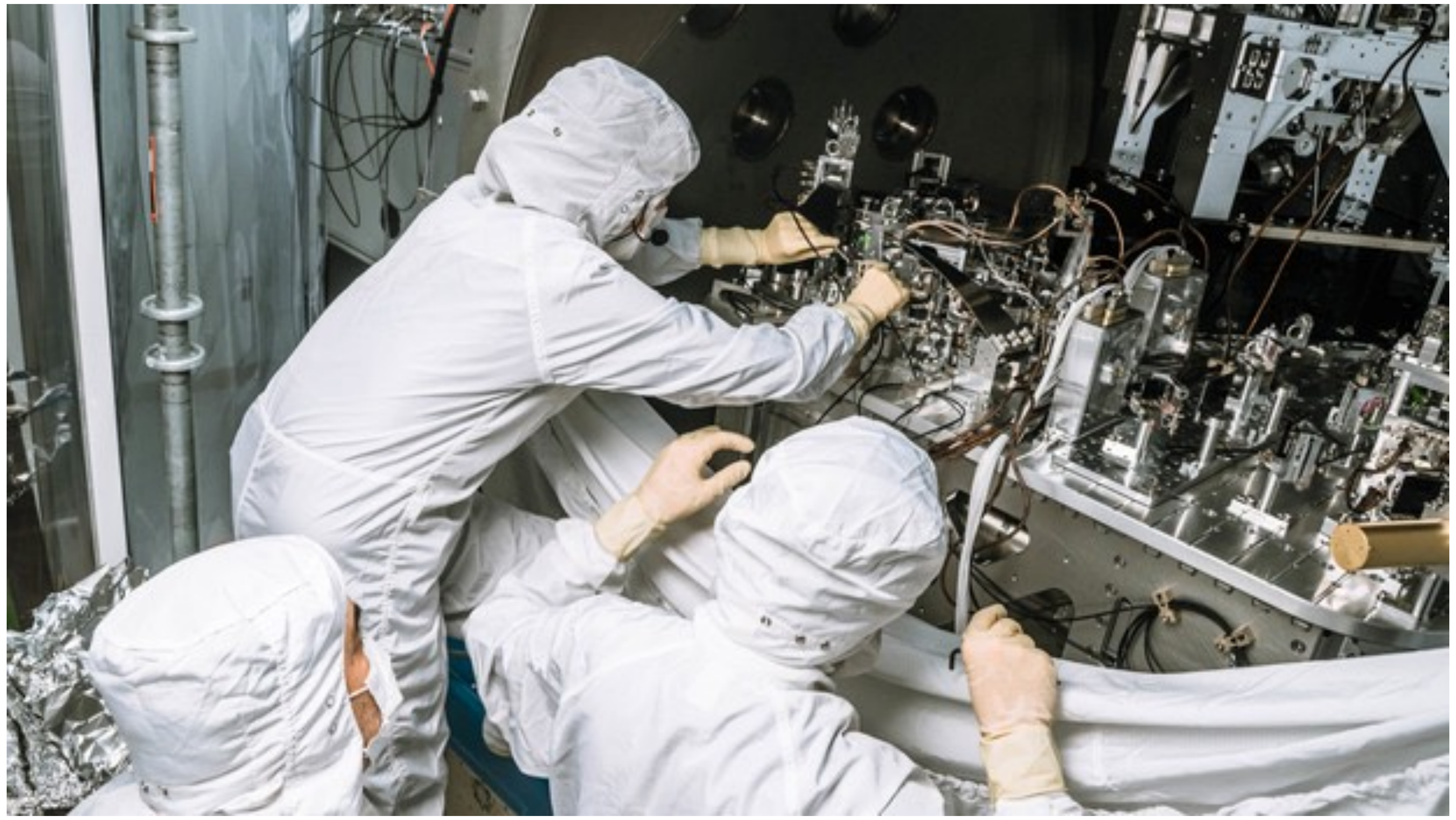
GWTC-3: the family is getting larger

When: Incorporate events detected in the second half of the 3rd observing run, from 1 November 2019, 15:00 UTC and 27 March 2020, 17:00 UTC
Where: Livingston, Hanford, Virgo (Kagra will join in O4, brief observing run of two weeks in April 2020)
What: 35 new compact binaries, 17 of which reported for the first time -> Total number of events for GWTC-3 is **90**!

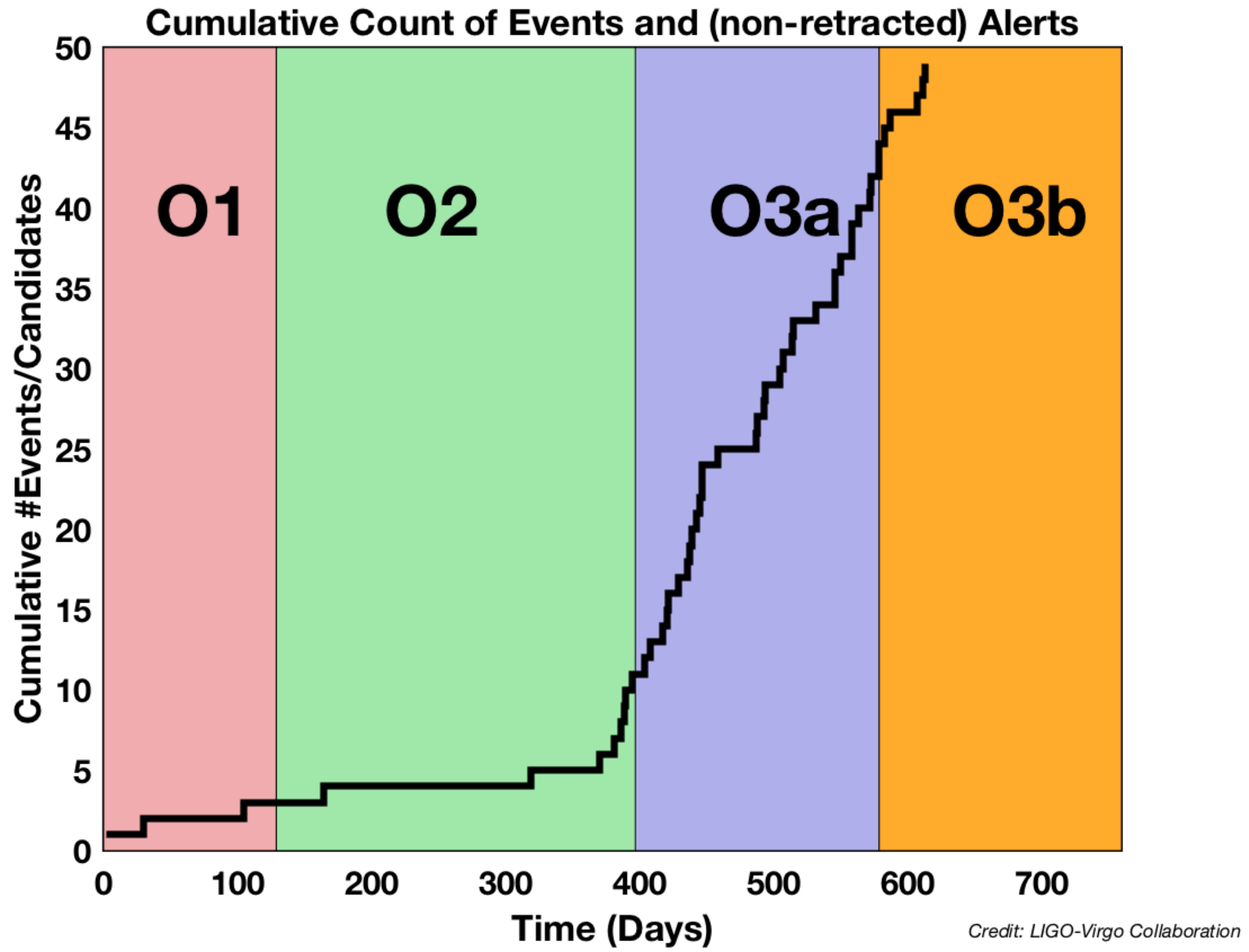


Better instruments, better data

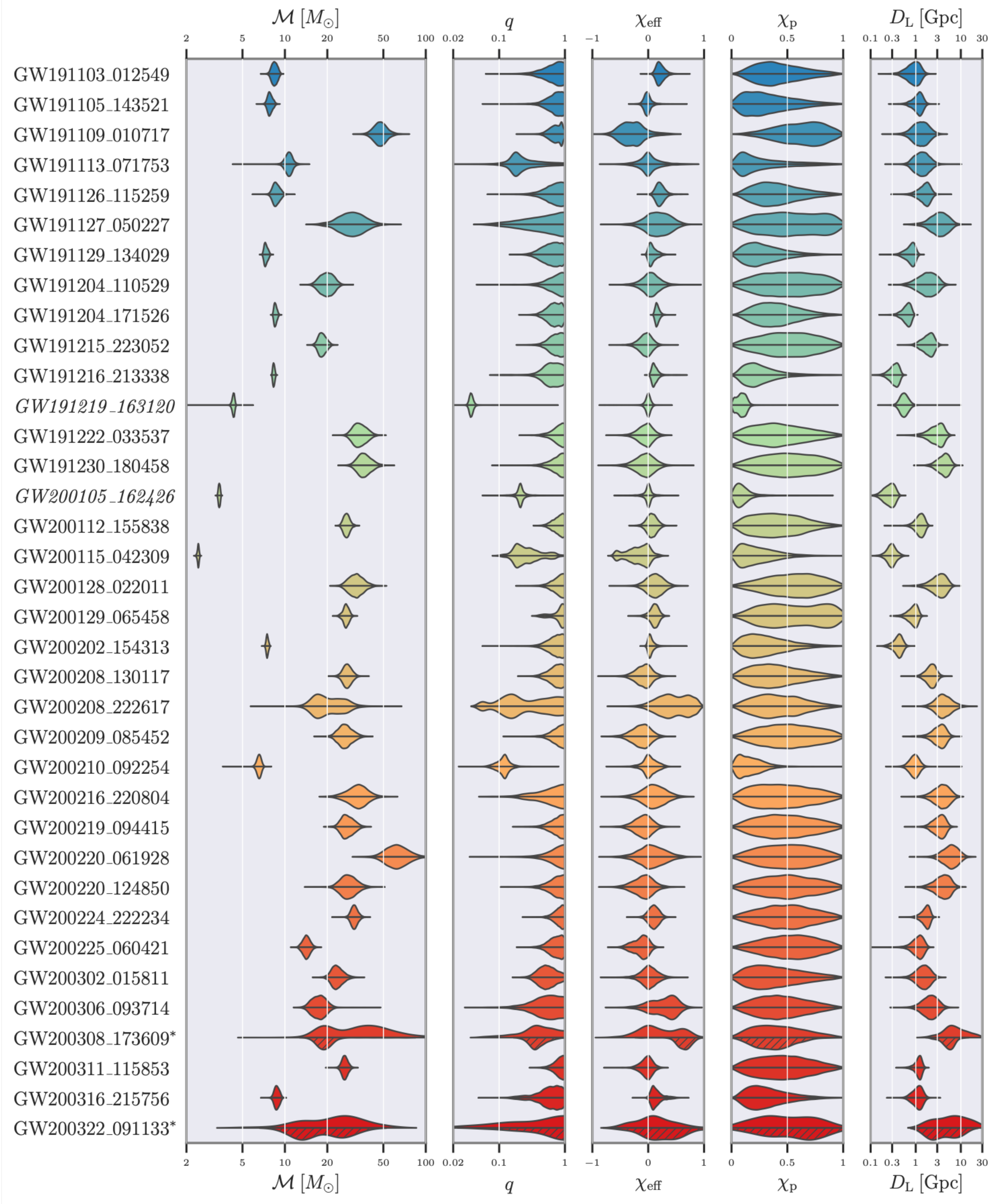
- Constant improvements to the instruments
    - Increased duty cicle: full network was in observing mode for 51.0% of the time in O3b (vs 44.5% in O3a)
    - Increased BNS inspiral range (the maximum distance at which a fiducial BNS system could be detected)



Credit: LIGO-Caltech



Black holes of all sizes



- All three types of ‘canonical’ compact binaries have been observed in different observing runs
- Huge variety of source parameters, lots of stress-tests for current models —> big motivation for constant upgrades!

LIGO-Virgo-Kagra Collaboration arXiv: arXiv:2111.03606

Implications for tests of GR

POSITIVE

- More stringent combined bounds expected due to the increased number of events

NEGATIVE

- Increased computational burden -> need to focus on loudest / most suitable events (depending on type of test)
- More non-vanilla events for which even GR models deliver contrasting results

Was Einstein wrong?

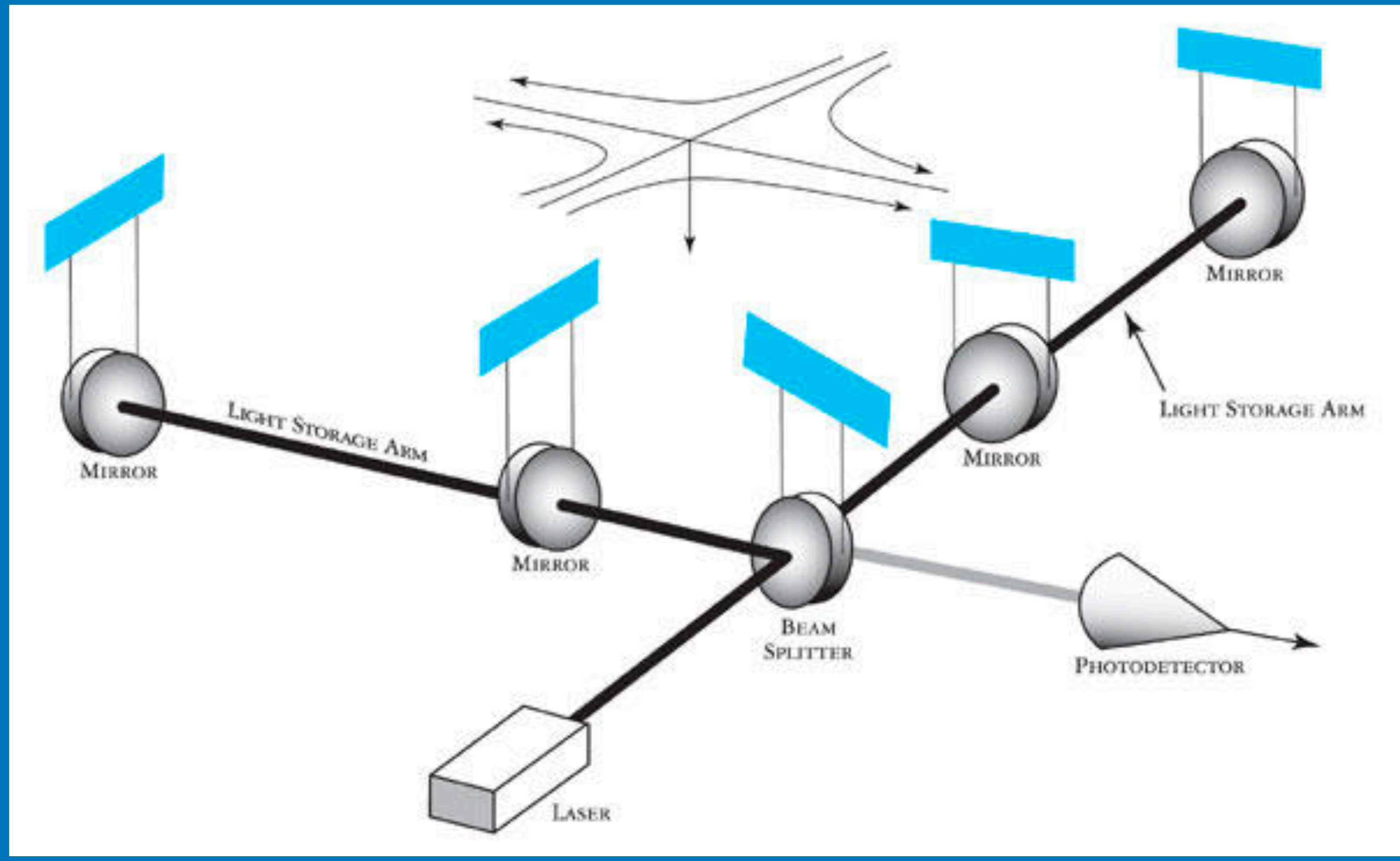
- Through genuine beyond-GR/exotic templates
  - Scarcity of templates, though catalogs of exotic waveforms are growing. Can deep learning come to the rescue? [Freitas+ arXiv:2203.01267v1]
  - PE on real data was using non-BH templates: e.g. GW190521(Bustillo+ PRL 126, 081101 (2021)). Discreteness of templates makes Bayesian inference tasks more subtle
- Common concerns raised about alternative theories of GR:
  - Stability
  - Well-posedness? Progress made in the weak-coupling limit (Okounkova+ PRD 96, 044020 (2017), Kovács&Reall, PRD 101, 124003 (2020))
- Parametrised tests are common but they come with caveats

Where can we look for departures from GR?

Residuals

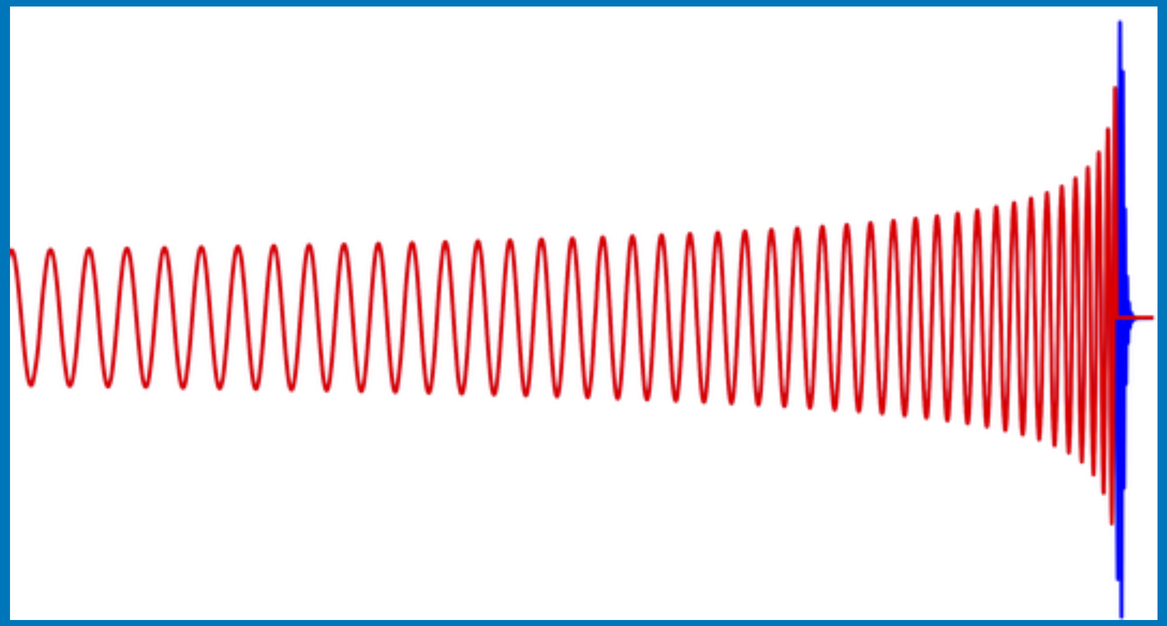
Inspiral-merger-ringown

Consistency tests



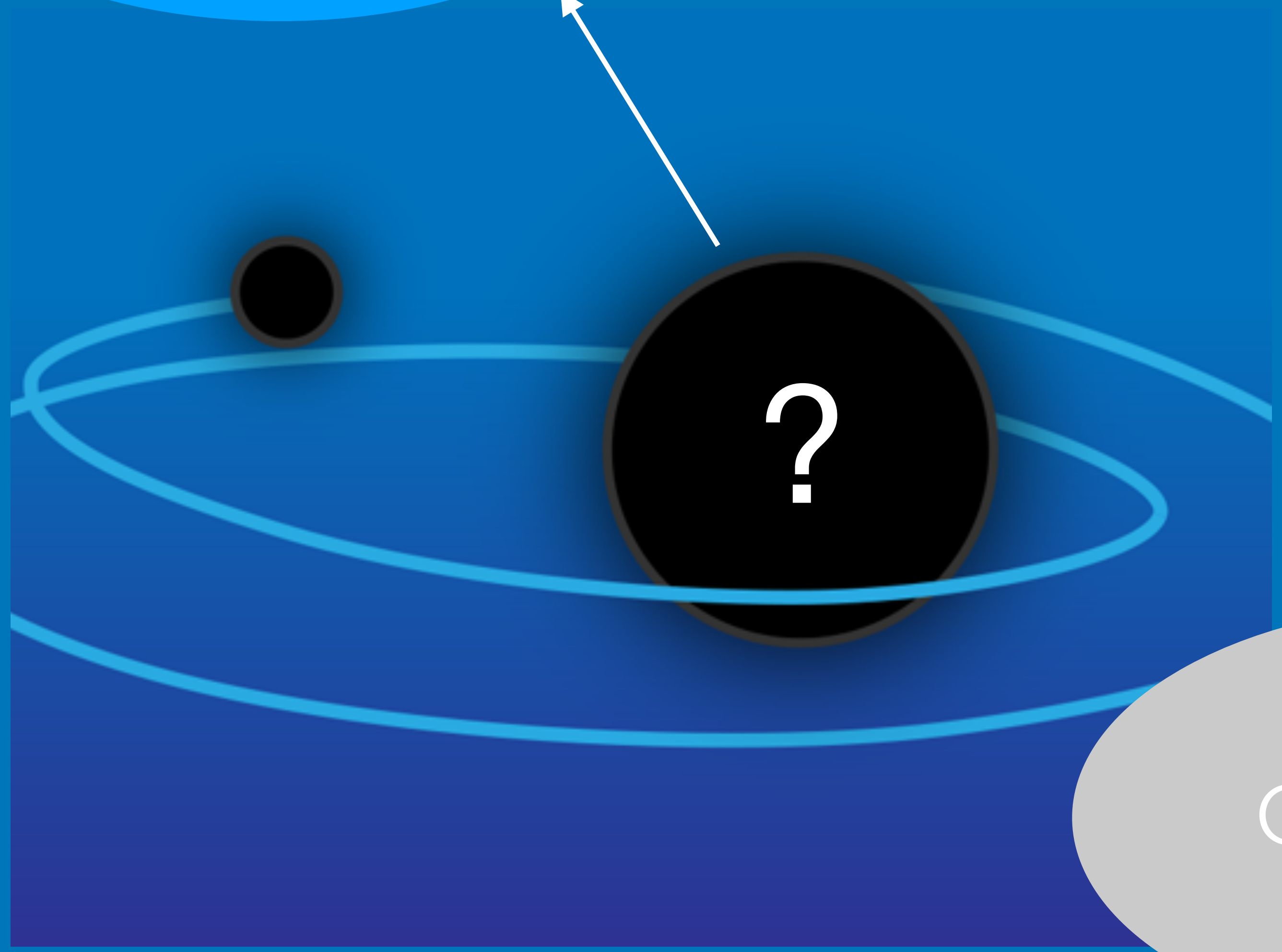
Caltech/MIT/LIGO Lab

Tests of BH nature



$h_+, h_\times$
...or...?

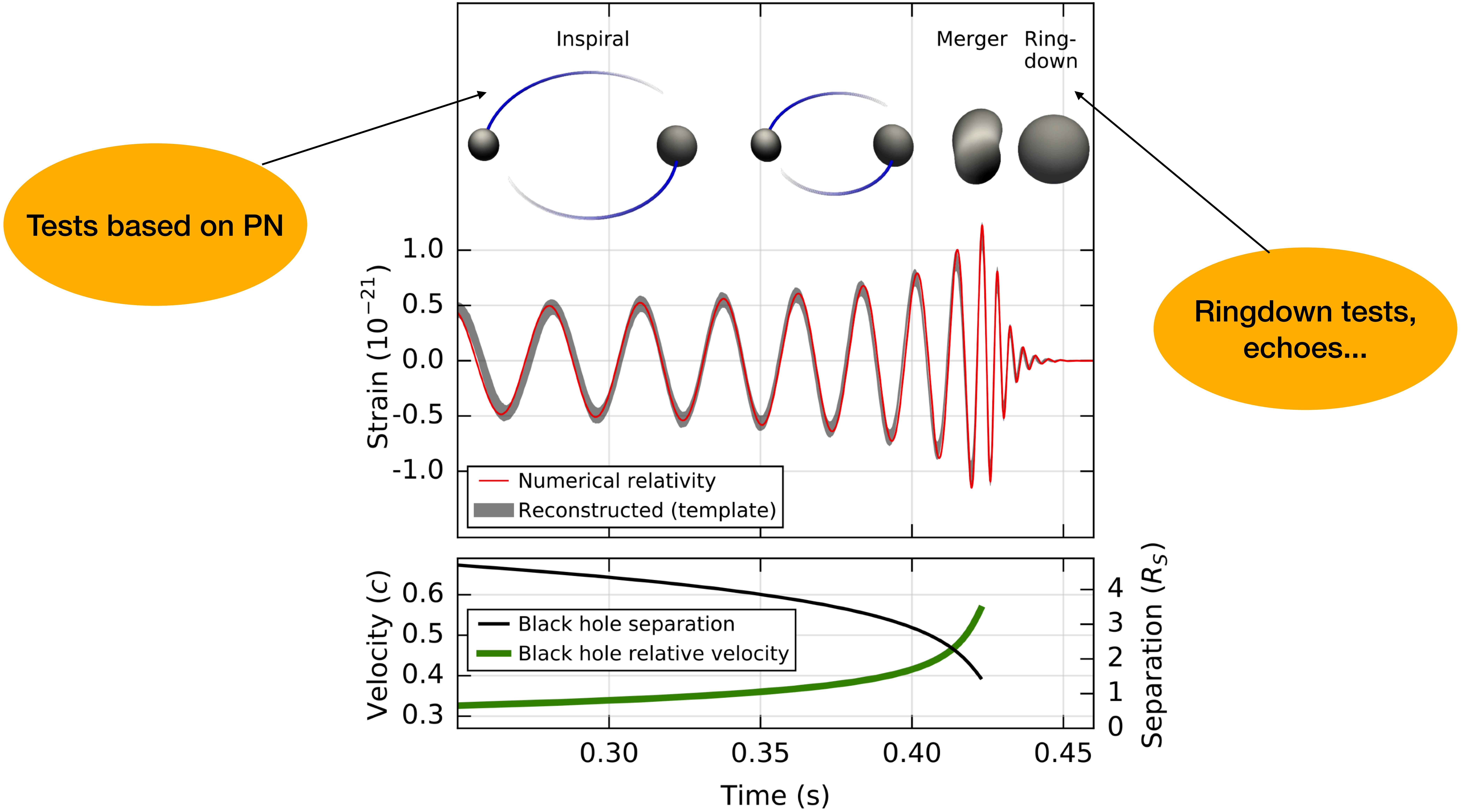
Polarization



Generation

APS/Alan Stonebraker

Propagation



LIGO-Virgo PRL **116**, 061102 (2016)

Residuals tests

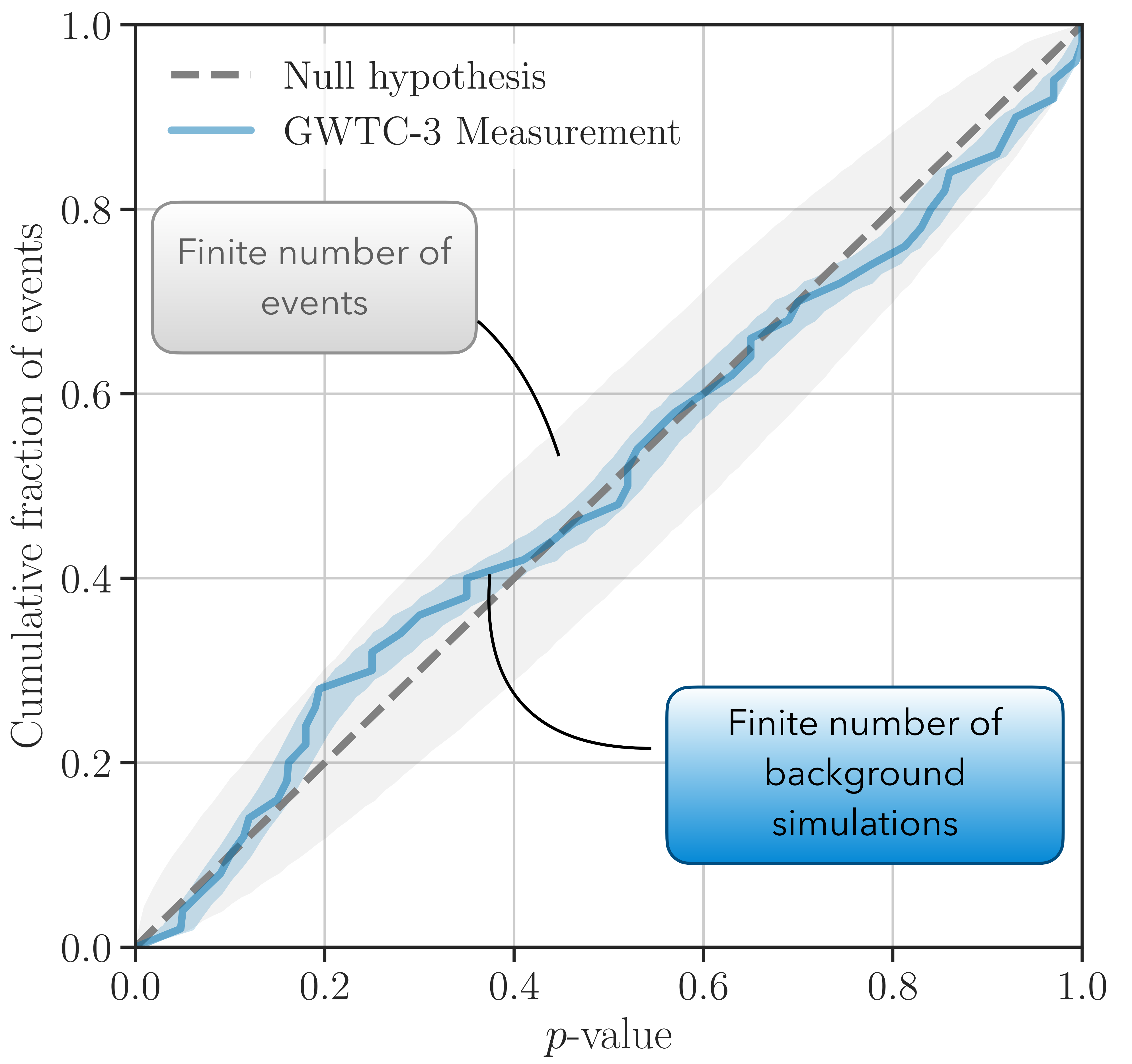
LVK Collaboration, arXiv 2112.06861 [gr-qc]

- Compute 90% credible upper limit on the left-over coherent network SNR after subtraction of $\max \mathscr{L}$ of fiducial template in a window of ~1s around the trigger

- For each event perform hundreds (200 for GWTC-3) additional runs on time segments near the trigger $\rightarrow p$-values: $p = P(\mathrm{SNR}_{90}^{n} \geq \mathrm{SNR}_{90})$

- Measurements consistent with null hypothesis within current uncertainties

LVC Collaboration, PRL, 116, 221101 (2016), LVC Collaboration, PRD, 100, 104036 (2019)[GWTC-1], LVC Collaboration PRD 103, 122002 (2021)[GWTC-2]

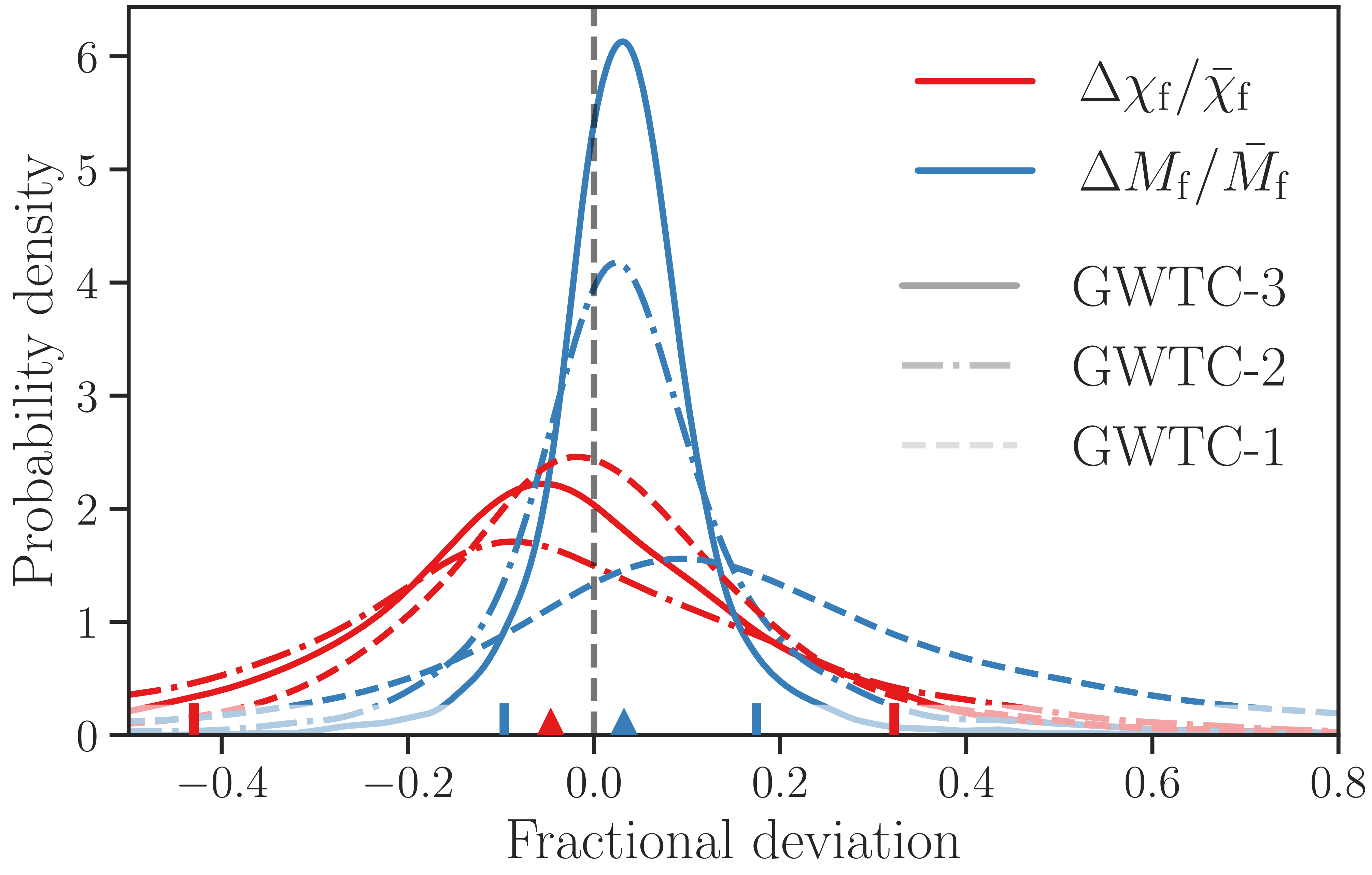


Inspiral-merger-consistency tests

- Compare inferred final mass and spin of the remnant using only inspiral or post-inspiral part of the signal

$$\frac{\Delta M_f}{\bar{M}_f} = 2\frac{M_f^{\rm insp} - M_f^{\rm postinsp}}{M_f^{\rm insp} + M_f^{\rm postinsp}}, \qquad \frac{\Delta \chi_f}{\bar{\chi}_f} = 2\frac{\chi_f^{\rm insp} - \chi_f^{\rm postinsp}}{\chi_f^{\rm insp} + \chi_f^{\rm postinsp}}$$

- Expect consistency between the two measurements when SNR is high enough in both regions



LVK Collaboration, arXiv 2112.06861 [gr-qc]

Propagation effects

Modified dispersion relationship

- Consider propagation of GWs on cosmological background and assume generalized dispersion relation, assuming generation effects are suppressed by powers of r/λ_g

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

- For $\alpha = 0$, can put bound on graviton mass [Will, PRD 57, 2061 (1998)]

$$m_g = \sqrt{A_0}c^{-2} \quad \text{(requires } A_0 > 0\text{)}$$

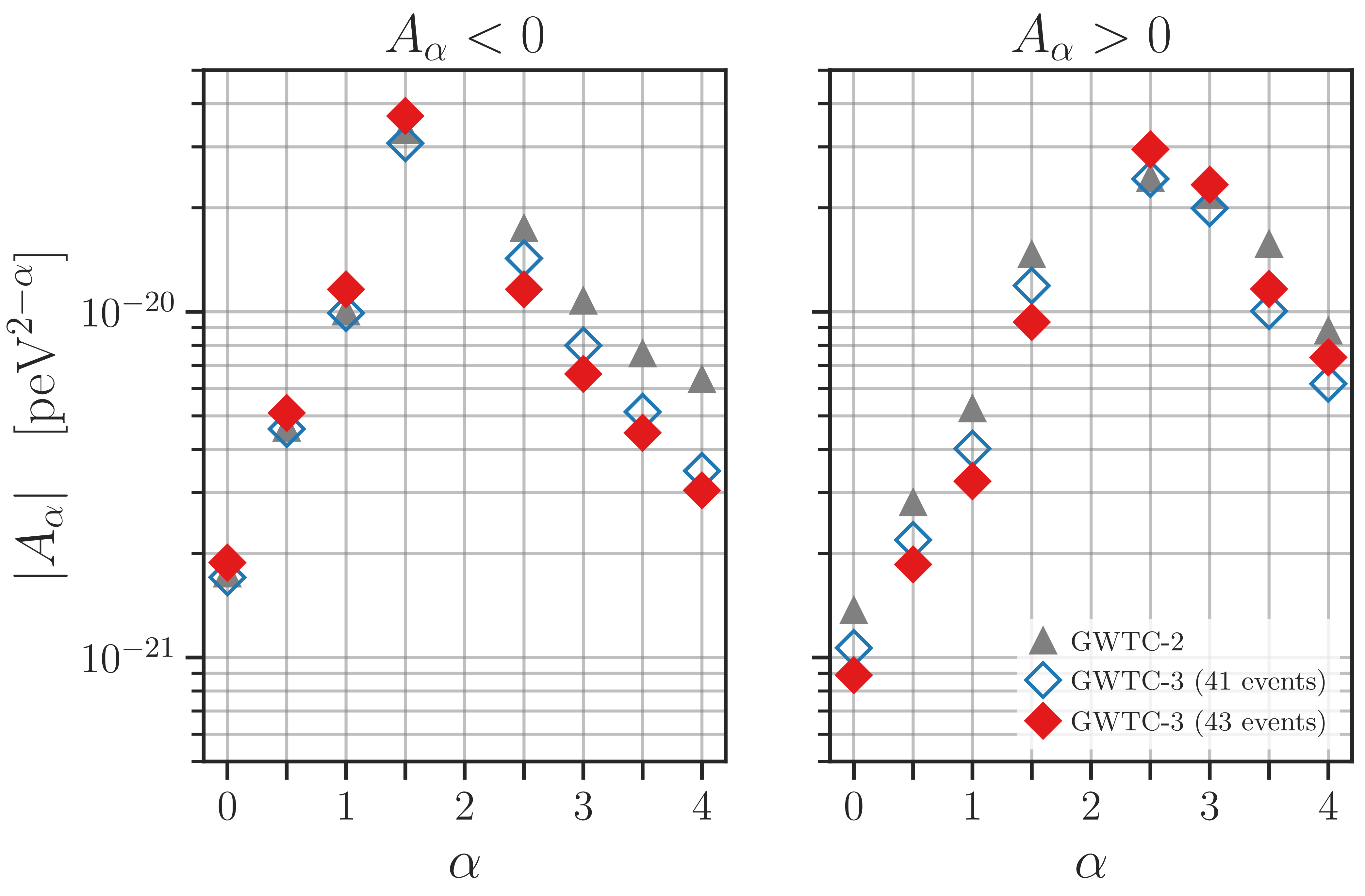
Fisher-matrix analysis gives

$$\lambda_g > \sqrt{\frac{\rho\, D_0\, \mathcal{M}}{(1+Z)}\frac{\pi}{\Delta^{1/4}}}$$

Mirshekari+ PRD 85, 024041 (2012)

- Non-birefringent analysis
- Allows to test modified dispersion relations even in the absence of electromagnetic counterpart

LVK Collaboration, arXiv 2112.06861 [gr-qc]



Dispersion tests with bright sirens

- GWs are dark sirens: they give information on luminosity distance but not redshift (redshift can be inferred by assuming a certain cosmological model)
- Bright sirens: events with EM counterpart
- Redshift: counterpart (e.g. GW170817) or statistical association to host galaxy to produce probabilistic constraint on it
- Measuring the interval between the arrival time of GWs and electromagnetic radiation, we can put limits on Lorentz invariance (LIGO-Virgo, Astrophys. J. Lett. 848, L13 (2017))

Dispersion tests with bright sirens

- GWs are dark sirens. Bright sirens: events with EM counterpart
- Good sky localisation helps: best localised source in O3b was had 90% credible area of 30 deg2 (was observed with all three detectors (LVK arXiv:2111.03606v2 **[gr-qc])**.
- Only a few percent of the sources detected until now have a localisation within 20 deg2.
- Median sky-localisation during O4 expected to be down to a few tens of square degrees during O4 (LVK Living Rev Relativity 23, 3 (2020))
- Measuring the interval between the arrival time of GWs and electromagnetic radiation, we can put limits on Lorentz invariance (LIGO-Virgo, Astrophys. J. Lett. 848, L13 (2017))

Tests of extra dimensions

- In higher-dimensional theories of gravity, propagation of GWs might be affected by their leakage into extra dimensions beyond a certain screening radius R_c

- This effect was constrained with GW170817 (LIGO-Virgo PRL 123, 011102 (2019))

$$\frac{1}{d_L^{\mathrm{GW}}} = \frac{1}{d_L^{\mathrm{EM}}}\left[1+\left(\frac{d_L^{\mathrm{EM}}}{R_c}\right)^n\right]^{-(D-4)/(2n)}$$

- Magaña-Hernandez (arXiv:2112.07650v1) analysed GWTC-3 events (redshifts informed by population model): updated constraints on D both with and without screening are consistent with propagation in four dimensions

Constraints on massive graviton

- Yukawa suppression of the gravitational potential applies in linearised regime of some massive gravity theories
- Solar system bound test from Bernus+, PRD 102, 021501 (2020):

  Fit planetary ephemeris to GR plus correction due to Yukawa suppression, for various Compton wavelengths -> Use likelihood threshold to determine bound on λ_g (m_g) at 90% C.L.

- $m_g \leq 3.16 \times 10^{-23} \mathrm{eV}/c^2$ Solar System
- $m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2$ GWs
- Will (Class Quantum Grav Letters, 17, 17LT01 (2018)) derives a bound of $O(10^{-24})$ using solar system data. Bernus+ argue fits should depend on λ_g as beyond-GR parameters are highly correlated to other parameters of the ephemeris

Other tests of Lorentz violations

- CPT violation can be related to Lorentz violation (Greenberg PRL 89:231602,2002)
- In the most general case, Lorentz-violating corrections can lead to anisotropic, birefringent and dispersive propagation of GWs
- Study gravitational waves in the presence of Lorentz-violating operators of arbitrary dimension, and compute covariant dispersion relation [Kostelecký&Mewes Physics Letters B,757,510-514 (2016)]
- Asymmetry in the propagation speed and amplitude damping between left and right-hand polarizations of a GW, which leads to phase and amplitude birefringence, respectively.
- Tests performed on GWTC-3 events
  - Zhao+ ApJ 930:139, 2022 (birefringence disfavoured)
  - Wang+ arXiv:2109.09718**:** for GW190521 and GW191109, find evidence in support of GW birefringence, however, authors underlines possible role of waveform systematics in interpreting results

Lensing and propagation effects

- Birefringent propagation can introduce time delays between different metric polarisations, leading to effect qualitatively similar to those expected for lensed signals
- Even if there's no perfect degeneracy between strong lensing and MDR effects lensing might be mistaken for MDR Ezquiaga+ arXiv:2203.13252 [gr-qc]
- Waveform morphology of lensed dispersive GWs depends on the graviton mass more sensitively than unlensed waves.
    - Chung&Li PRD 104 124060 (2022): conclude that 1 lensed signal could constrain graviton's mass as tightly as ~1000 unlensed events. Considered microlensing (point-mass lenses), which is expected to be rare for LIGO

Parametrised tests of GR

- Additional fields in alternative theories of gravity might get activated in the strong-field region, providing new radiative channels
- No monopole or dipole radiation in GR due to due to the conservation of the stress-energy tensor
- No longer true in beyond-GR models. E.g.: scalarized objects ->dipole radiation->faster inspiral (Barausse+ 2013, Palenzuela+ 2014, Sennett+ 2017)
- Flexible, though implicitly requires a certain smoothness in the activation of beyond-GR effects: might not capture more abrupt changes, induced by e.g. dynamical scalarization, resonances

Parametrised PN tests in LIGO-Virgo analyses

- In the inspiral, introduce theory-agnostic deviations at individual PN orders in the phasing resulting from applying the stationary phase approximation to the chirp

- $$\varphi_{\rm PN} = 2\pi f t_{\rm c} - \varphi_{\rm c} - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi\tilde{f}\right)^{-5/3}\sum_{i=0}^{7}\left[\varphi_i + \varphi_{i\,l}\log(\pi\tilde{f})\right]\left(\pi\tilde{f}\right)^{i/3}$$

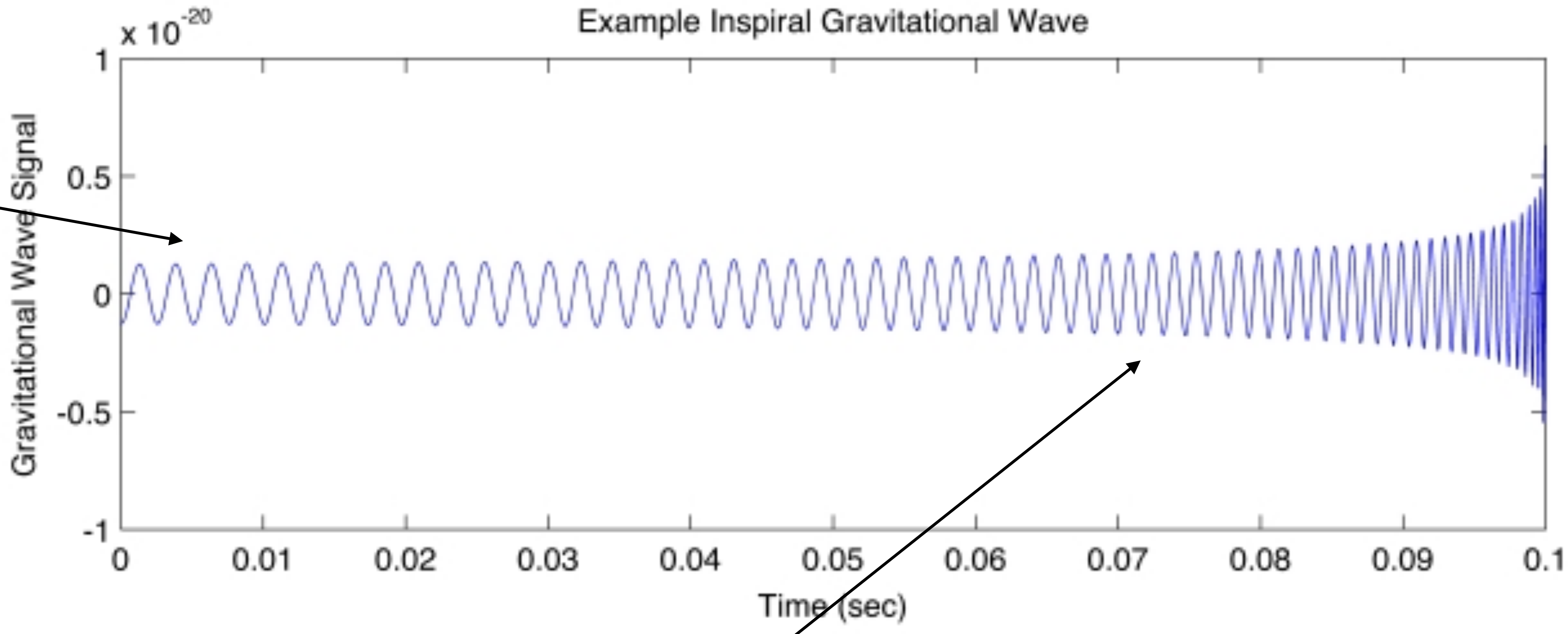
Terms scaling like $\approx \tilde{f}^{(-5+i)/3}$ at $i/2$-th PN order

- LIGO/Virgo analyses constrain -1PN plus orders in the [0 PN,3.5 PN] interval, in terms of fractional/absolute deviations $\delta\hat{\varphi}_i$

- -1PN has been used to place constrain on dipole radiation. Other types of negative terms might come from environmental effects [Cardoso&Maselli Astron.Astrophys. 644 (2020)], time-varying G or extra dimensions (see Chamberlain&Yunes PRD **96**, 084039)

PN-based inspiral tests

Low order PN terms

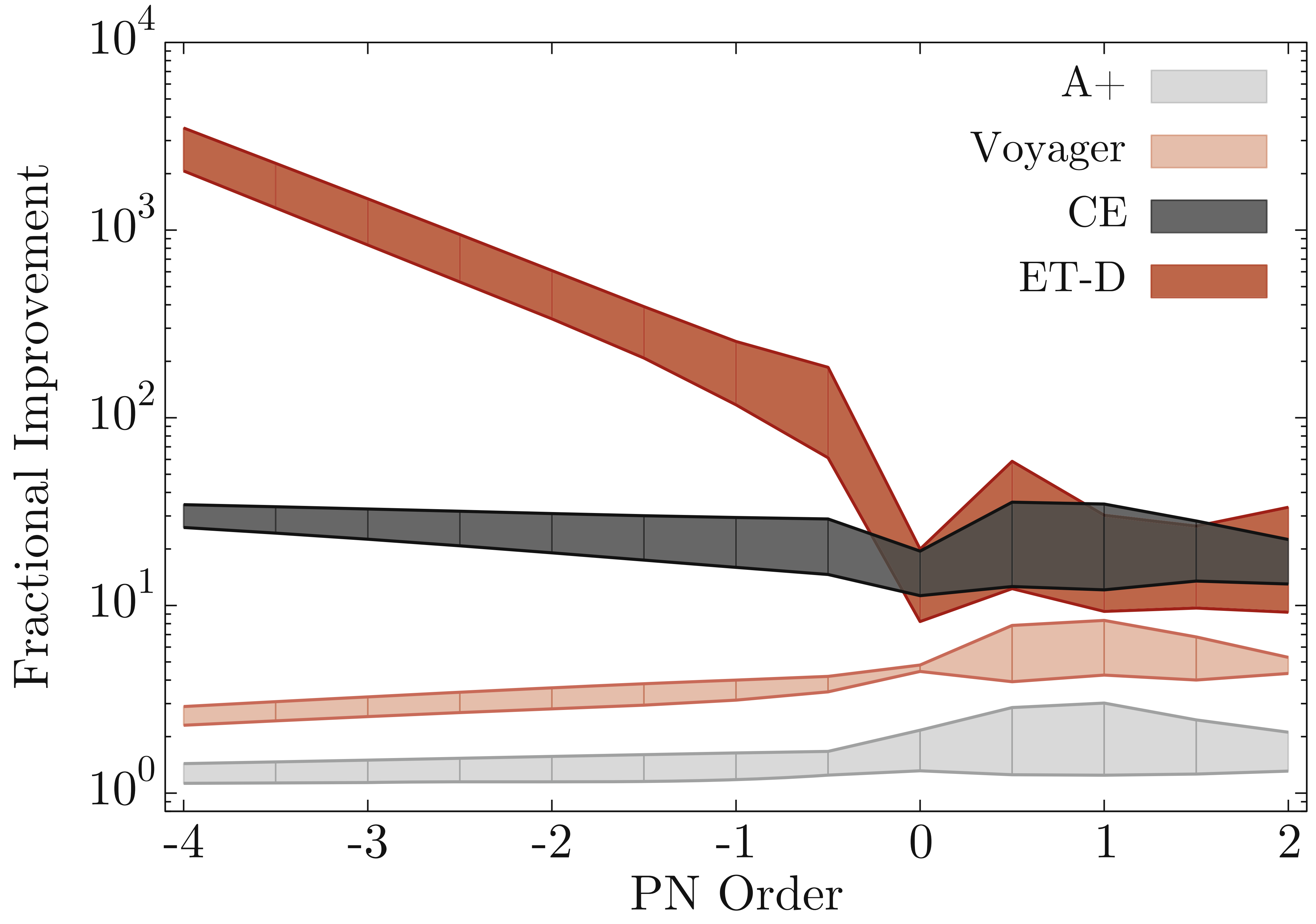


Credit: LIGO

High order PN terms

Terms scaling like $\approx \tilde{f}^{(-5+i)/3}$ at $i/2$-th PN order

Expected improvements with 3G detectors

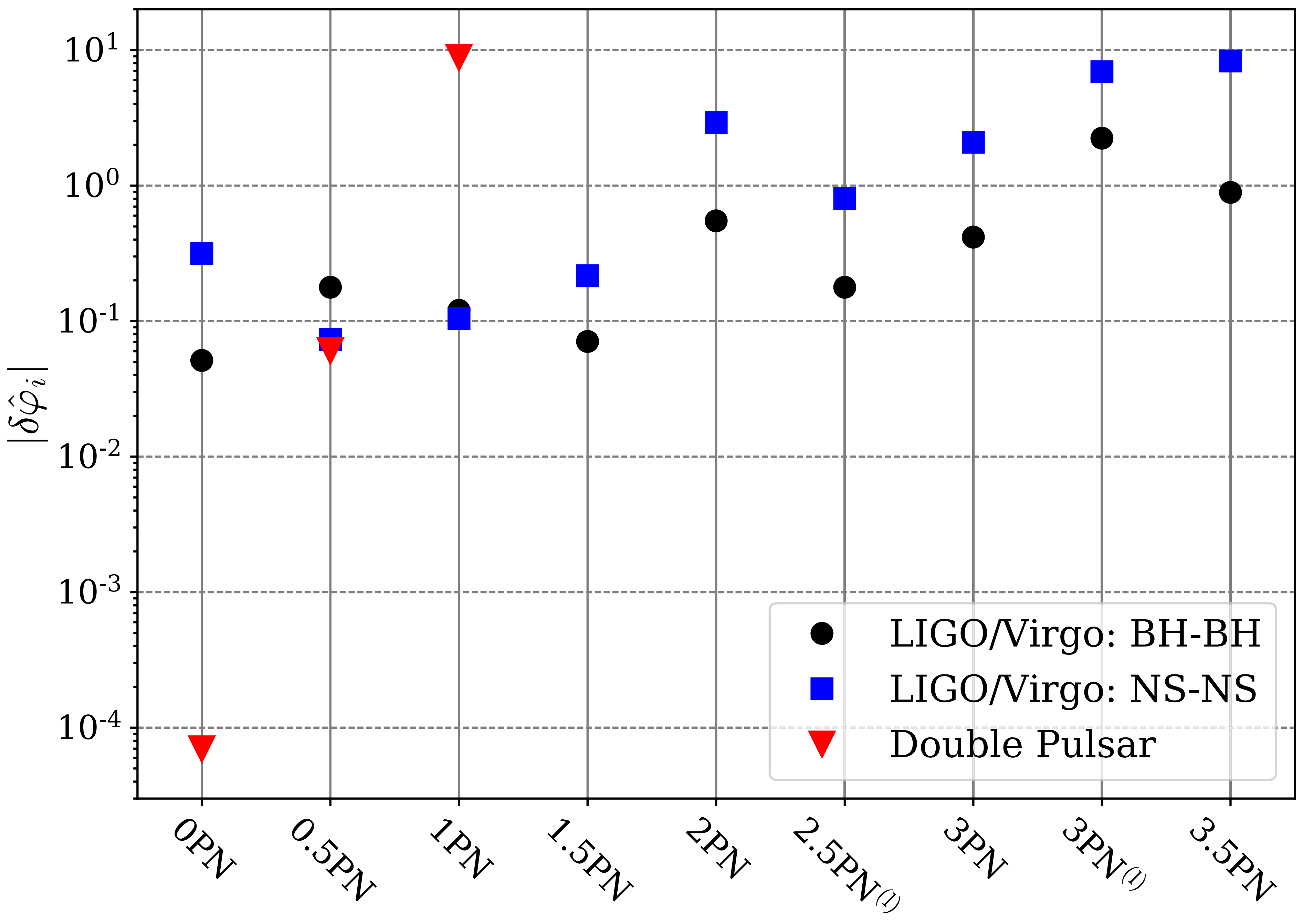


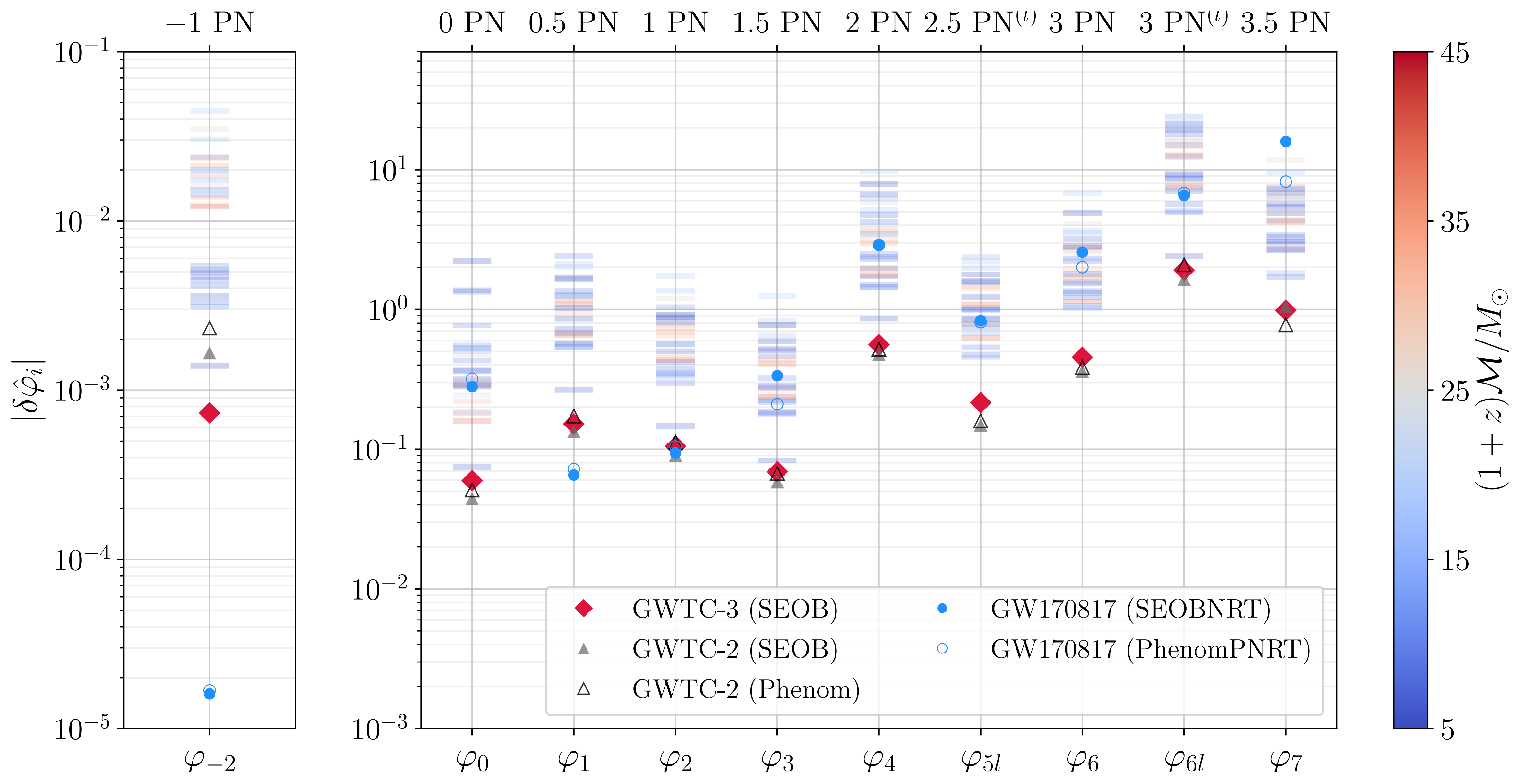
From: Chamberlain&Yunes PRD **96**, 084039

- Estimate on individual events, compared to aLIGO design sensitivity
- Combined bounds will be in general stronger by a factor ~$\sqrt{N}$

LIGO vs double-pulsar constraints

- Double-pulsar constraints obtained with double pulsar PSR J0737-3039A/B in Kramer+ PRX 11, 041050 (2021)
- Complementary tests
  - different regimes (mildly vs strongly relativistic)
  - different binary systems (BNS vs BBH/NSBH): in some scalar-tensor theories, source for scalar field might depend also on matter-independent terms (Yagi+ PRD 93, 024010 (2016))
  - DP tests degrade at high frequencies (higher PN orders)





Joint-likelihood approach (assume shared value of deviations across **all** events)

Constraints on dipole radiation

- If we parametrise deviations from GR emission as

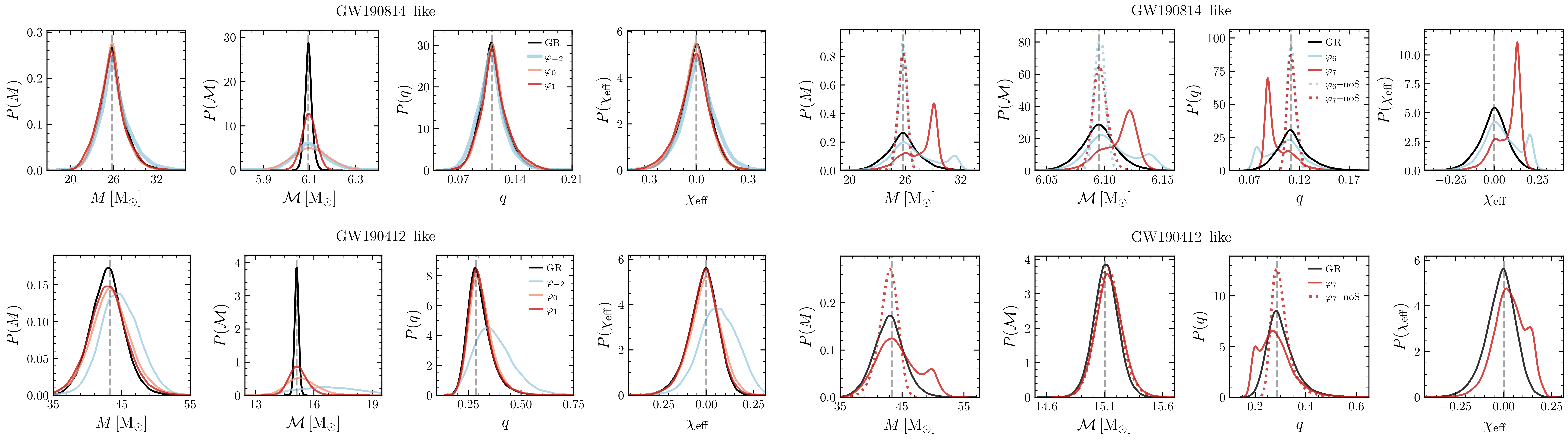
$$\mathcal{F}_{\rm GW} = \mathcal{F}_{\rm GR}(1 + Bv^2/c^2)$$

  - GW170817 : $B \leq 1.2 \times 10^{-5}$ *LIGO-Virgo PRL **123**, 011102 (2019)*
  - Double pulsar: $B \leq 4 \times 10^{-10}$ *Kramer+ PRX 11, 041050 (2021)*

- Better sensitivity of double-pulsar tests at low PN orders (low frequencies) due to the large number of cycles observed: approximately 60000 since 2003 for the double pulsar! Observed cycles for GW170817 were one order of magnitude less.

Parametrised post-Newtonian tests

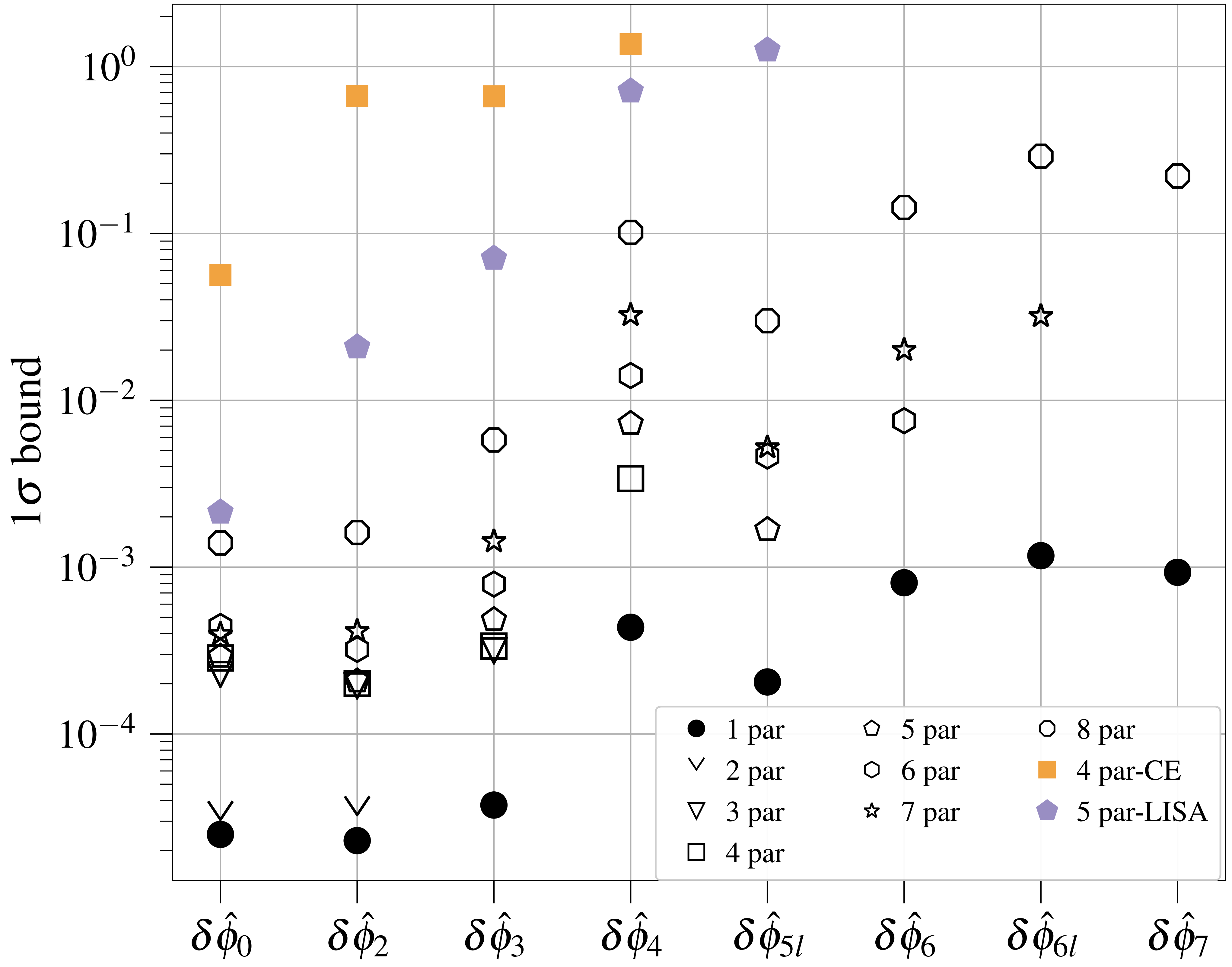
- Bounds depend on **many** details: PSDs, internal choices of the analysis, characteristics of the events, waveform model used to approximate GR signal etc…
- Parametrised deviations can be strongly correlated with source parameters



Mehta+ arXiv:2203.13937 **[gr-qc]** (2022)

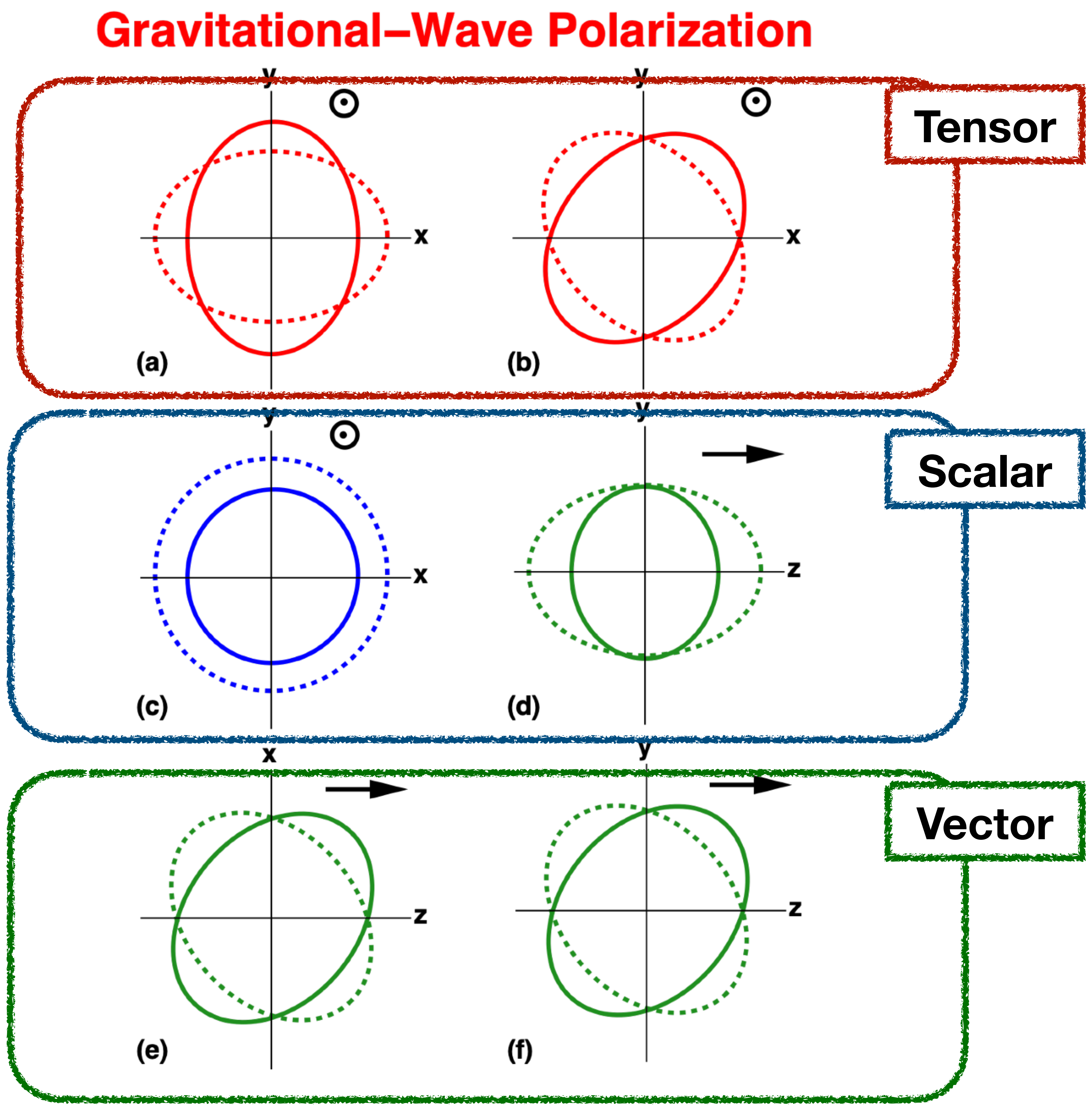
Parametrised post-Newtonian tests (The tricky parts II)

- Bounds on individual PN deviation coefficients, but in alternative theories of gravity multiple coefficients will be different from GR
- Multiparameter tests: Multiband observations of stellar-mass binary black holes will help [Gupta+ PRL 125, 201101 (2020)]
- Can use PCA to find linear combinations of parameters yielding best constraints. Diagonalization of covariant matrix is event-dependent so "combined" PCA parameters need to be computed from combined N-dimensional posterior (for N event). [Pai&Arun, CQG 30, 025011 (2013), Saleem+ PRD 105, 084062 (2022)]
- Neglect of physical information, such as eccentricity, might lead to biases in the PN deviation coefficients [Saini+ arXiv:2203.04634]



From: Gupta+ PRL 125, 201101 (2020)

Polarizations



Will, Living Rev. Relativity 17 (2014)

- Generic metric theory of gravity can have up to 6 polarisation states
- Longitudinal and breathing modes for interferometers are not linearly independent
- Detector has a specific response to different polarisations encoded in the antenna pattern functions

$$h(t) = F_{+}h^{+} + F_{\times}h^{\times} + F_{\rm se}h^{\rm se} + F_{\rm sn}h^{\rm sn} + F_{\rm b}h^{\rm b} + F_{\rm L}h^{\rm L}$$

- The addition of new detectors to the network (KAGRA, LIGO India) will improve the sensitivity to different polarisations

Null streams

$$
\begin{bmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \vdots \\ \tilde{d}_D \end{bmatrix}
=
\begin{bmatrix}
F_1^{+} & F_1^{\times} & F_1^{\rm se} & F_1^{\rm sn} & F_1^{\rm b} & F_1^{\rm L} \\
F_2^{+} & F_2^{\times} & F_2^{\rm se} & F_2^{\rm sn} & F_2^{\rm b} & F_2^{\rm L} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
F_D^{+} & F_D^{\times} & F_D^{\rm se} & F_D^{\rm sn} & F_D^{\rm b} & F_D^{\rm L}
\end{bmatrix}
\begin{bmatrix} \tilde{h}_{+} \\ \tilde{h}_{\times} \\ \vdots \\ \tilde{h}_{\rm L} \end{bmatrix}
+
\begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ \vdots \\ \tilde{n}_D \end{bmatrix}
$$

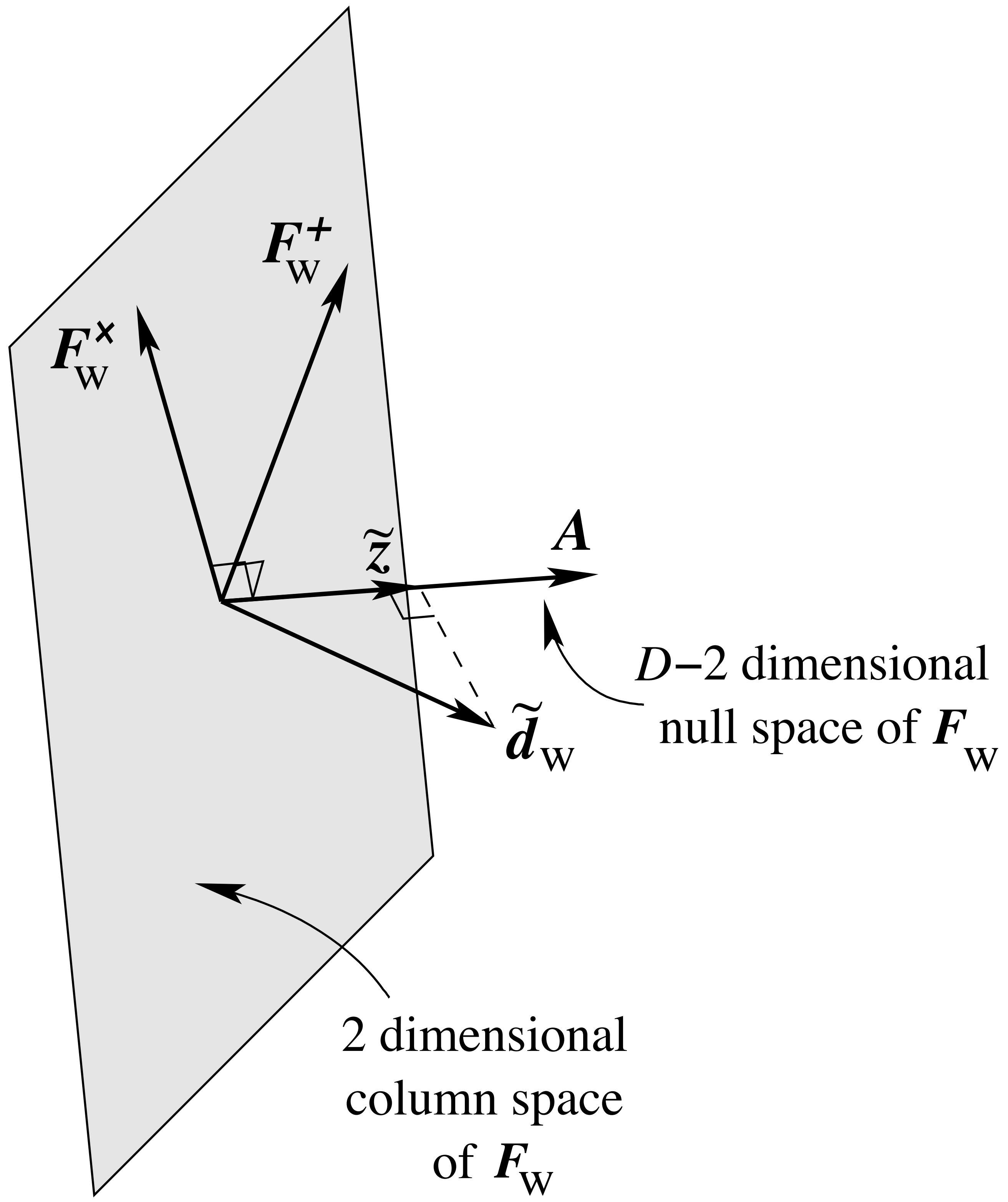
Output from D detectors

Beam pattern functions

Polarisation states

Noise

Build a null projector



From: Chatziioannou + PRD 86 022004, 2012

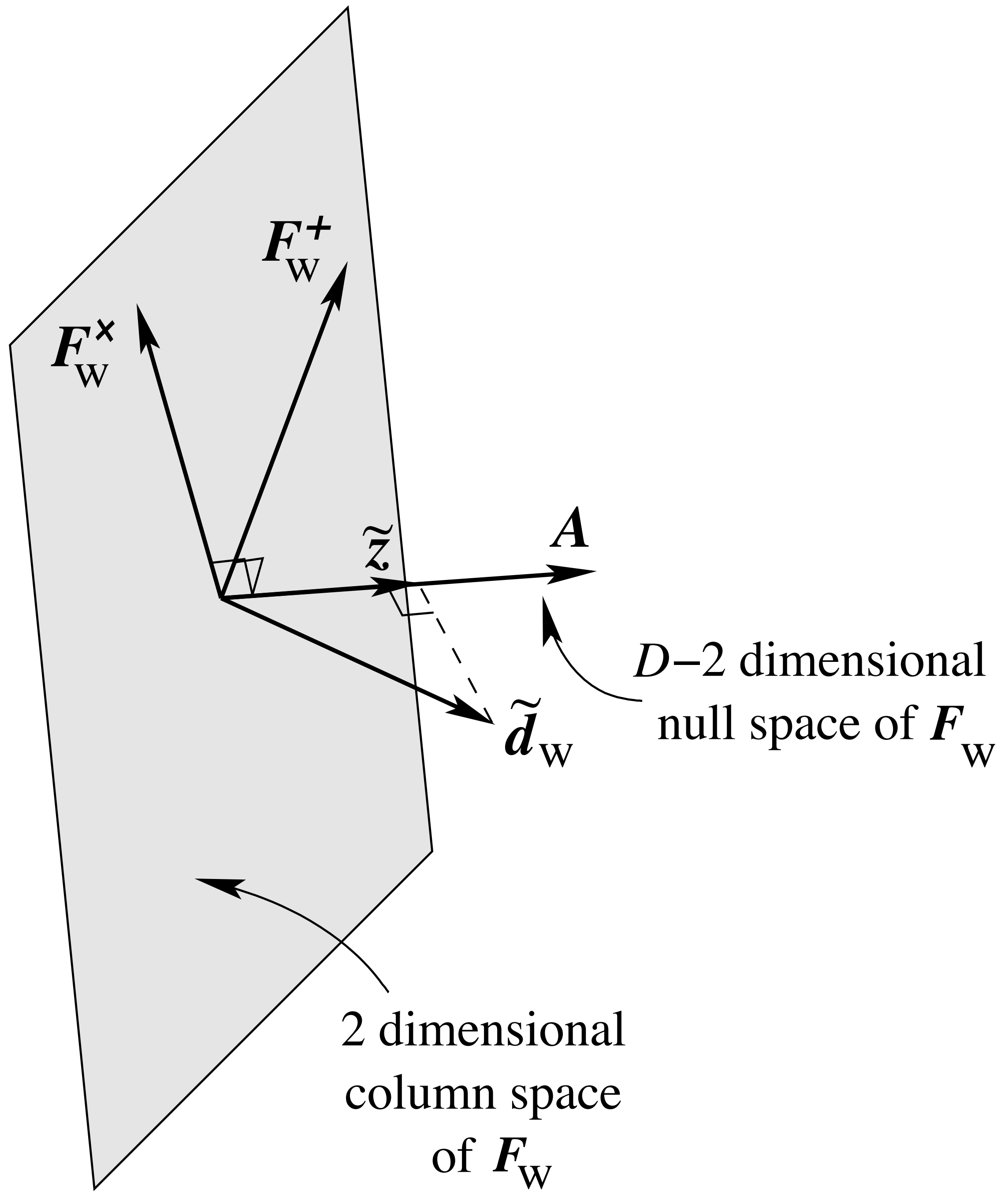
From: Chatterji+ Phys.Rev.D74:082005,2006

One can construct at most D-Npol independent null streams: e.g. for Npol=2 (GR) we can construct one null stream with the output of 3 detectors

Polarisation tests

NULL STREAM

- Can compute excess power after null projection and check whether it's consistent with noise -- originally applied to distinguish GW bursts from instrumental noise [Gürsel&Tinto 1989, Wen&Schutz 1996, Chatterji+ 2006]
- Depending on the way the projector operator is built, can test either pure (as in LIGO-Virgo[GWTC-1,GWTC-2] or mixed polarisations LIGO-Virgo [GWTC-3], Wong+ 2021].
- Strongest single-event constraint coming from GW170817 (BF~20 in favour of purely tensorial polarisation of signal) (LIGO-Virgo [1811.00364])
- Latest LIGO analysis combines BFs of events from O1-O2-O3 events finding no statistically significant evidence of alternative polarisations



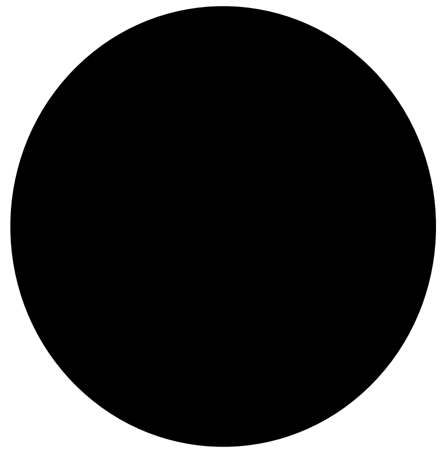
- Mixed polarizations could be also tested using sums of sine-Gaussian wavelets (BayesWave) [Chatziioannou+ 2021]

- Constraints on mixed polarisation possible even w/out fully breaking degeneracies among all possible states

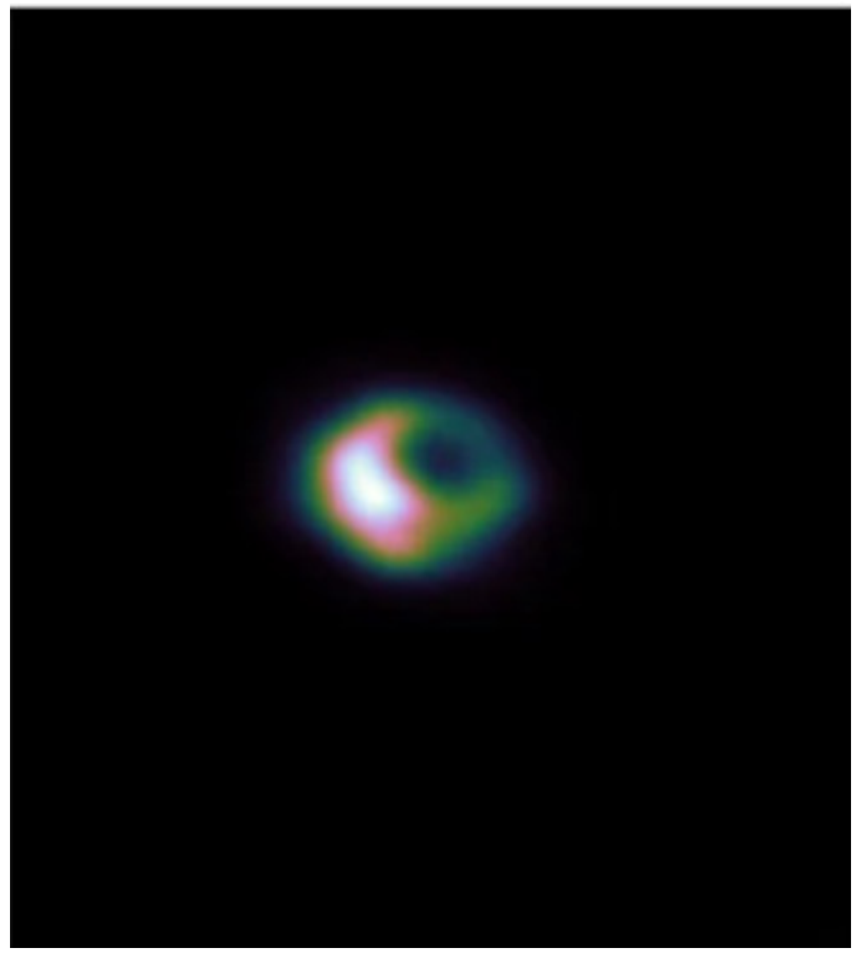
Tests of black hole nature

Was it a BH after all?

Classical BH

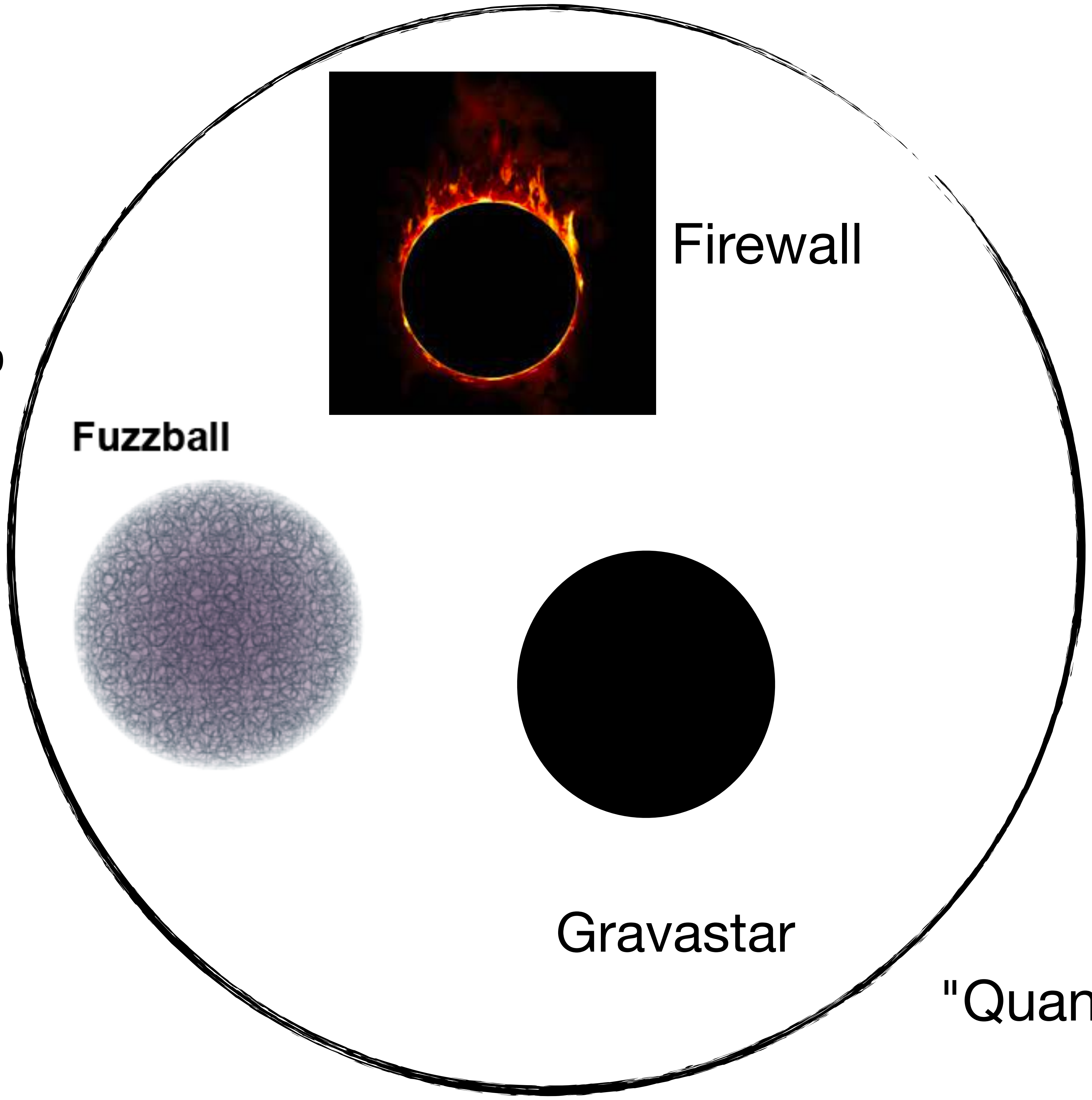


Boson star



Credit: Olivares et al., MNRAS, 2020

Wormholes



"Quantum BHs"

- Semi-classical description of BH -> information paradox
- Horizons as a probe of quantum effects

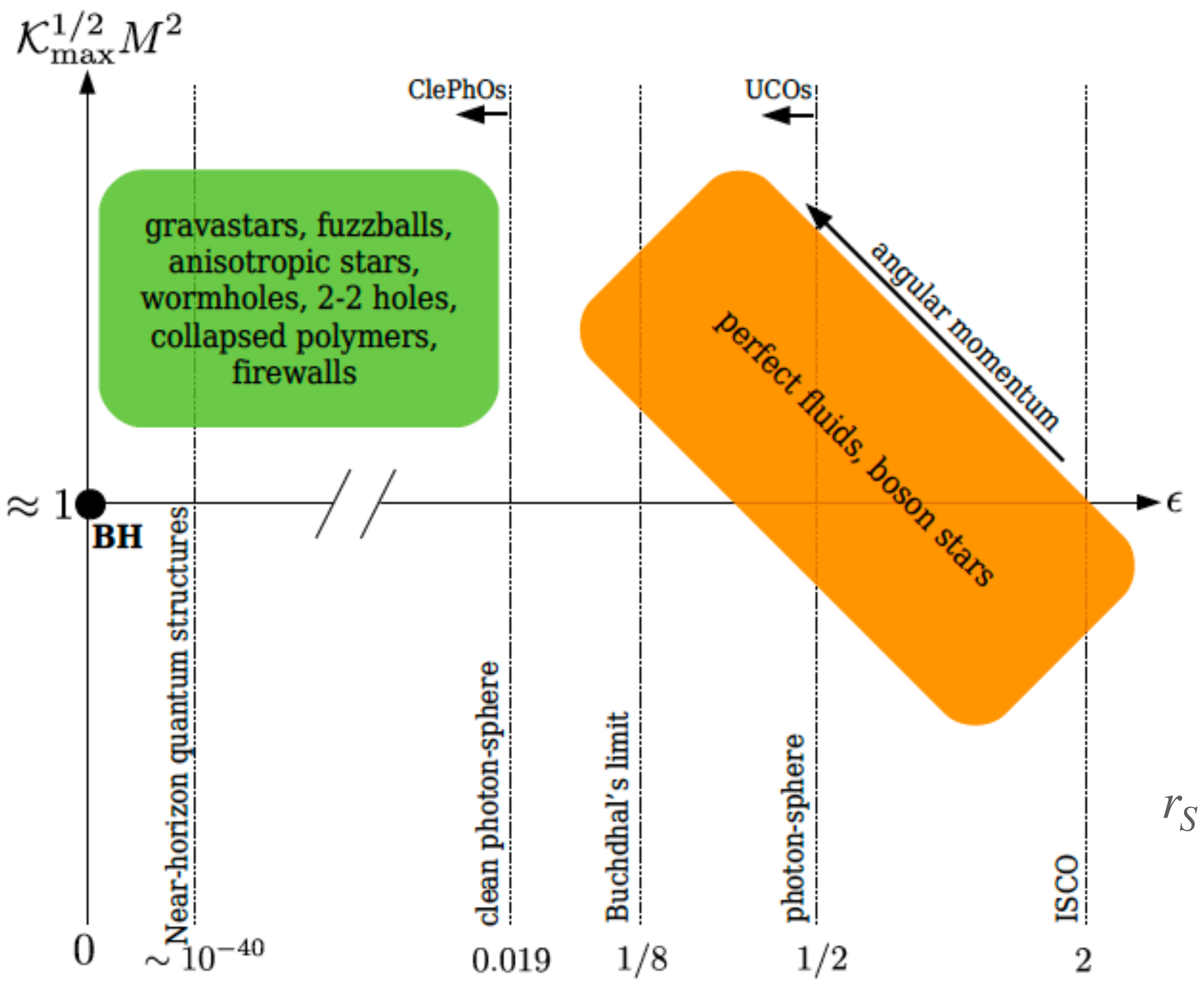
- CBCs considered as good candidates to observe effects coming from new types of weakly interacting particles and new fields addressing fundamental physics puzzles

- Not all the available alternatives have been equally explored in terms of formation/stability/ observation signatures (see Cardoso&Pani arXiv:1904.05363v3)

Was it a BH after all?

- Some tests directly question the nature of the compact objects we detect through GWs
- The different properties of the object can manifest themselves during the inspiral or during the ringdown phase of the coalescence.

Curvature normalised to BH value



$r_S = r_+(1+\epsilon)$

From: Cardoso&Pani arXiv:1904.05363

Spin-induced quadrupole moments tests

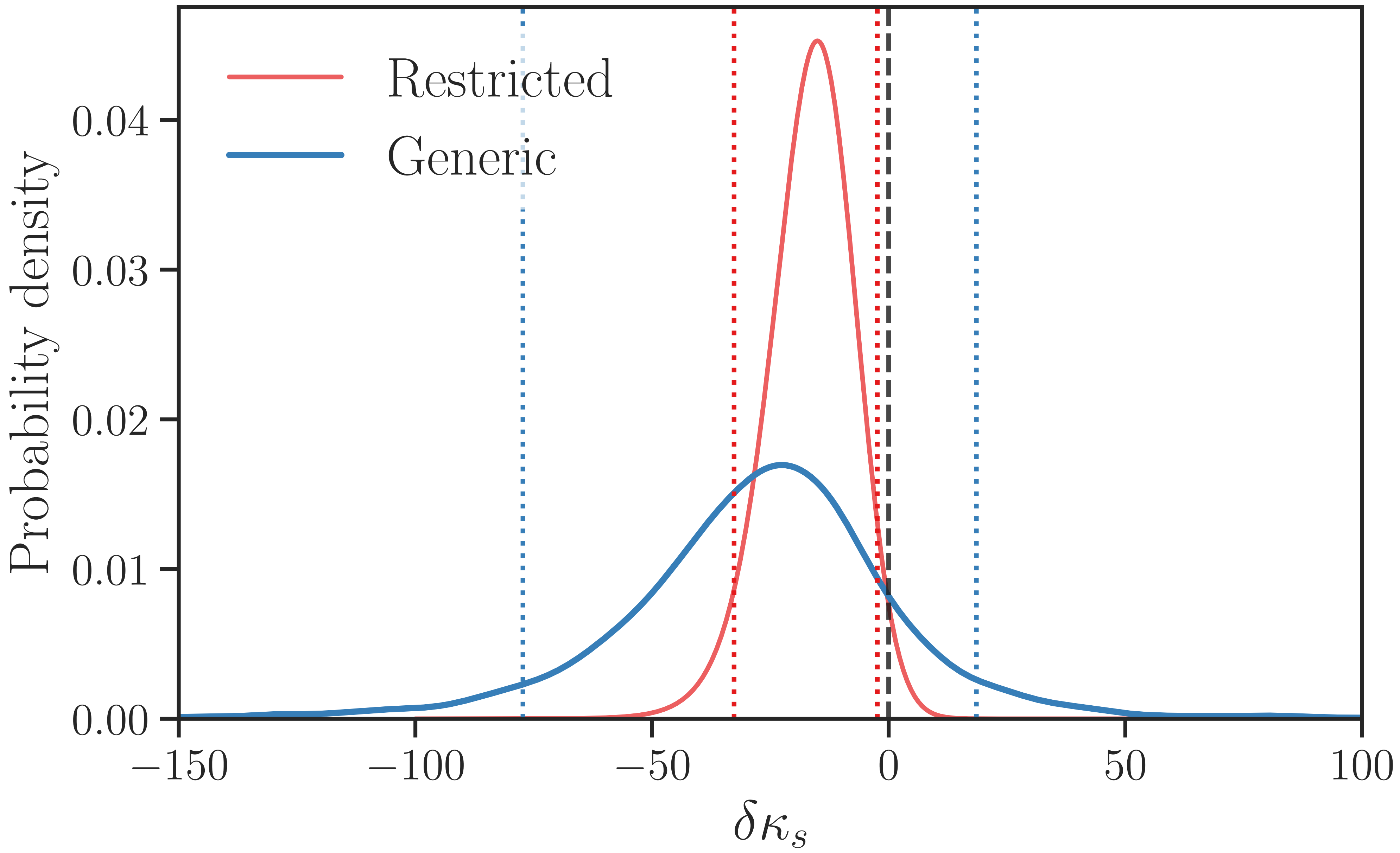
- No-hair theorem → multipole moments of a Kerr BH are entirely determined by its mass and spin

- Spin-induced quadrupole moments leave observable signatures in GWs, leading-order correction at 2PN

$$Q = -\kappa\chi^2 m^3$$

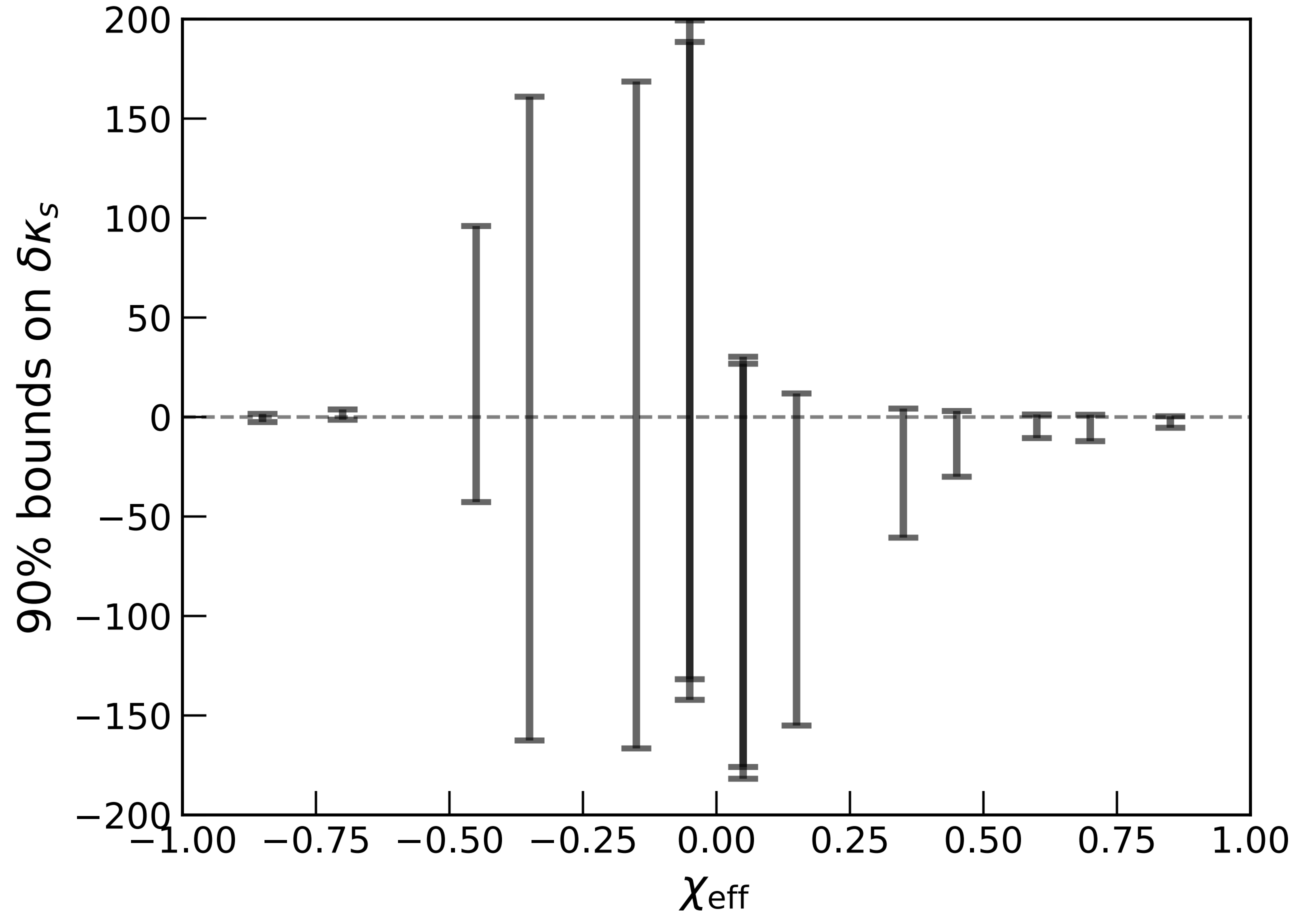
- Assume two objects have the same κ, and measure symmetric combination

$$\kappa_s = \frac{\kappa_1 + \kappa_2}{2} \longrightarrow 1 + \delta\kappa_s$$



LVK Collaboration, arXiv 2112.06861 [gr-qc]

Krishnendu+ PRL 119, 091101 (2017)
PRD 99, 064008 (2019), PRD 100, 104019 (2019)



Constraints expected to drastically improve with LISA/DECIGO Krishnendu&Yelikar CQG, 37 205019 (2020)

From: Krishnendu+ PRD 100, 104019 (2019)

Tidal Love numbers

- Tidal Love numbers are different for ECOs than BHs, tidal corrections appear at 5PN [Cardoso, PRD 95, 084014 (2017)]
- Encapsulate conservative response to external fields
- Recent controversies about Love and Kerr BHs [Le Tiec&Casals,2020, Chia 2020, Goldberger+ 2020, Charalambous+ 2021].
- It is now accepted that Love numbers are 0 for Kerr BHs in 4 dimensions

		Tidal Love numbers			
		k_2^E	k_3^E	k_2^B	k_3^B
NSs		210	1300	11	70
ECOs	Boson star	41.4	402.8	-13.6	-211.8
	Wormhole	$\frac{4}{5(8+3\log\xi)}$	$\frac{8}{105(7+2\log\xi)}$	$\frac{16}{5(31+12\log\xi)}$	$\frac{16}{7(209+60\log\xi)}$
	Perfect mirror	$\frac{8}{5(7+3\log\xi)}$	$\frac{8}{35(10+3\log\xi)}$	$\frac{32}{5(25+12\log\xi)}$	$\frac{32}{7(197+60\log\xi)}$
	Gravastar	$\frac{16}{5(23-6\log 2+9\log\xi)}$	$\frac{16}{35(31-6\log 2+9\log\xi)}$	$\frac{32}{5(43-12\log 2+18\log\xi)}$	$\frac{32}{7(307-60\log 2+90\log\xi)}$
BHs	Einstein-Maxwell	0	0	0	0
	Scalar-tensor	0	0	0	0
	Chern-Simons	0	0	$1.1\frac{\alpha_{CS}^2}{M^4}$	$11.1\frac{\alpha_{CS}^2}{M^4}$?

From: Cardoso, PRD 95, 084014 (2017)

Love numbers of spherically symmetric, static background geometries

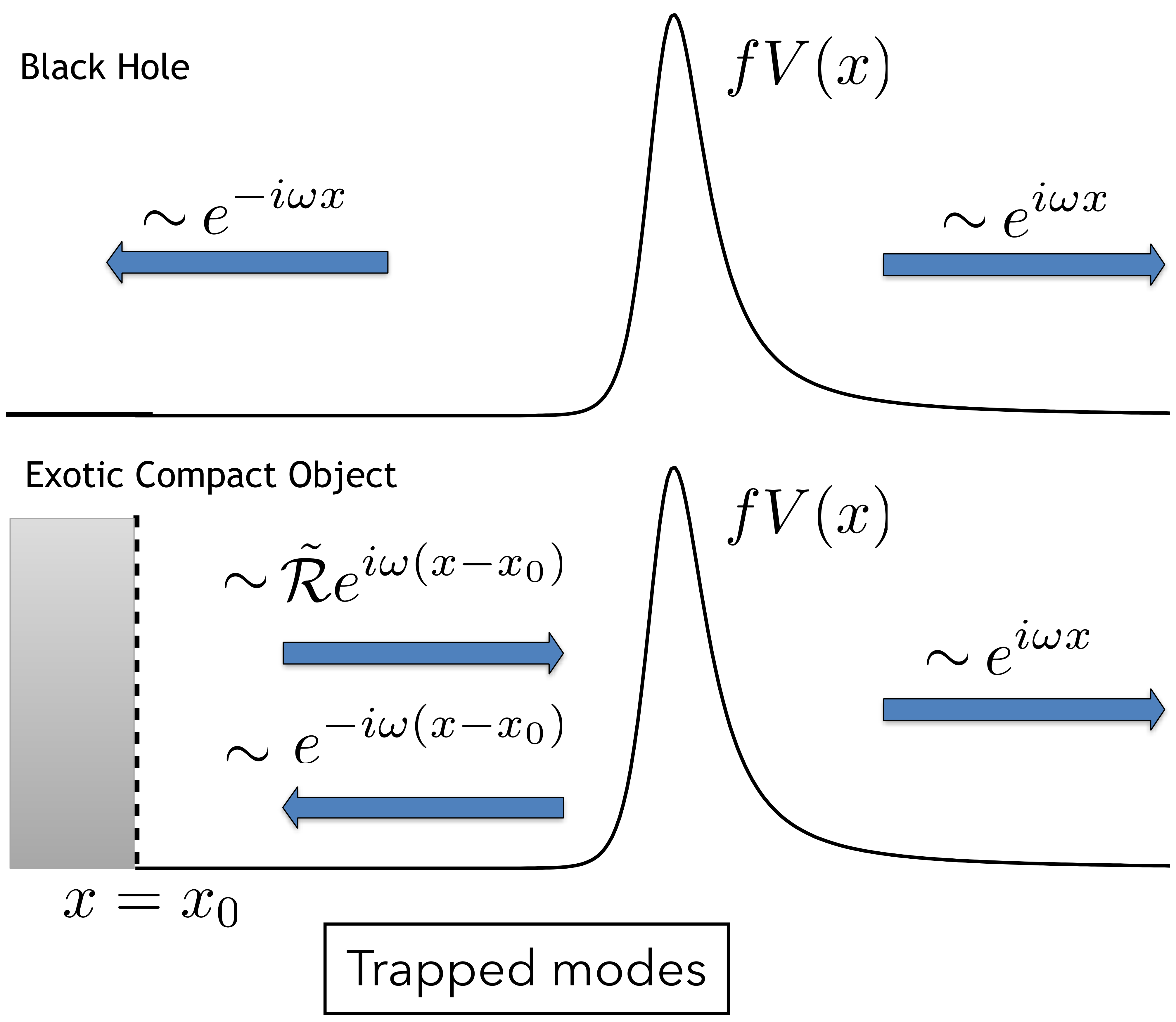
Tidal heating

- BHs: the horizon is a one-way surface. Flux of energy and angular momentum across the BH's will change its mass and spin leading to tidal heating (torquing) (Poisson&Sasaki PRD 51, 5753 (1995), Alvi PRD64, 104020 (2001)). These tidal effects will backreact on the orbit leaving an imprint in the GW signal.
- GWs can escape from horizonless objects -> Dissipation is expected to be small for ECOs as compared to BHs -> tidal heating can be taken as a measure of the black-hole nature of a compact object (even when external geometry of the objects is very similar)
- In PN, gives corrections starting at 2.5PN order (for spinning objects, else at 4PN) .
- Measurability for 2G and 3G detectors investigated in Mukhrejee+ arXiv:2202.08661 [gr-qc]. Poor constraints from LIGO, would need golden binary (exceptionally close, low mass event),
- Expected to be mostly negligible for LIGO except for high mass ratio high aligned spins (Isoyama&Nakano CQG 35, 2, 024001 (2018), importance of tidal heating increases with mass ratio [Mano+ Prog. Theor. Phys., 98:829-850, 1997, Hartle, PRD, 8:1010–1024 (1973), Hughes PRD, 64,084004 (2001)]
- Absorption expected to be significant for EMRIs with tidal heating suggested as probe of reflective properties of ECOs [Datta+ PRD 101, 044004 (2020), Datta, PRD 102, 064040](2020)

Echoes

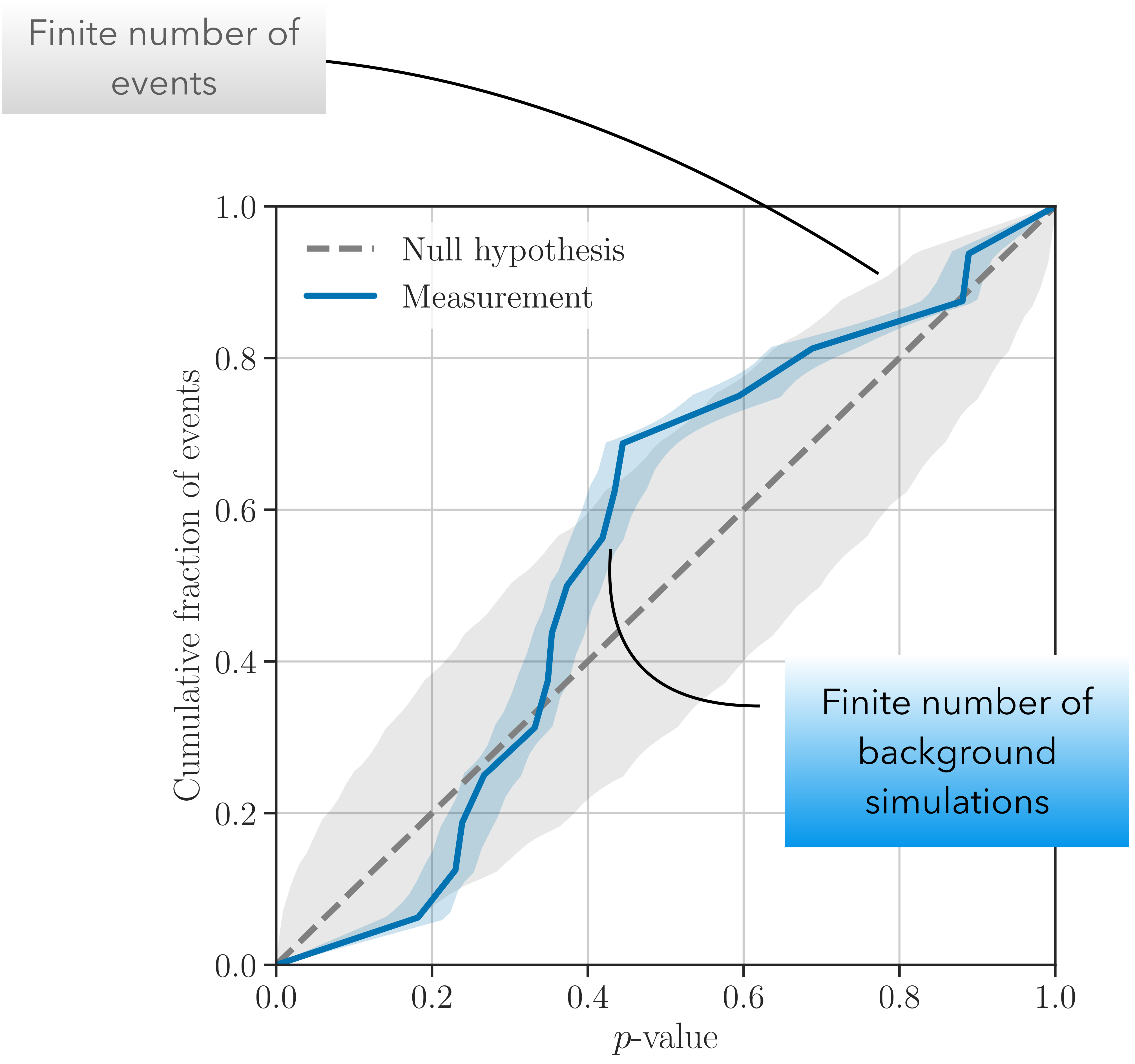
From: Mark+ PRD 96, 084002 (2017)

- If event horizon is not there, no purely ingoing boundary conditions
- For ultra-compact objects, prompt ringdown might be followed from echoes: trapped modes slowly leak out of potential barrier producing a train of pulses in the post-merger signal
- Can be modeled
  - by adding the echo signal to an IMR BBH template (LIGO-Virgo, PRD 103, 122002 (2021))
  - in waveform-agnostic way (LIGO-Virgo arXiv 2112.06861, TGR-GWTC-3) .
- Contrasting claims in the literature following Abedi+ arXiv:1612.00266v2, in which the authors looked at O1 data. See Abedi+ arXiv:2001.09553v1 for a review.



Echoes

- Latest LIGO-Virgo analysis models pulses as combs of decaying sine-Gaussians using BAYESWAVE to perform a morphology-independent search method
- Echo signals are expected to be close to detection threshold, so understanding of background behaviour is crucial -> Compute background distributions for the log Bayes factors $\log_{10}\mathscr{B}^{\mathrm{S}}_{\mathrm{N}}$ in 200 trials around the event
- Hard to understand best parametrization and choice of priors



LVK Collaboration, arXiv 2112.06861 [gr-qc]

Ringdown tests

- In GR, mass and spin determine the spectrum of post-merger emission (consequence of no-hair theorem)
- Typically modelled as a linear superposition of damped sinusoids (follows from linear perturbation theory)

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

- Despite apparent simplicity of the template used, many subtle points that can lead to discrepant results:
    - Impact of noise
    - Choice of ringdown regime start time
    - FD vs TD
    - Contribution of inspiral-merger signal

Beyond linear effects...

Nonlinear effects might play a non-neglible role through non-linear, self-coupling of first-order modes (Ripley+ PRD 103, 104018 (2021)), and dynamically excited due to variation of the remnant's parameters ("absorption-induced mode excitation" - Sberna+ PRD ***105****, 064046 (2022))*

Ringdown tests

- Controversies related to various detection claims:
    - **221 Overtone in GW150914**: total mass of system and high SNR make it an ideal candidate for RD tests (MRD falls in detector's sweet spot).
        - YES! Isi+ arXiv:1905.00869v2, arXiv:2202.02941v2
        - NO! Cotesta+ arXiv:2201.00822
        - MAYBE? Finch&Moore arXiv:2205.07809v1
    - **Higher modes in GW190521 ringdown:**
    - **NO** (LIGO-Virgo [TGR-GWTC-2, arXiv:2010.14529v2])
    - **YES** (Capano+, arXiv:2105.05238): find statistically significant evidence of (2,2) and (3,3) harmonics

Credit: iTHEMS

As it's common in tests of GR, results appear to strongly depend on how the background is factored in, as well as on internal settings of the analysis

Parametrised ringdown tests

pSEOBHM

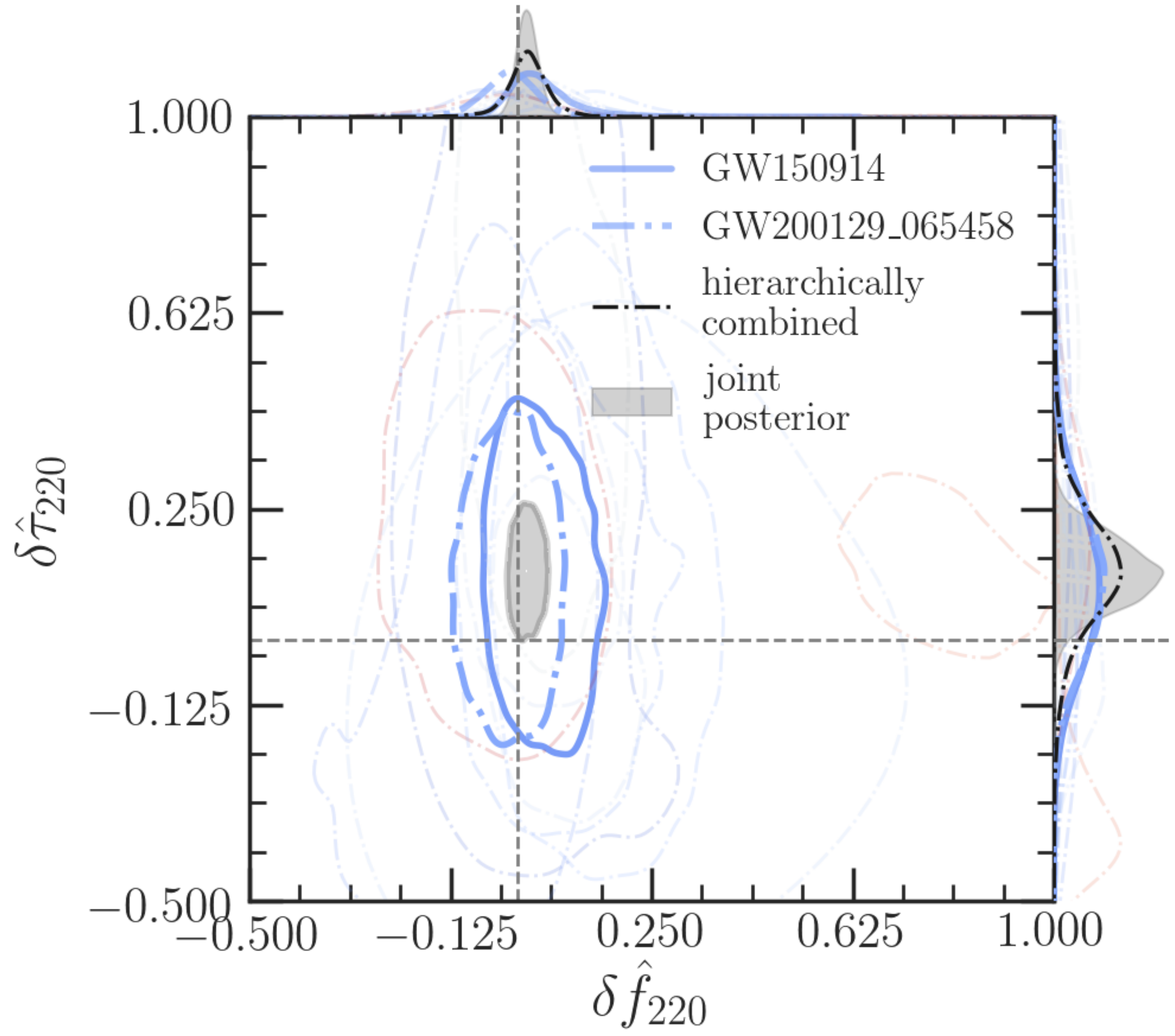
- Complementary to ringdown analyses focussing only on post-merger signal, ringdown start time is in-built in the model
- Introduce fractional deviations in the frequency and damping time of least-damped dominant QNM in the IMR model SEOBNRv4HM

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

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

- Possible issues:
    - Known degeneracies between deviation parameters and source parameters
    - Choice of priors
    - Impact of noise

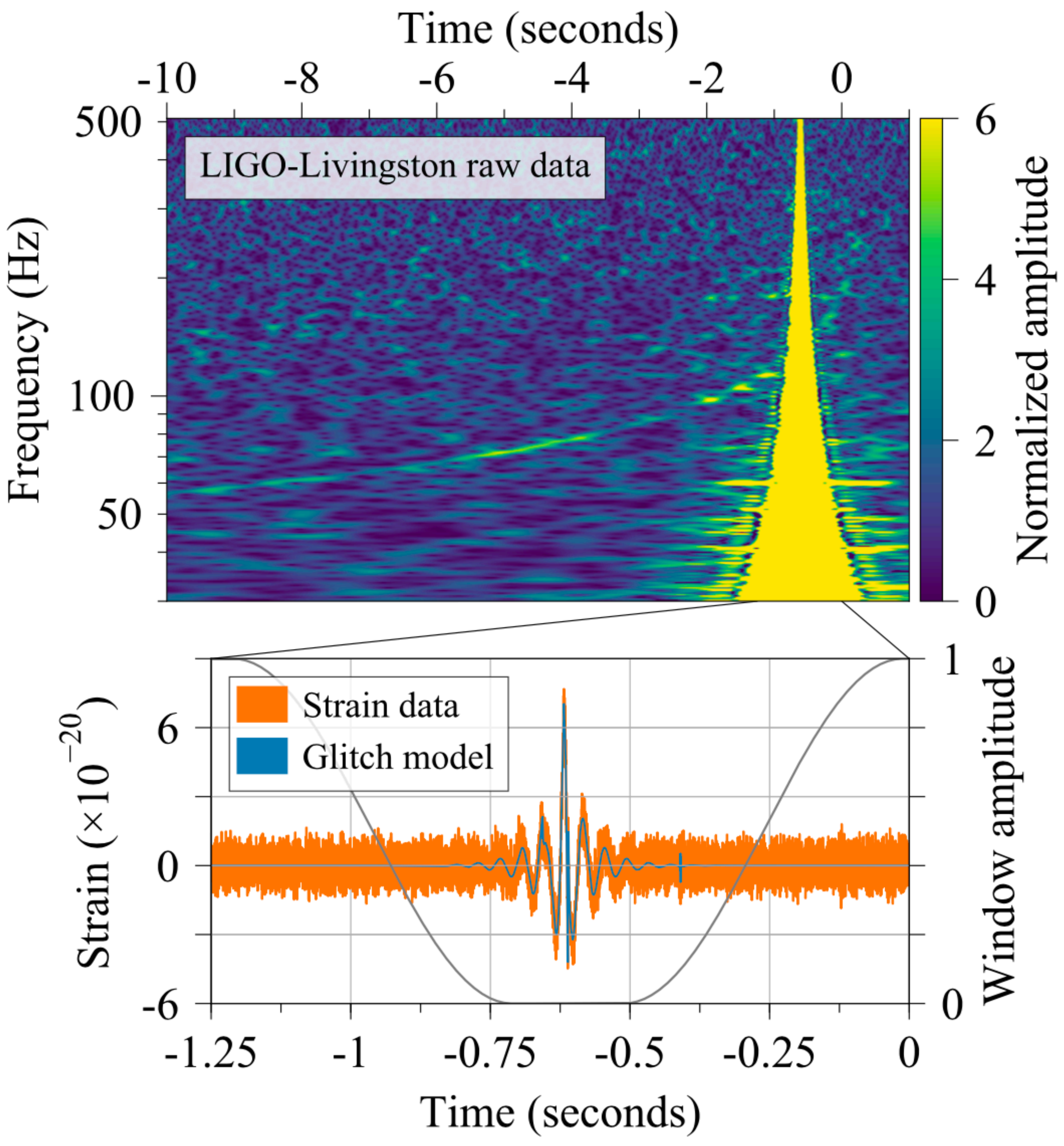
LVK Collaboration, arXiv 2112.06861 [gr-qc]



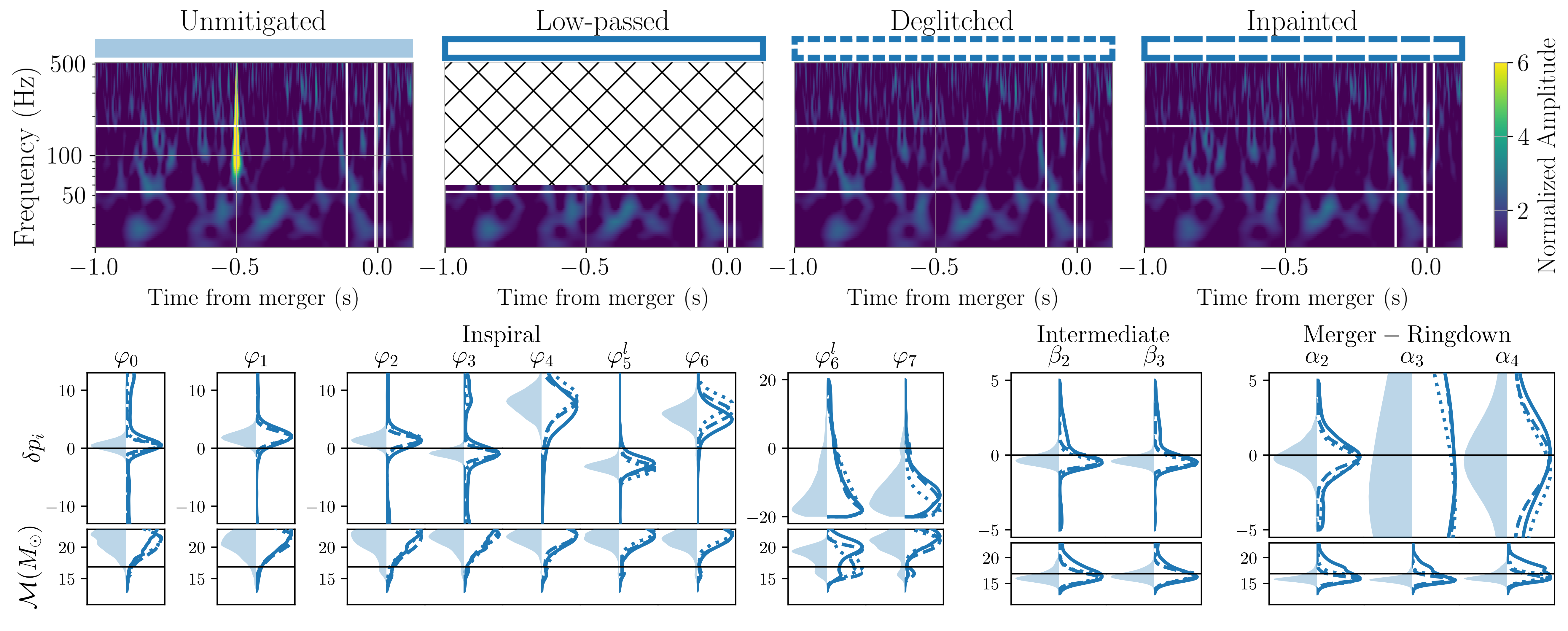
Practical challenges in TGR: a recap

- Phenomenological parametrization chosen to describe beyond-GR effects and its degeneracies to source parameters
- Non-trivial choice of priors for theory-agnostic models
- Gaussian noise fluctuations expected to impact a fraction of the events: different combination methods might be less/more sensitive to this
- For template-based tests, missing physics might also mimic GR violations .
- Detector data can be affected by glitches which can mimic deviations from GR
    - Kwok et al. arXiv:2109.07642v3 studied the effect of glitches and mitigated glitches on tests of GR, by injecting PhenomPv2 waveforms into H1-L1-V1 at times when all three detectors are operating and a glitch is affecting either H1 or L1

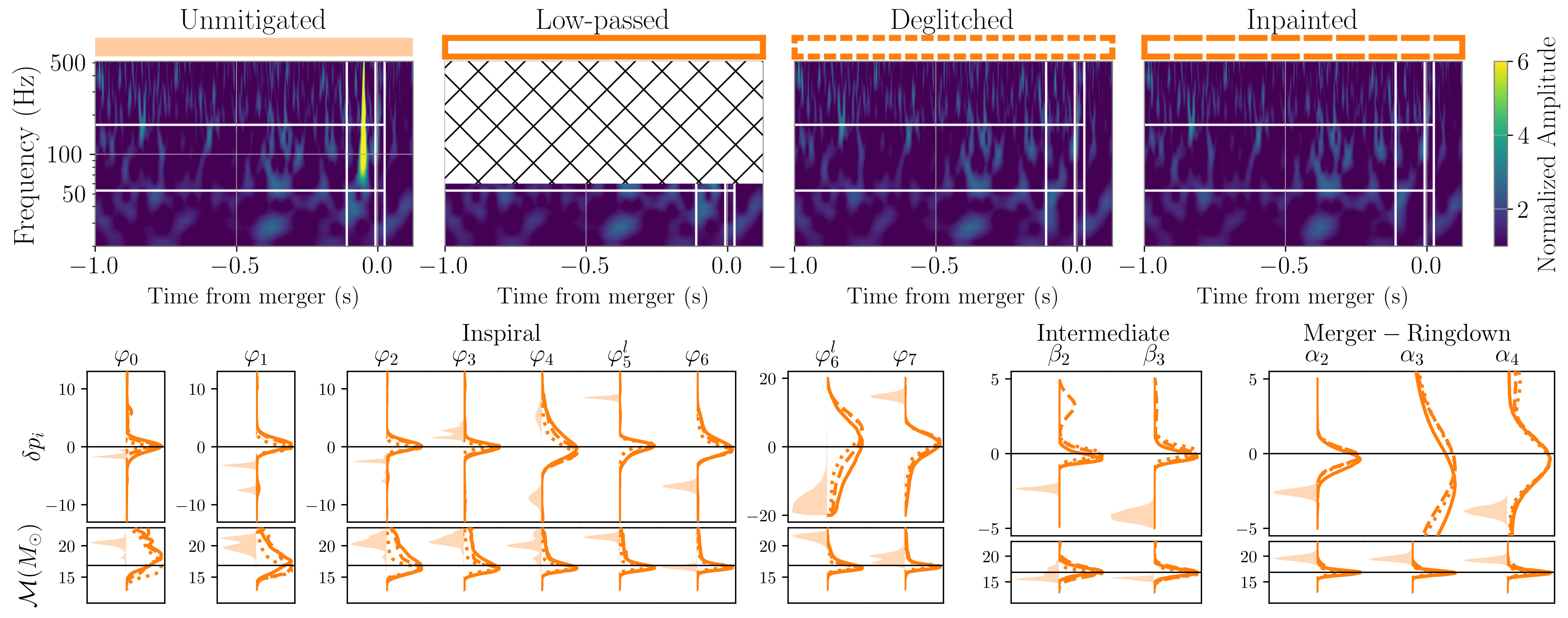
What if there is a glitch?



The blip glitch affecting L1 data for GW170817.
From: LIGO-Virgo 119 161101 (2017)



(a) Simulated GW190828_065509-like signal overlapped with a H1 blip glitch at inspiral stage in the time domain.



(b) Simulated GW190828_065509-like signal overlapped with a H1 blip glitch at intermediate stage in the time domain.

From: Kwok+ arXiv:2109.07642v3

Conclusions

- Current 2G detectors: training camp for tests of GR.
- Many subtleties which need to be addressed before more sensitive instruments become operational, which will drastically reduce statistical uncertainties.
- Further work on GR templates is required to allow unbiased tests based on them!
- Template banks of beyond-GR waveforms: a great tool to cross-check theory-agnostic results.