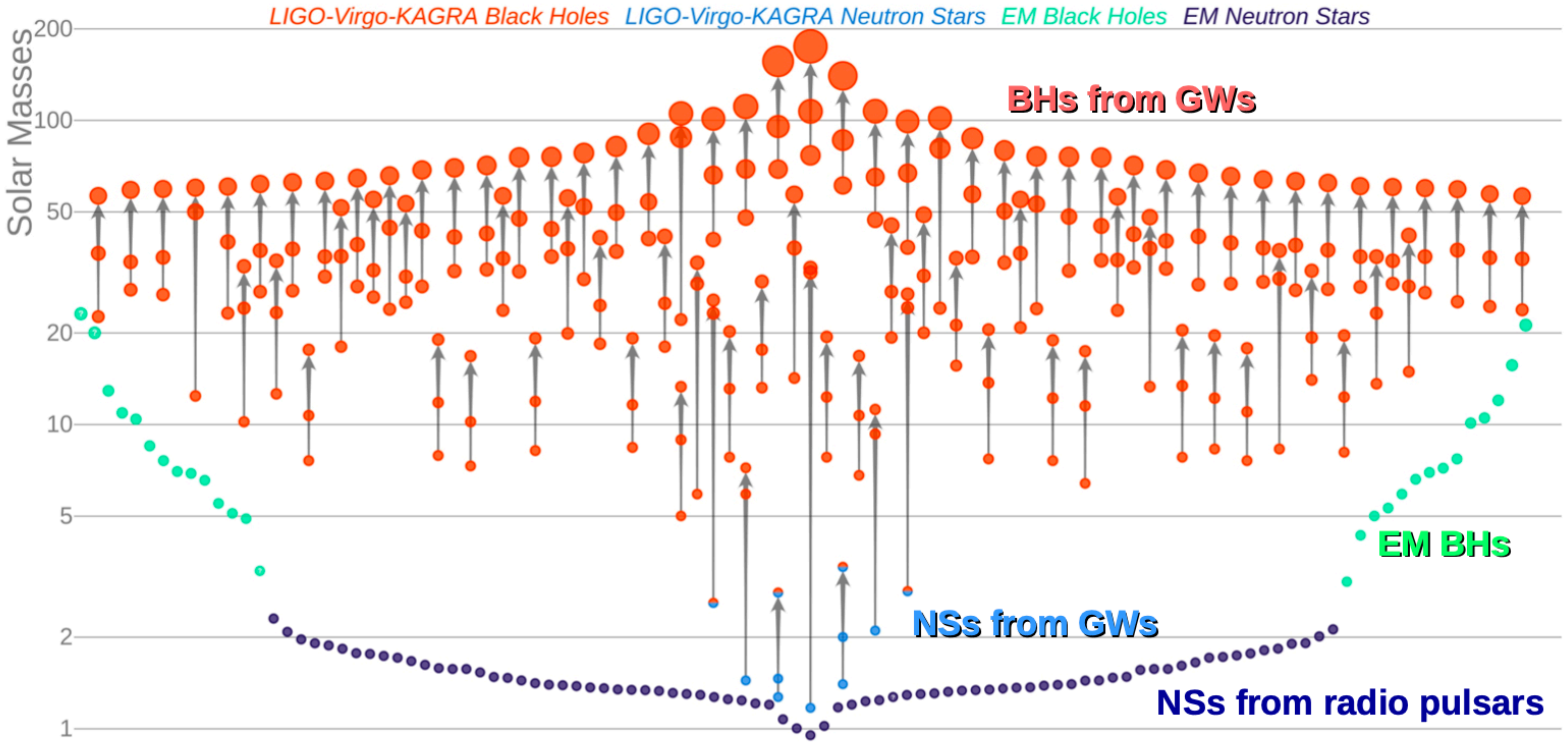
Fundamental physics with gravitational waves observations

Walter Del Pozzo

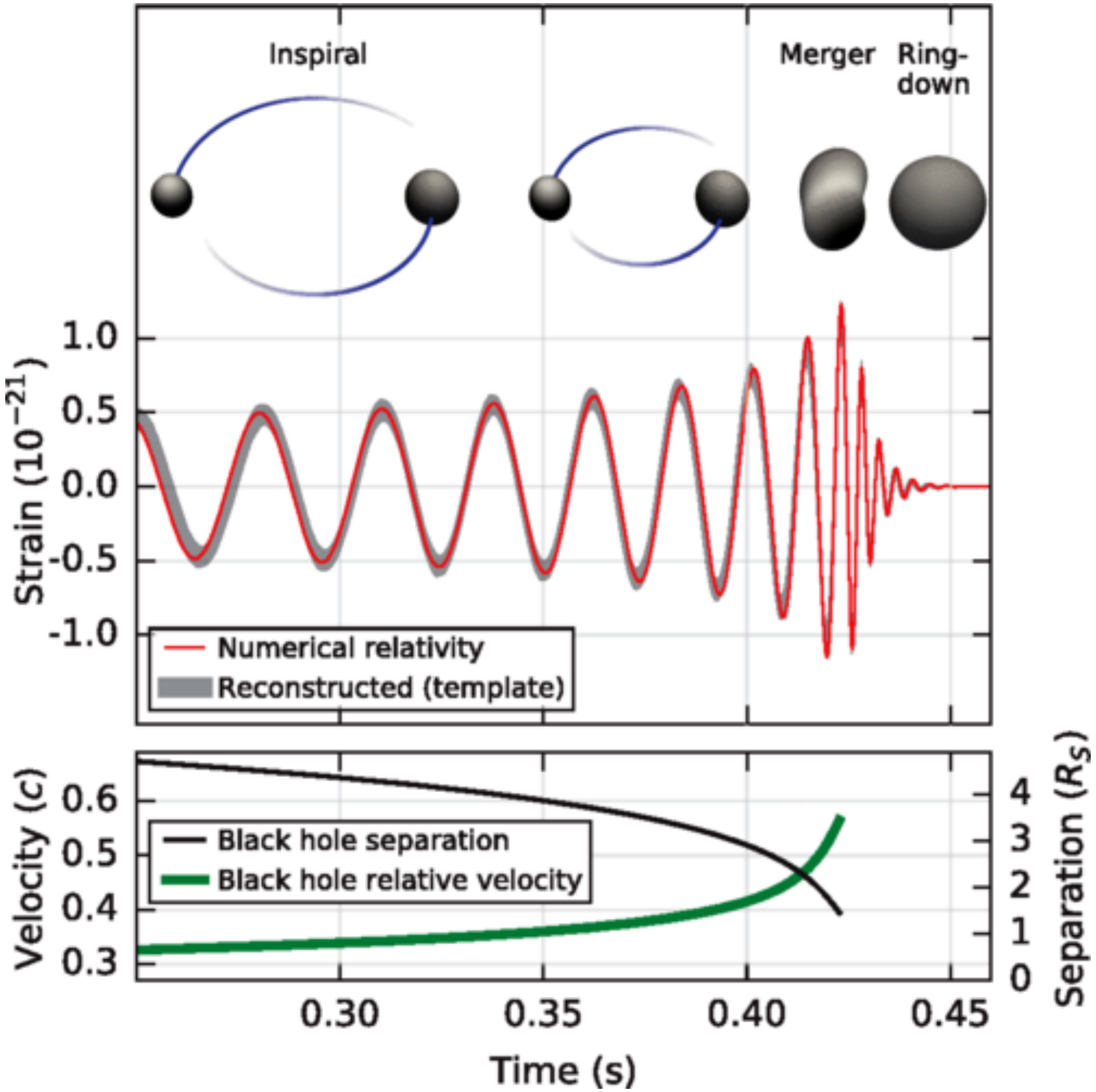
The GW Universe



credit: LIGO-Virgo-KAGRA | A. Geller | Northwestern

Fundamental aspects of GW physics

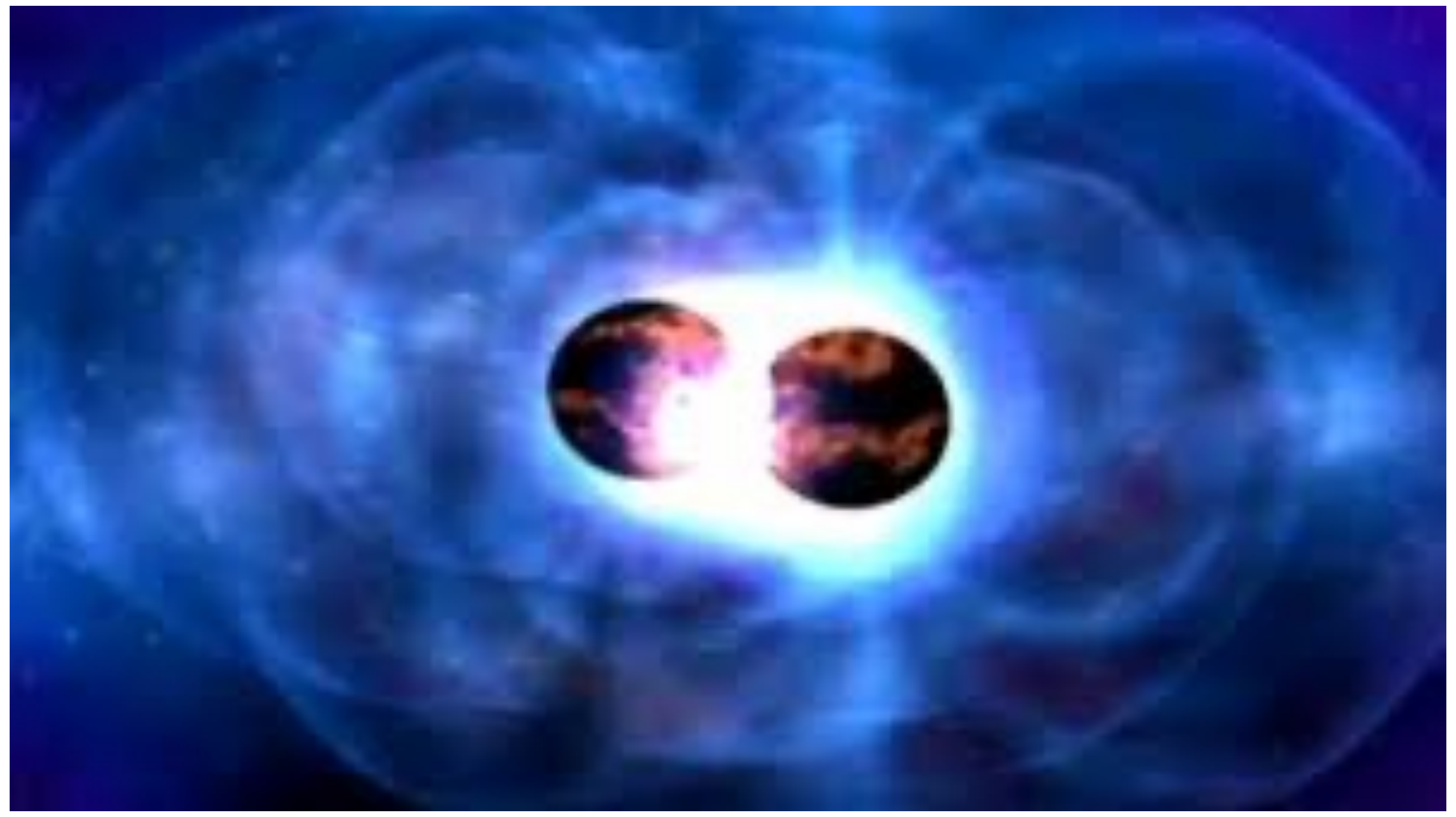
- In GR, gravitational waves (GW) are wave solutions to Einstein's equations generated from time varying mass quadrupoles and propagating at the speed of light
- Shape of GW signal carries information about
    - binary dynamics and component nature
    - non-linear dynamics of space-time
    - final object nature



LVC, arXiv:1602.03837

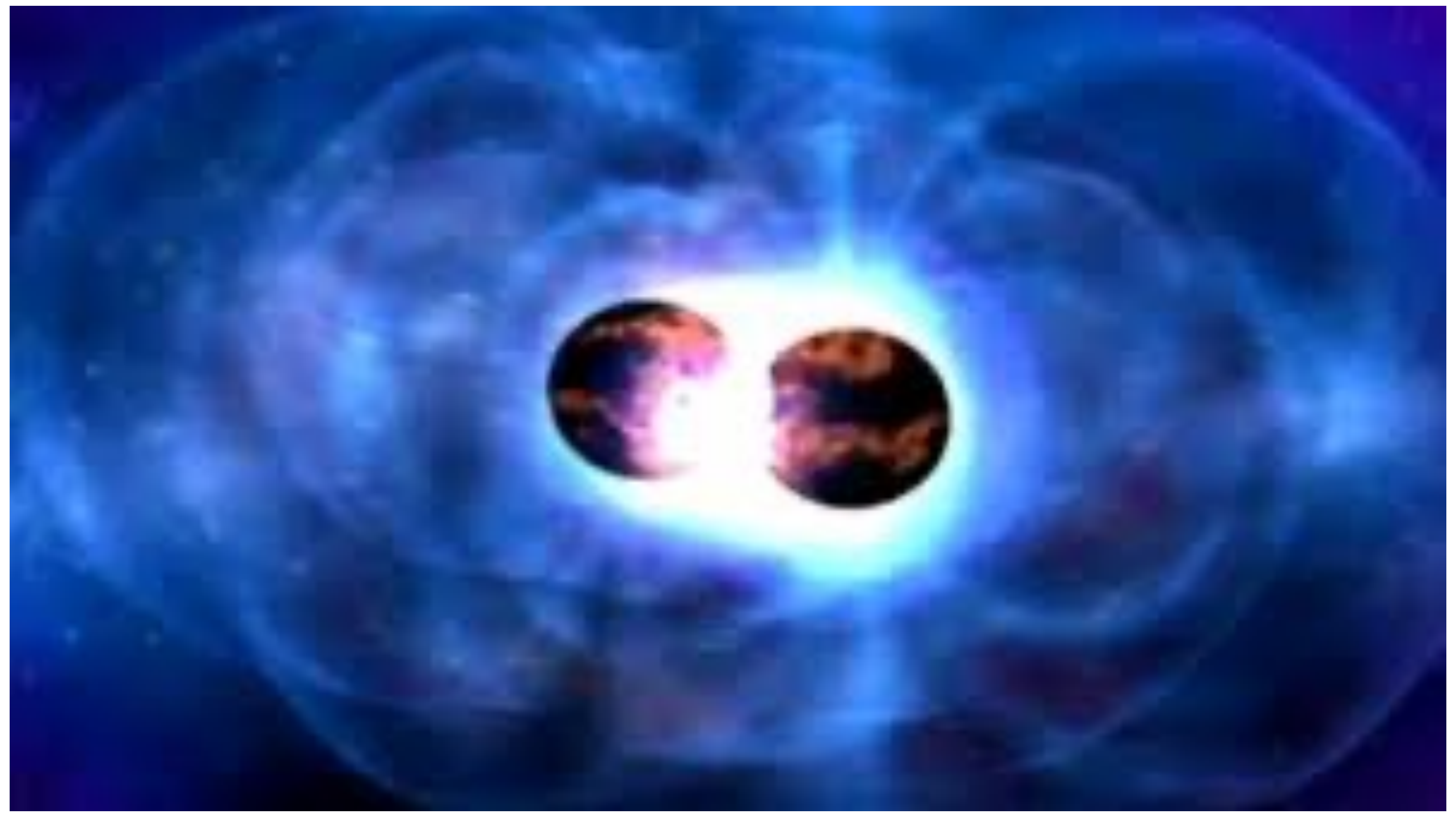
What physics can be probed

- Matching observed data with a solution to Einstein's equations allows to probe
  - Laws of space-time dynamics
  - Nature of black holes
  - Equation of state of neutron stars
  - Cosmology



What physics can be probed

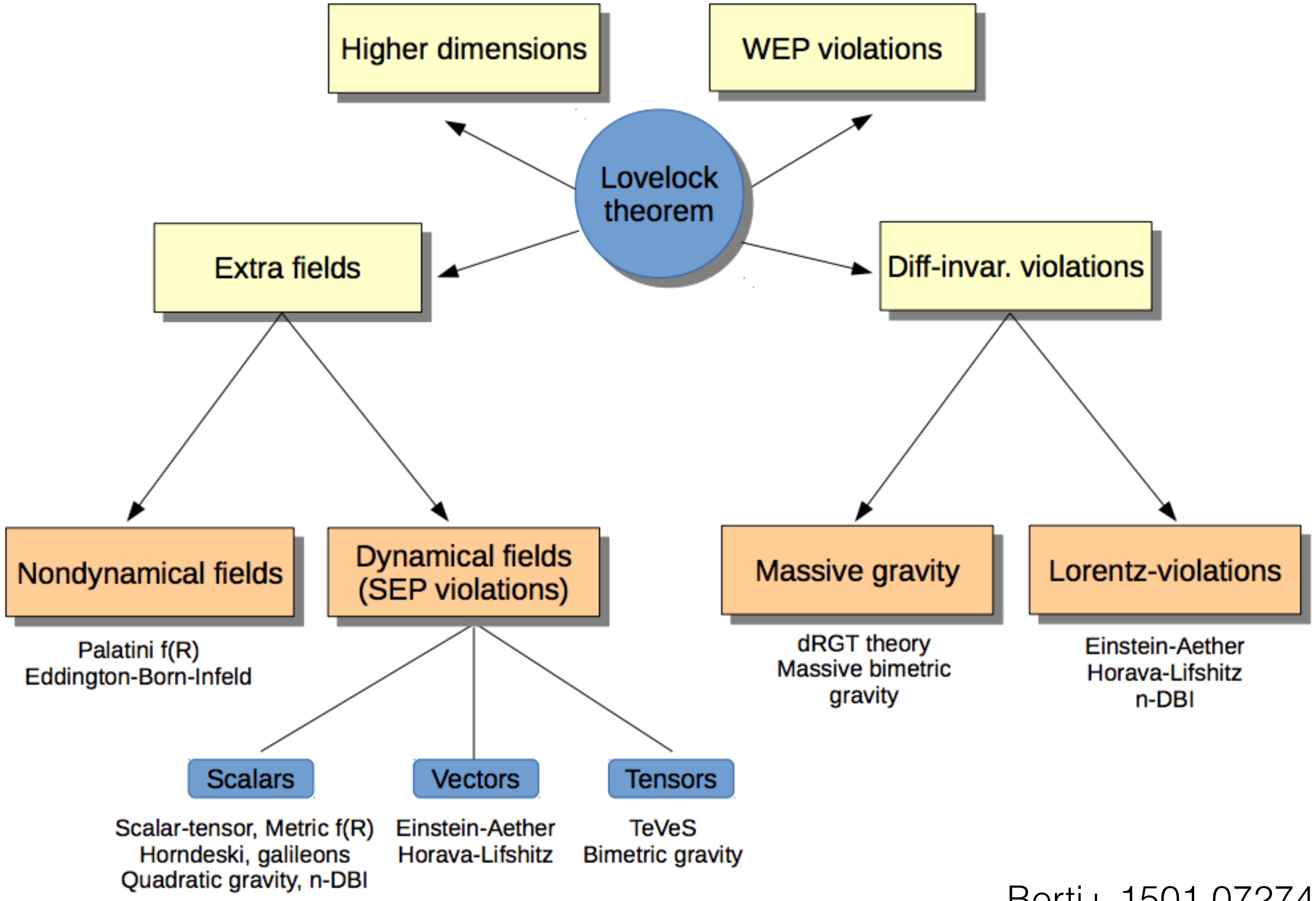
- Matching observed data with a solution to Einstein's equations allows to probe
  - Laws of space-time dynamics
  - Nature of black holes
  - Equation of state of neutron stars
  - Cosmology



Extensions of GR

- Alternative theories
  - Introduce extra degrees of freedom:
    - additional fields
    - higher-curvature terms
  - Challenge GR assumptions:
    - Lorentz invariance
    - Equivalence principle
- Need tests in the strong-field

Lovelock theorem: In 4D, the only divergence free symmetric rank-2 tensor constructed only by the metric and its derivatives up to 2nd order and preserving diffeomorphism invariance is the Einstein tensor plus a constant.

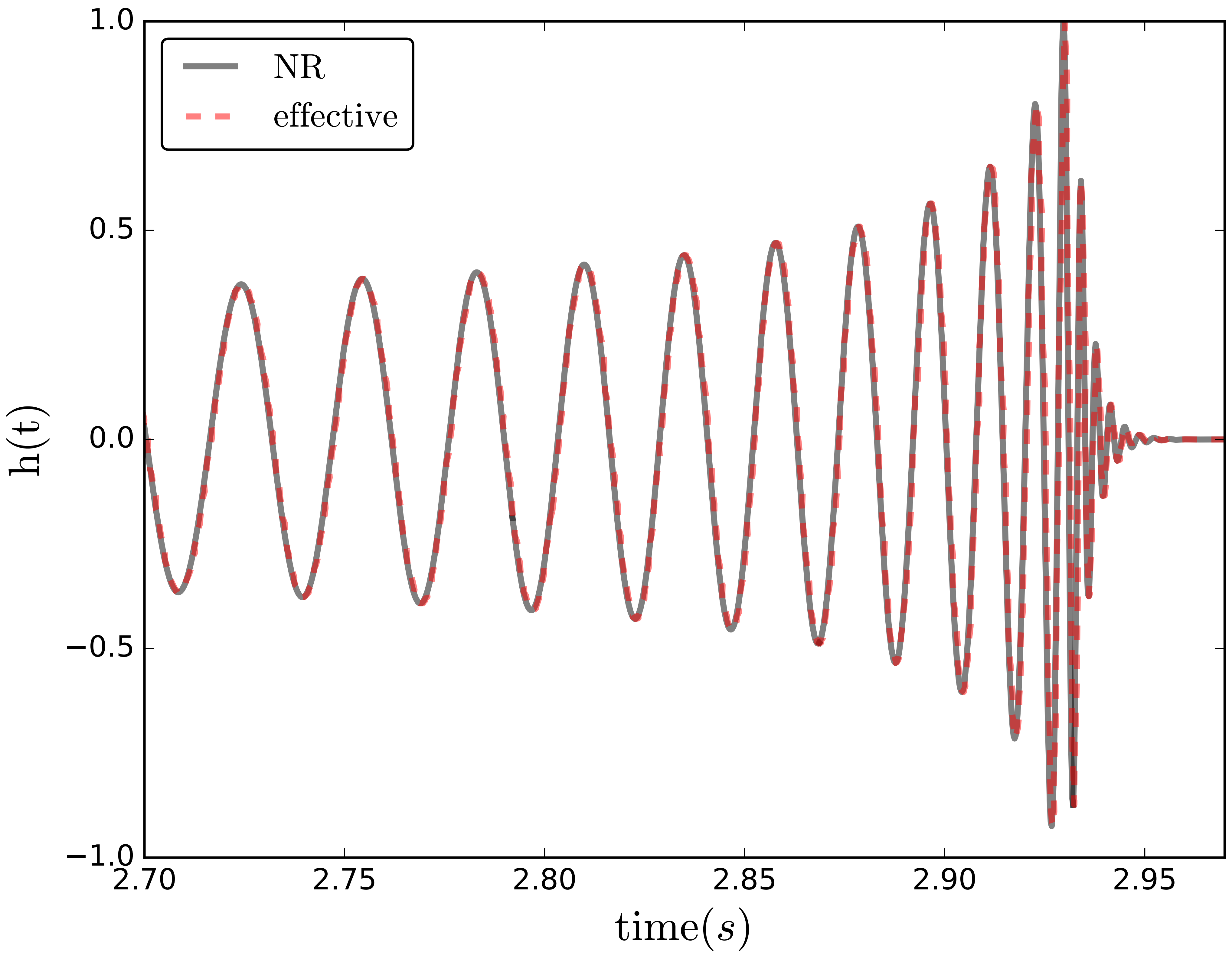


Berti+,1501.07274

GW templates in GR

- Analytical, parametric description of GW solutions in GR (Pratten et al, arXiv:2004.06503, Ossokine et al, arXiv:2004.09442, Varma et al, arXiv:1905.09300, Nagar et al, arXiv:1806.01772 and many more)

- Suitable for detection, parameter estimation and parametric tests of general relativity



GW in alternative gravity

- Alternative to GR can introduce extra-fields, curvature terms, challenge GR pillars, …
- Almost no full solution in non-GR known (but see Okounkova et al, arXiv:1705.07924)
- GW phase is modified:
    - non-GR action (extra fields, higher curvature, …): no full non-linear description, only post-Newtonian
    - Propagation (Lorentz violations, graviton mass, …): GR-like BBH dynamics, but modified GW propagation
    - non-GR BHs (extra-fields, exotic objects):
        - Anomalous quadrupole moments
        - ringdown spectrum
        - Echoes

The LVK approach

- Multitude of potential extensions
- Modelling limitations imply agnosticism, we know GR
    - overall and self-consistency checks
    - perturb around the GR expectation and let the data speak
    - GW generation, propagation and polarizations, BH ringdown hypothesis, post-merger echoes

Event	Tests performed							
	RT	IMR	PAR	SIM	MDR	POL	RD	ECH
GW191109_010717	✓	–	–	–	–	✓	✓	✓
GW191129_134029	✓	–	✓	✓	✓	–	–	✓
GW191204_171526	✓	–	✓	✓	✓	✓	–	✓
GW191215_223052	✓	–	–	–	✓	✓	–	✓
GW191216_213338	✓	–	✓	✓	✓	✓	–	✓
GW191222_033537	✓	–	–	–	✓	✓	✓	✓
GW200115_042309	✓	–	✓	–	–	–	–	✓
GW200129_065458	✓	✓	✓	✓	✓	✓	✓	✓
GW200202_154313	✓	–	✓	–	✓	–	–	✓
GW200208_130117	✓	✓	–	–	✓	✓	–	✓
GW200219_094415	✓	–	–	–	✓	✓	–	✓
GW200224_222234	✓	✓	–	–	✓	✓	✓	✓
GW200225_060421	✓	✓	✓	✓	✓	✓	–	✓
GW200311_115853	✓	✓	✓	–	✓	✓	✓	✓
GW200316_215756	✓	–	✓	✓	–	–	–	✓

LVK, arXiv:2112.06861

Residuals - GWTC-3

- After subtraction of the best fit GR waveform, the residuals must be consistent with Gaussian noise

$$p(residuals) \sim p(n)$$

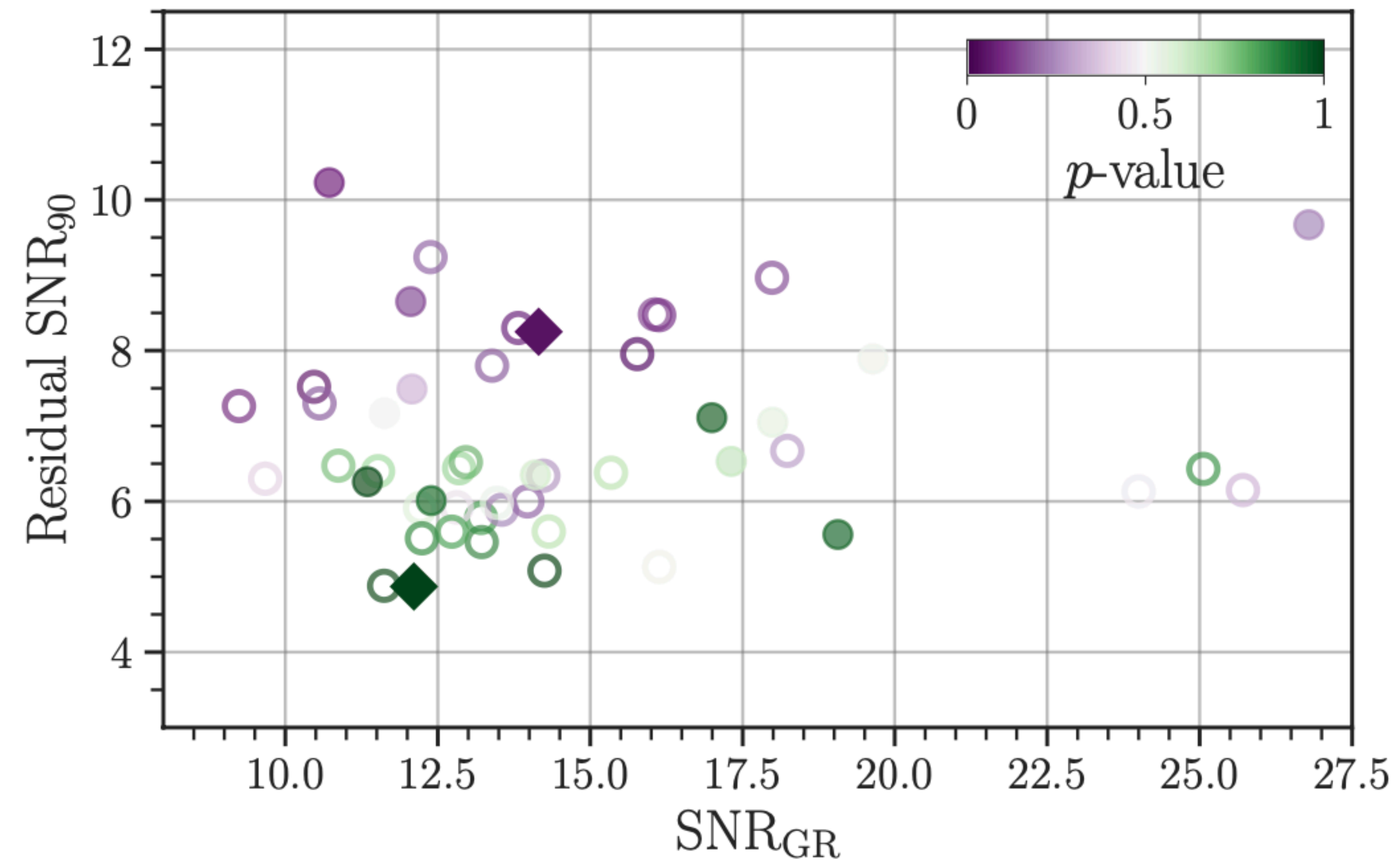
- Use BayesWave (Cornish & Littenberg, arXiv:1410.3835) to search for coherent power in the residuals

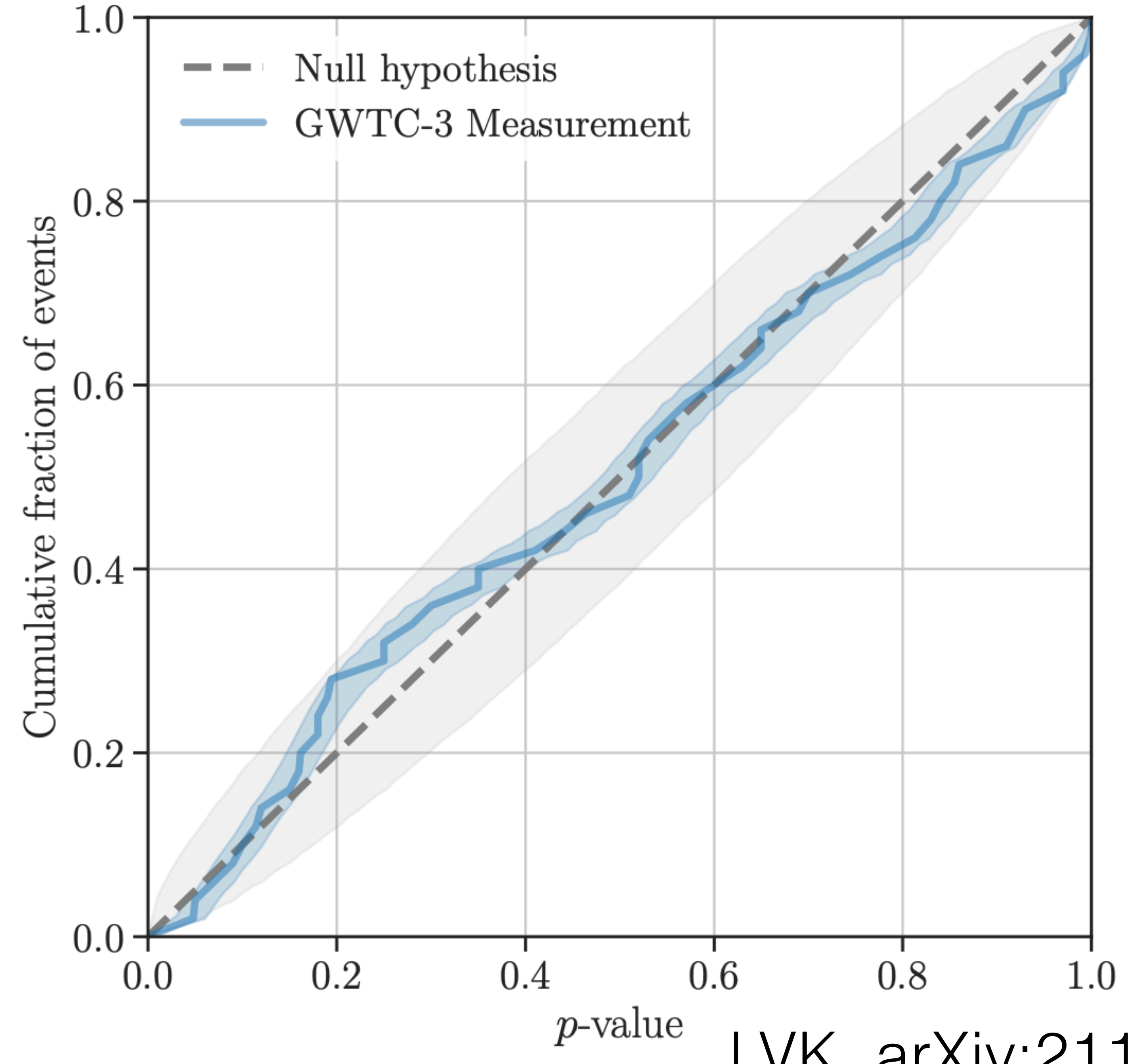
- Residual SNR gives the fitting factor $$FF = \sqrt{\frac{SNR^2_{det}}{SNR^2_{det} + SNR^2_{res}}}$$

- Match between GW150914 and the best GR template > 96%

- Analysis repeated for all GWTC-3 events

- No violation of GR observed

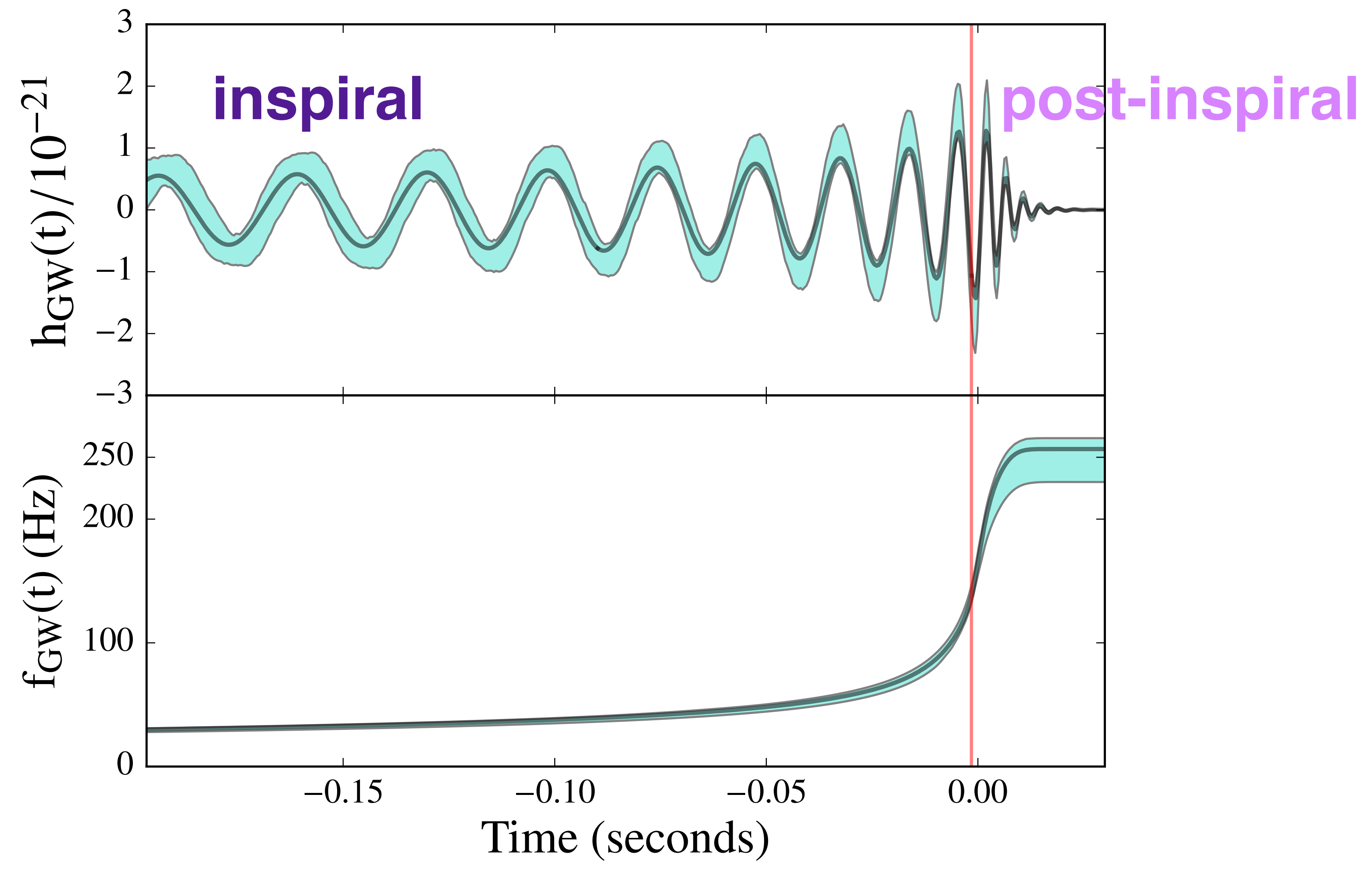


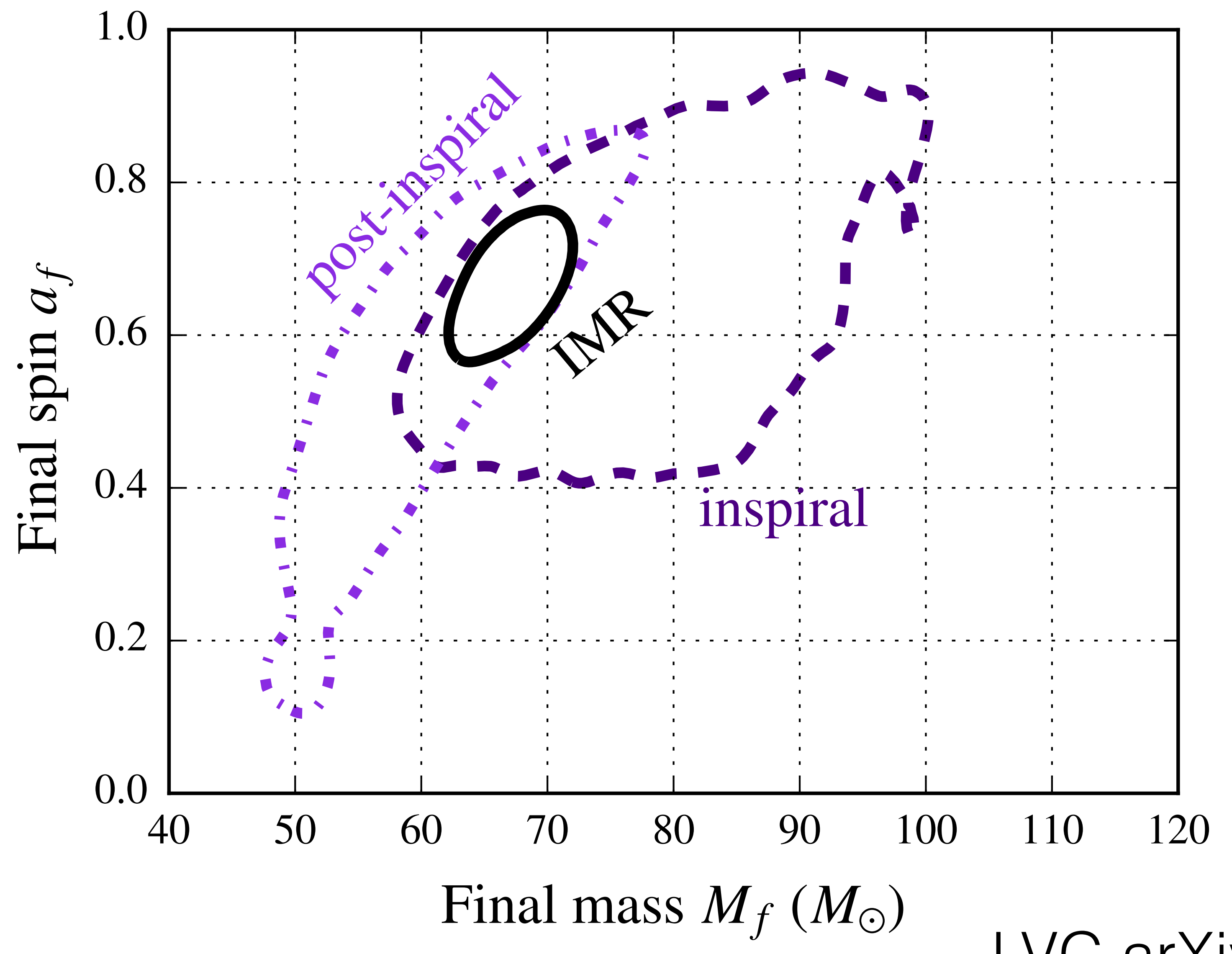


LVK, arXiv:2112.06861

Waveform self-consistency

- Waveform models are (approximate) solutions to GR
- Split waveform in two:
  - Early stage (inspiral): predict final mass and spin predicted using NR
  - Late stage (post-inspiral): measure final mass and spin
- Inspiral-Merger-Ringdown consistency test (IMRCT)(Ghosh et al, 2016)





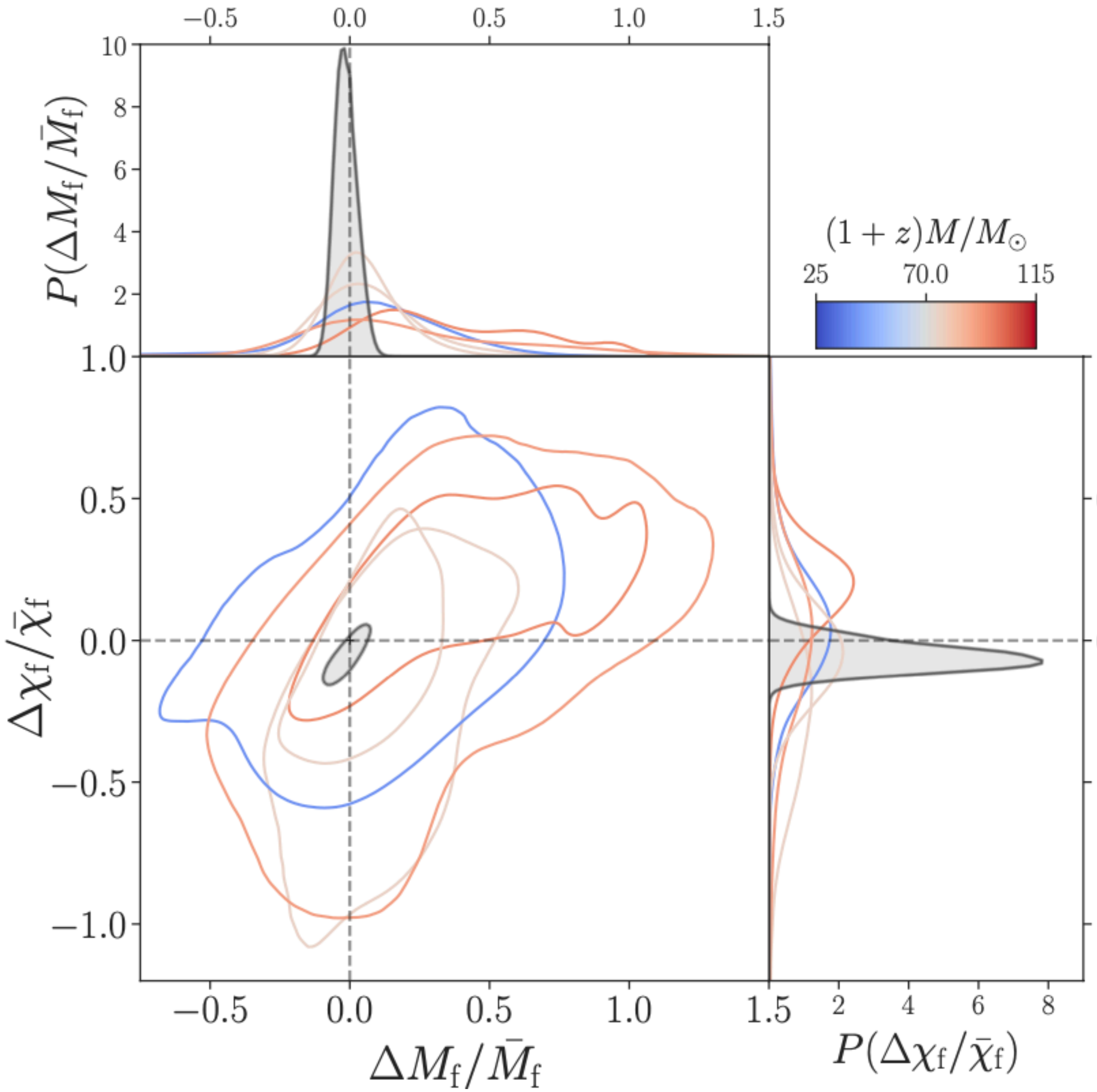
LVC,arXiv:1602.03841

IMRCT in GWTC-3

- Distribution of relative differences should be centred on 0

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

- No violation of GR observed



LVK, arXiv:2112.06861

Parametrised tests of GR

- GW waveforms are expressed in terms of effective series, for the Phenom family:

$$h(f;\theta) = A(f;\theta)e^{i\Phi(f;\theta)}$$

$$\Phi(f;\theta) = \sum_{k=0}^{7}(\varphi_k + \varphi_k^{(l)})f^{(k-5)/3} + \sum_{i\neq k}\varphi_i g(f)$$

post-Newtonian series — effective series

$$\varphi_j \equiv \varphi_j(m_1, m_2, \vec{s}_1, \vec{s}_2)$$

- Modified theories of gravity change the series (e.g. PPE: Yunes & Pretorius, arXiv:0909.3328, Cornish+,arXiv:1105.2088)

- Perturb the GW phase around GR (Li+,arXiv:1110.0530, Agathos+,arXiv:1311.0420)

$$\hat{\varphi}_j \equiv \varphi_j^{GR}(1 + \delta\hat{\varphi}_j) \qquad \delta\hat{\varphi}_j = 0 \iff \text{GR}$$

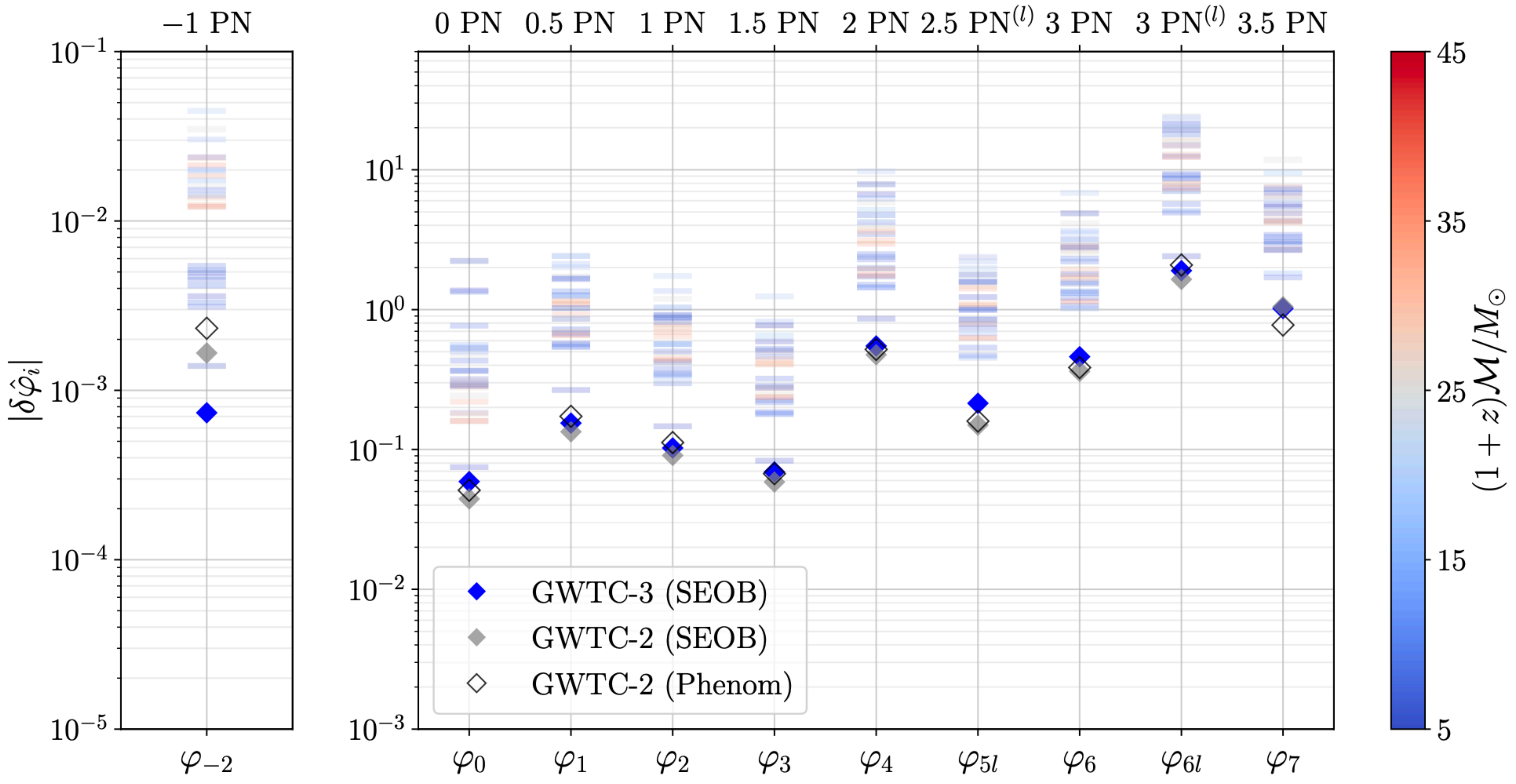
- Bound violations by computing posterior distributions for the $\delta\hat{\varphi}_j$ in concert with the physical parameters of the system

waveform regime	parameter	f−dependence	
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	post-Newtonian
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	
	$\delta\hat{\varphi}_2$	f^{-1}	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	effective
	$\delta\hat{\beta}_3$	f^{-3}	
merger–ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	
	$\delta\hat{\alpha}_3$	$f^{3/4}$	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af+b)$	

LVC, arXiv:1602.03841

Post-Newtonian constraints

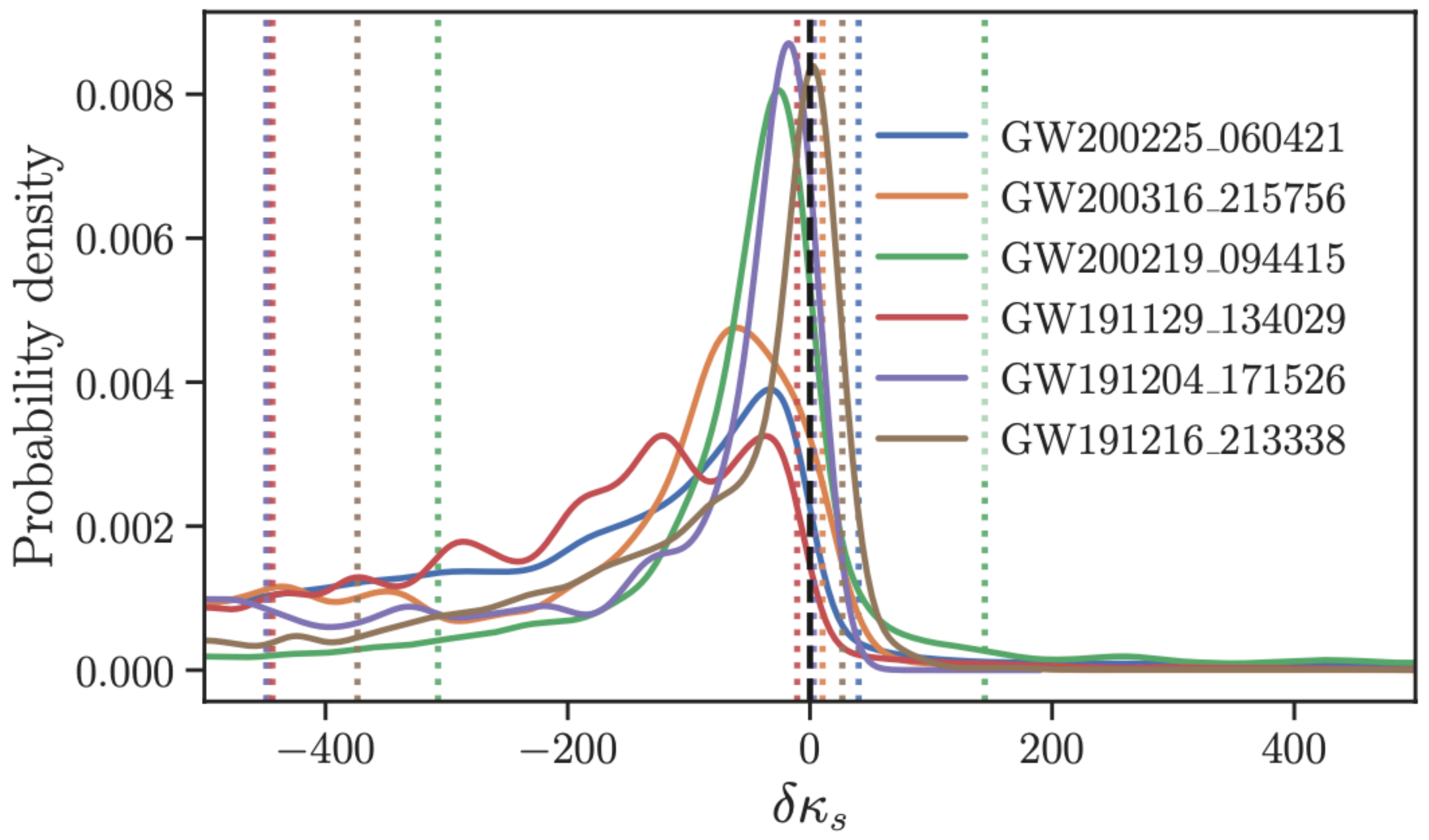
- Constraints on the space-time dynamics
- Can be mapped to the space of specific theories (e.g. Yunes+,arXiv:1603.08955)
- Posterior distributions for $\delta\varphi_i$ show no evidence for violations of GR
- Constraints better than 10% level on the 0PN and 1.5PN coefficients

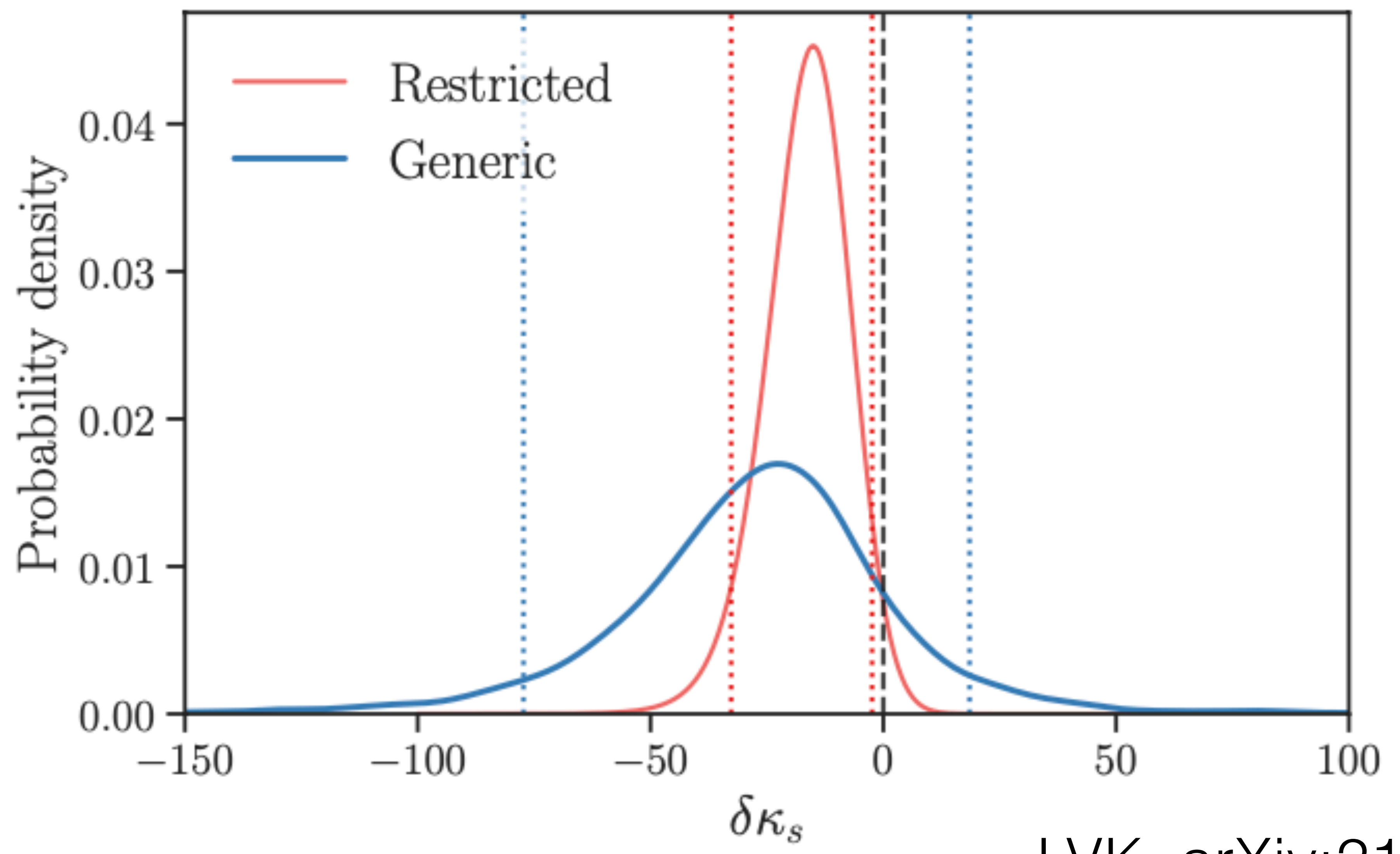


LVK, arXiv:2112.06861

Spin-induced quadrupole moment

- BH uniqueness implies than spin induced multipoles have a unique structure
- Leading order $Q = -\kappa a^2 m^3$, $\kappa = 1$ for Kerr
- Constraints on BH mimickers

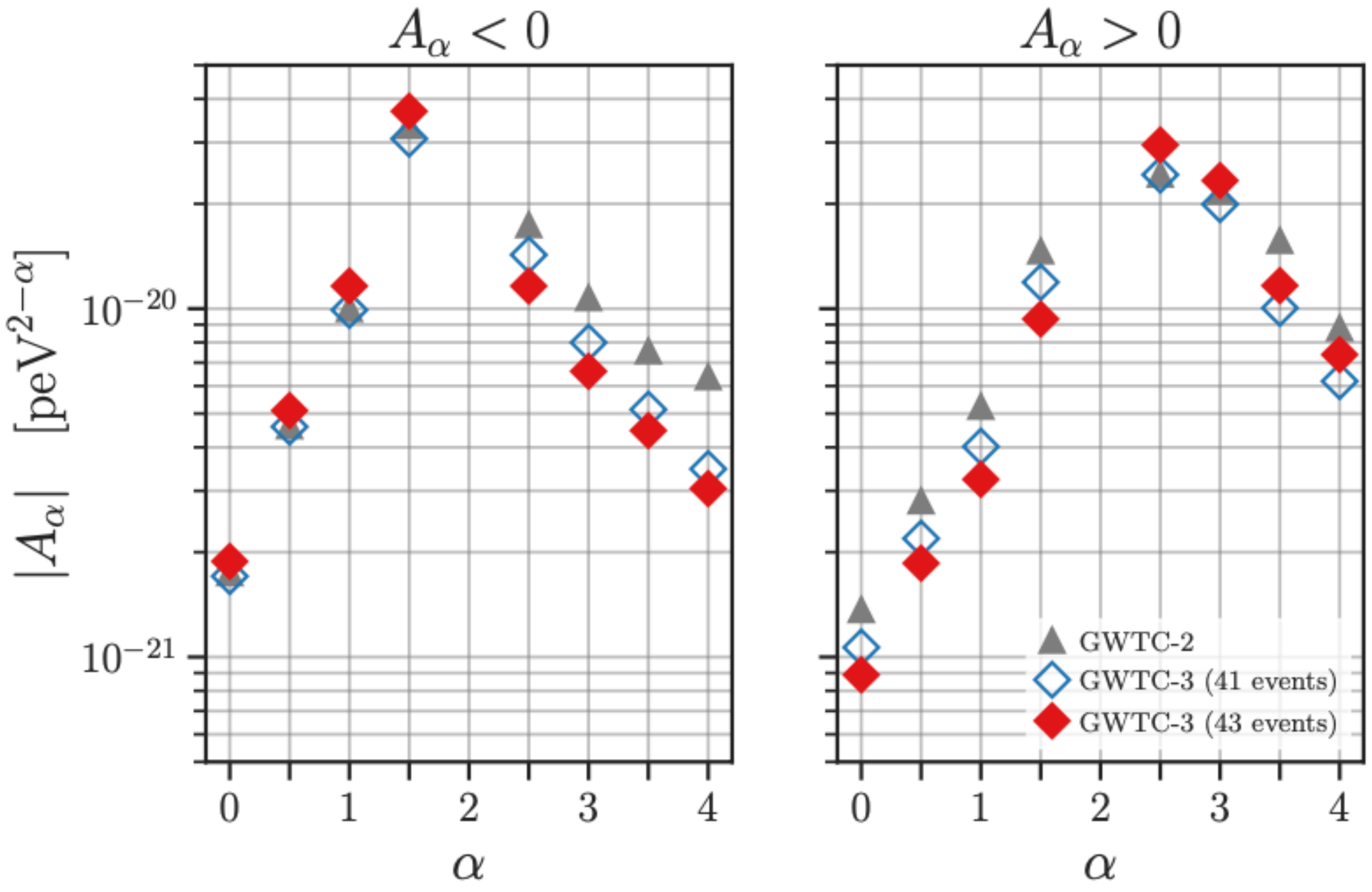




LVK, arXiv:2112.06861

Propagation tests

- GWs are non-dispersive
- Modifications to GR predict the opposite
- Parametrisation $E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$
- E.g. $\alpha = 0$, "massive graviton" with mass $m_g = \sqrt{A_0}$

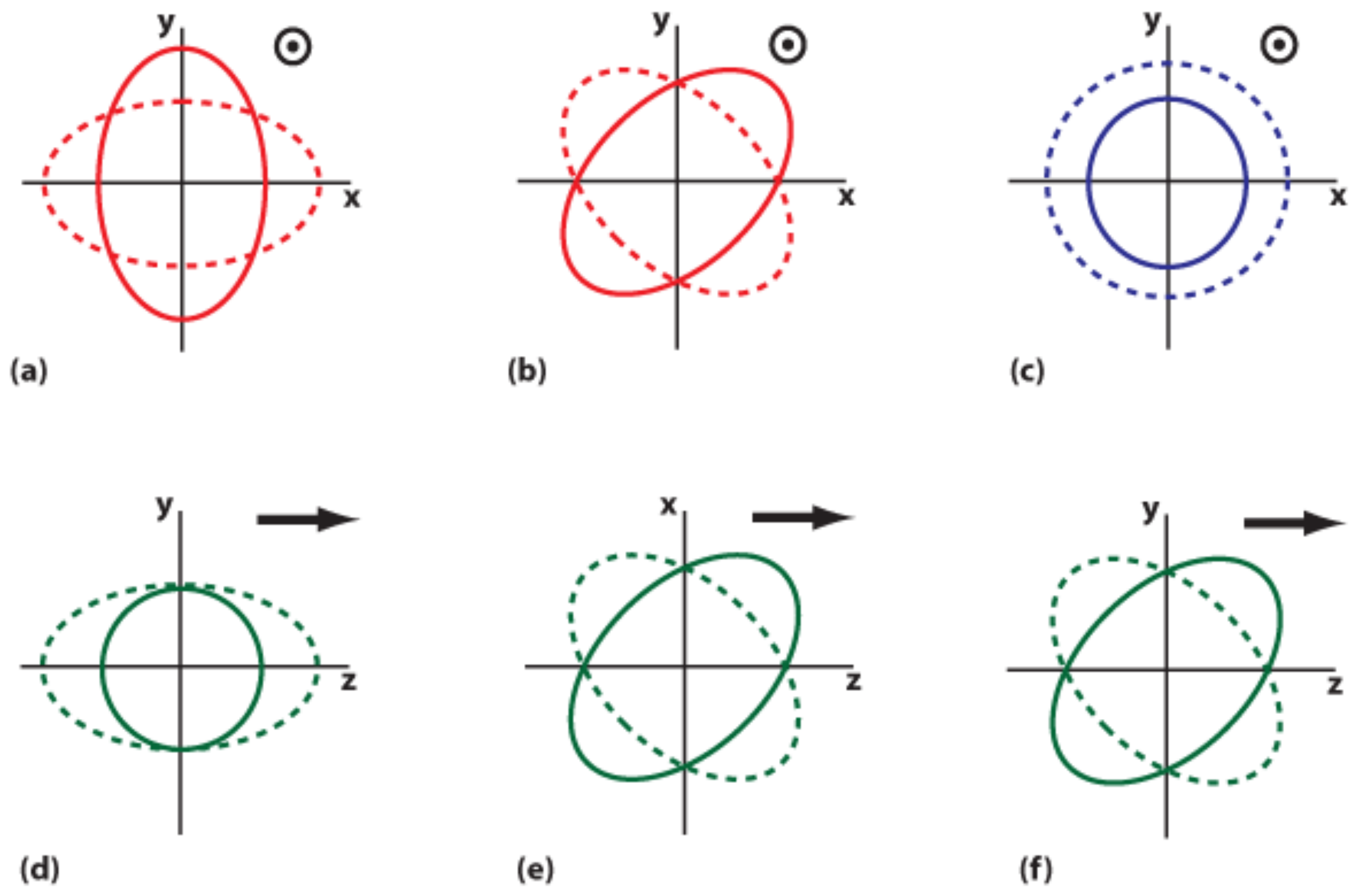


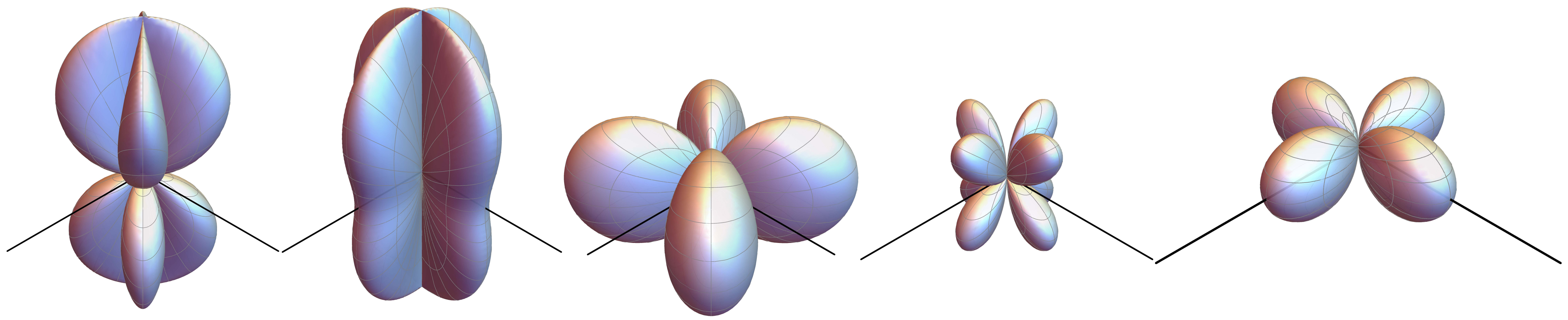
LVK, arXiv:2112.06861

Gravitational wave polarisation states

Will, arXiv:1403.7377

- Gravitational waves in general relativity are transverse, tensorial waves
- Extensions to general relativity predict up to six polarisation states
  - Two transverse tensor states
  - Two longitudinal vector states
  - Two scalar states, one longitudinal and one “breathing”
- No evidence for the presence of non-GR modes





Courtesy of Max Isi

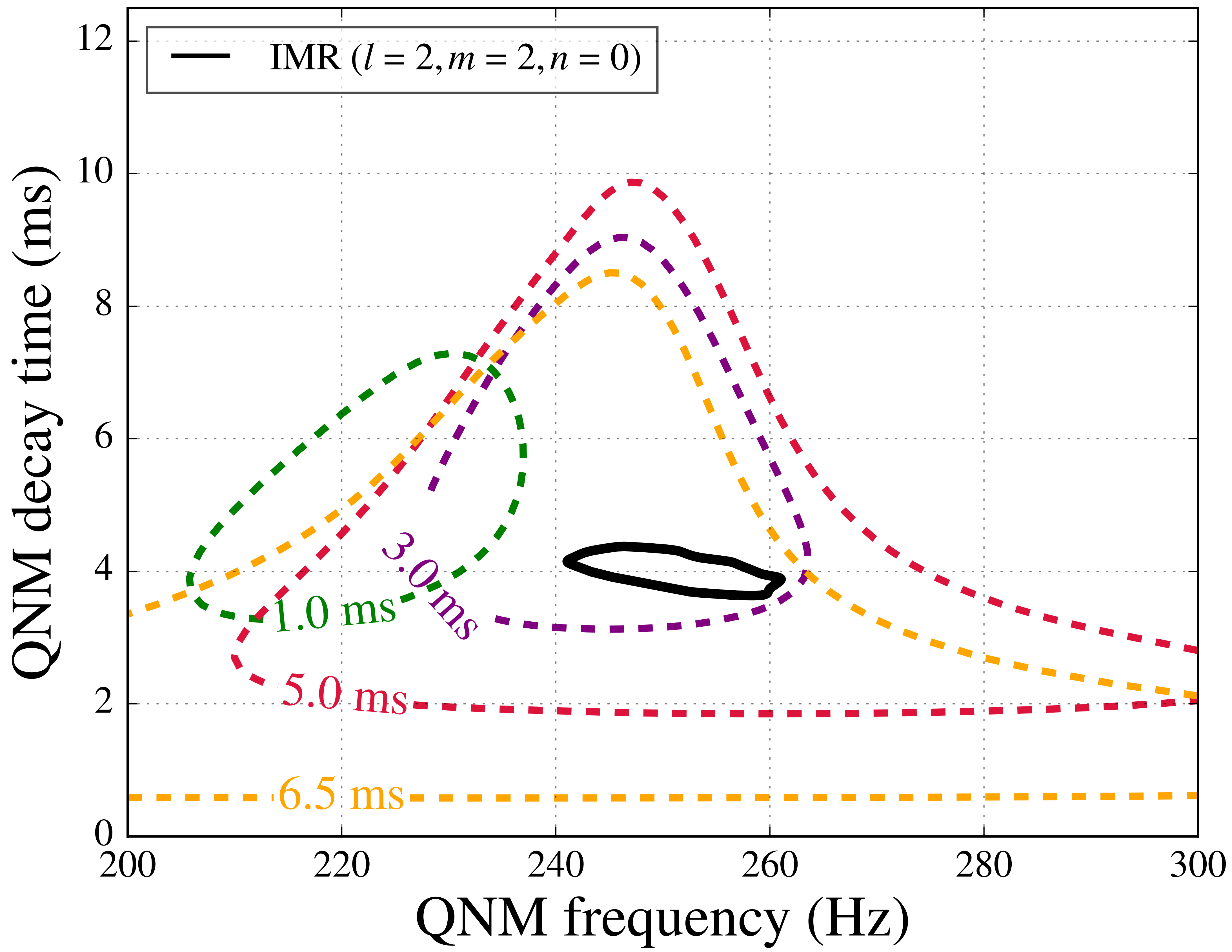
The nature of the final object

- BH perturbation theory predicts that BHs “vibrate”:

$$h(t) = \sum_{nlm} A_{nlm} e^{-\frac{t-t_0}{\tau_{nlm}}} \cos(\omega_{nlm}(t-t_0) + \varphi_{nlm})$$

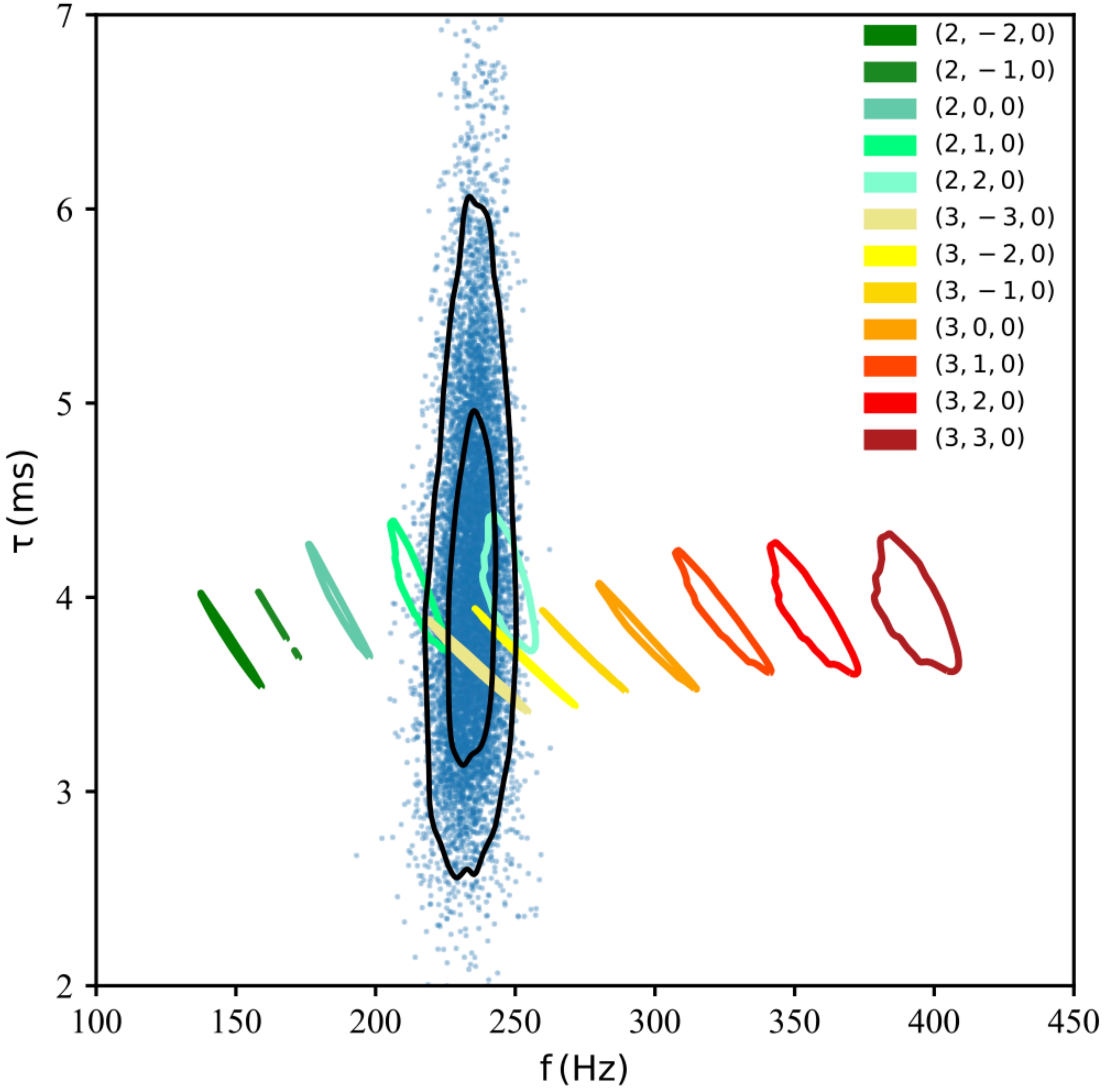
- Central frequencies ω_{nlm} and decay times τ_{nlm} are functions of BH mass and spin only (manifestation of the BH uniqueness hypothesis, Berti et al, arXiv:0512160)

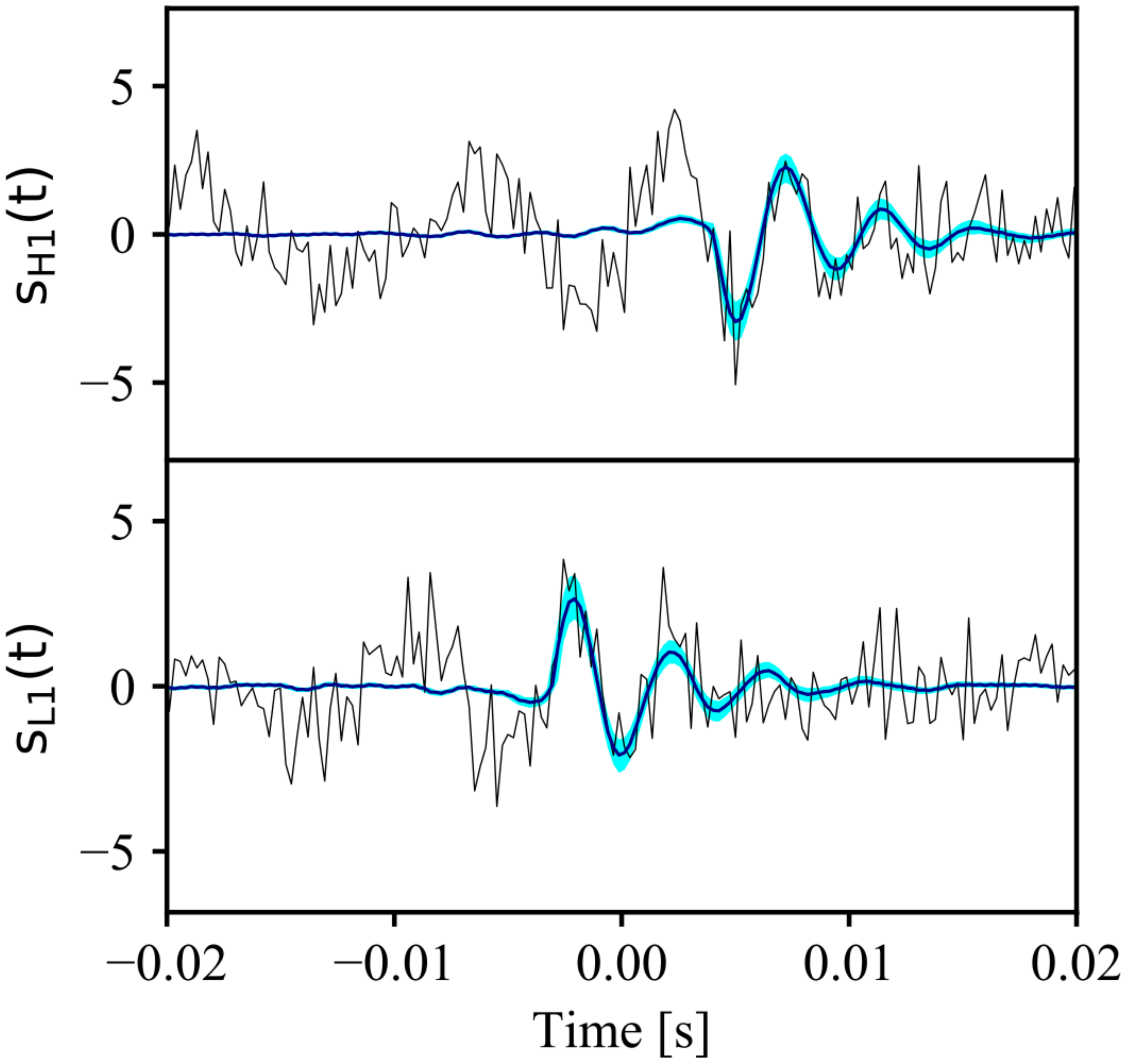
- First observation: GW150914



LVC,arXiv:1602.03841

Ringdown constraints: pyRing



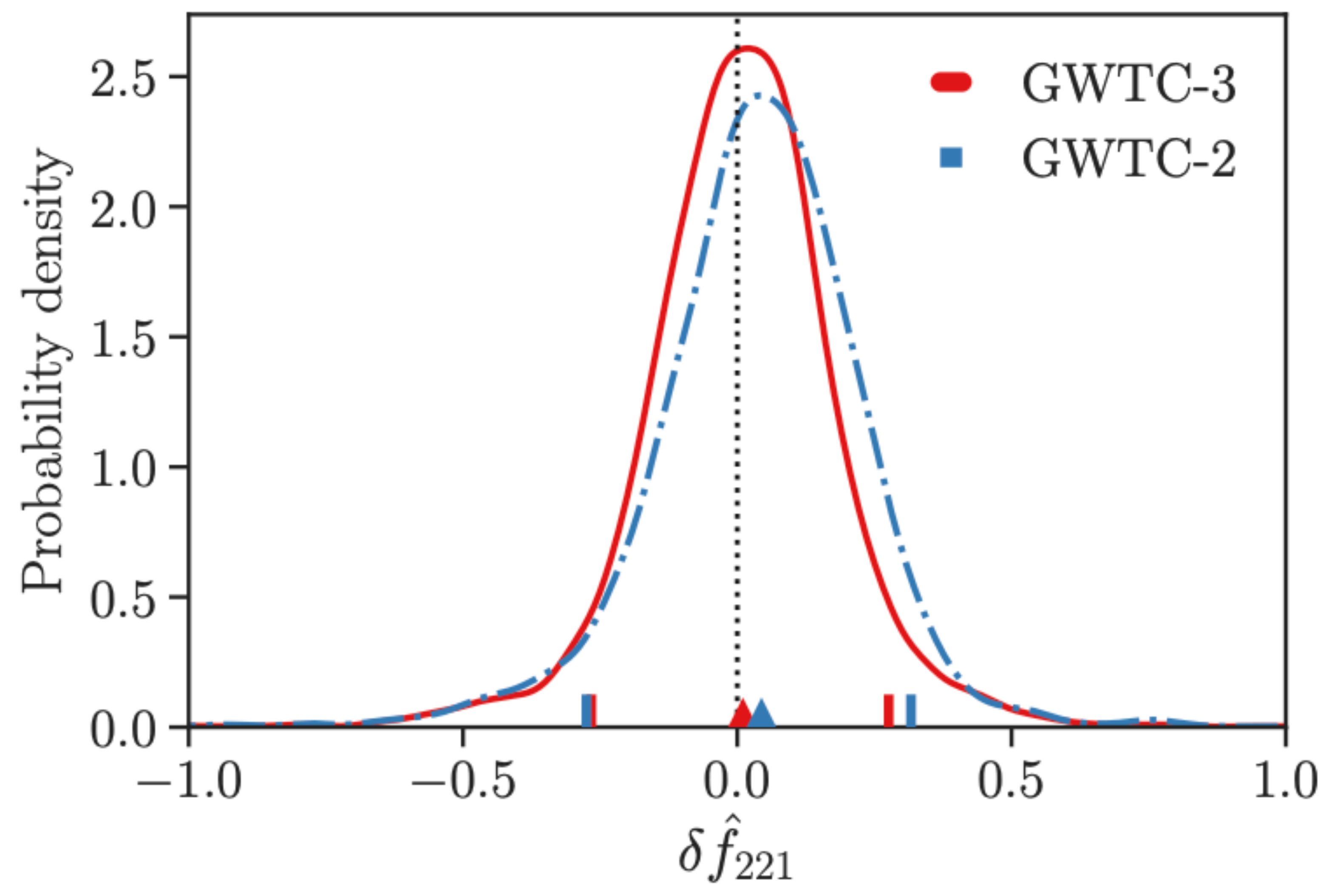


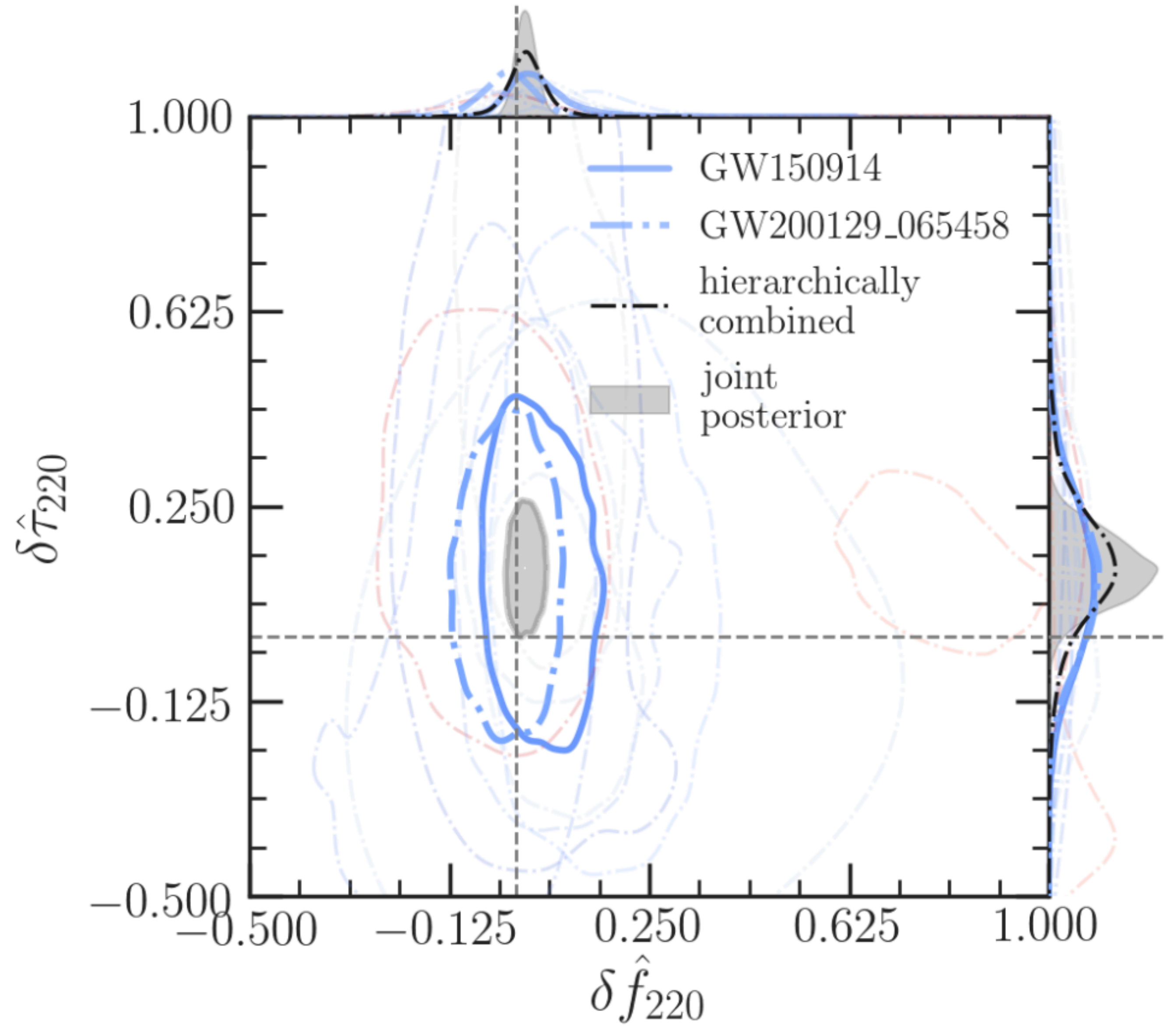
Carullo, Veitch, Del Pozzo, arXiv:1902.07527

GWTC-3 Ringdown

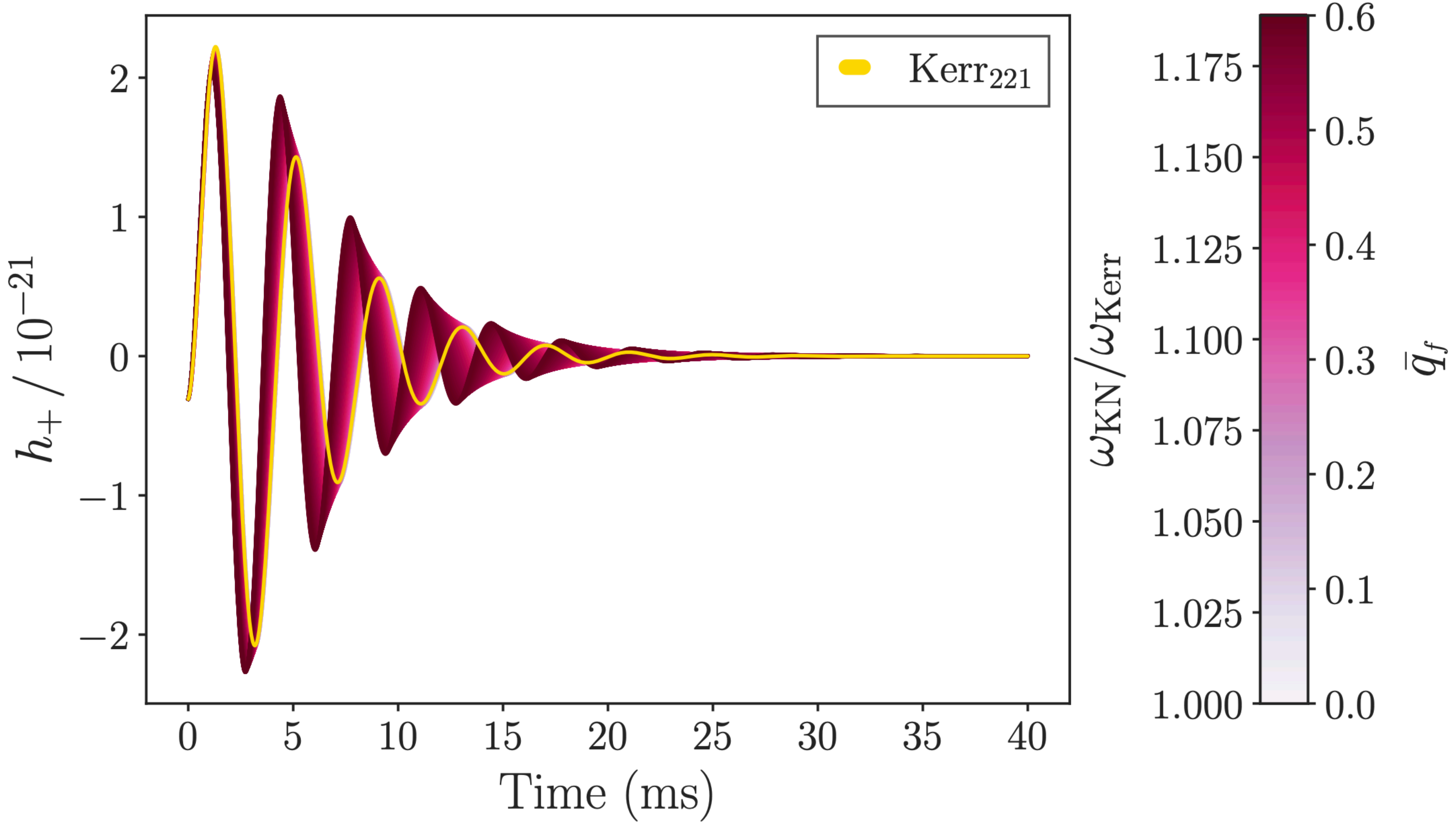
- Ringdown observed in several BBH remnants
  - pyRing (Carullo et al, arXiv:1902.07527): ringdown only time domain analysis
  - pSEOBNR (Ghosh et al, arXiv:2104.01906): modified SEOBNR waveform
- Independent determination of final parameters
- Tests of BH uniqueness

$$\log B_{GR,nGR} \sim 1$$



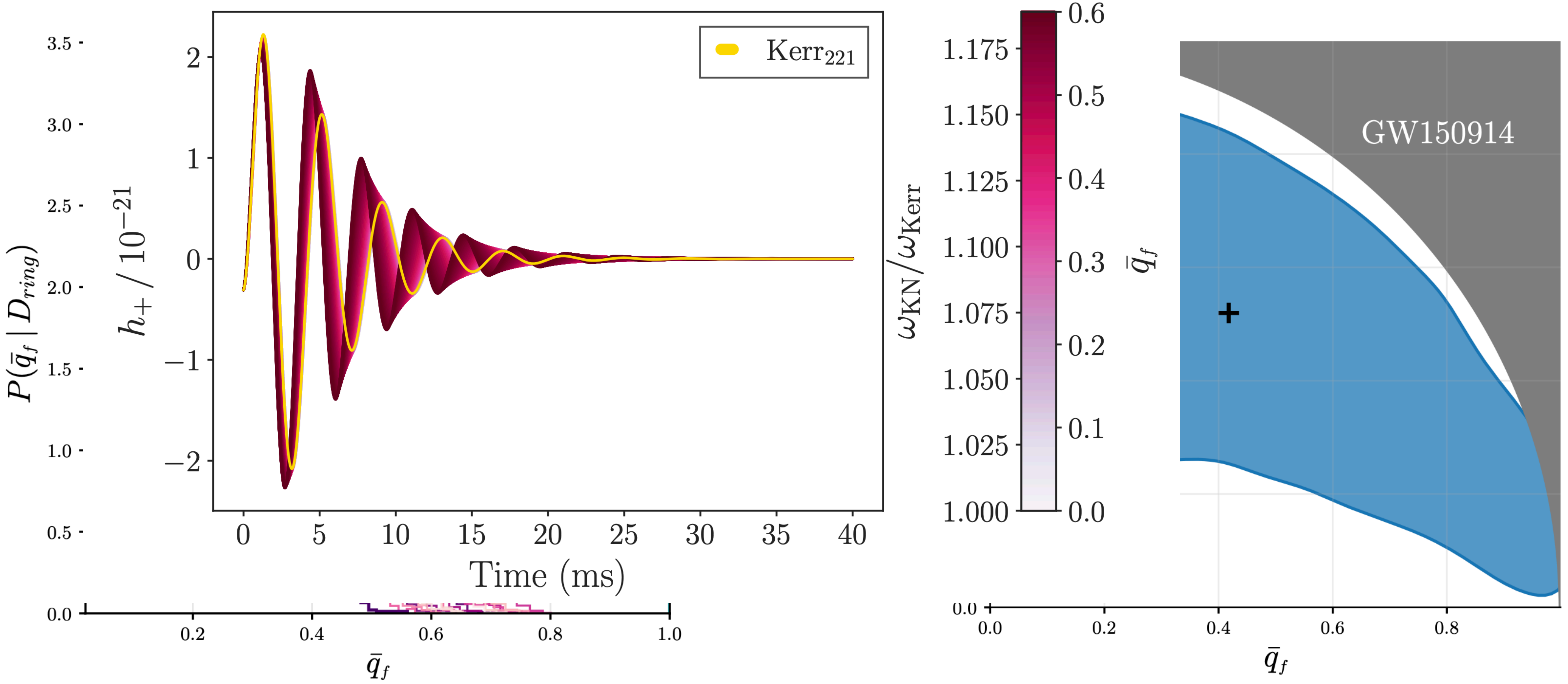


Constraints on BH charge



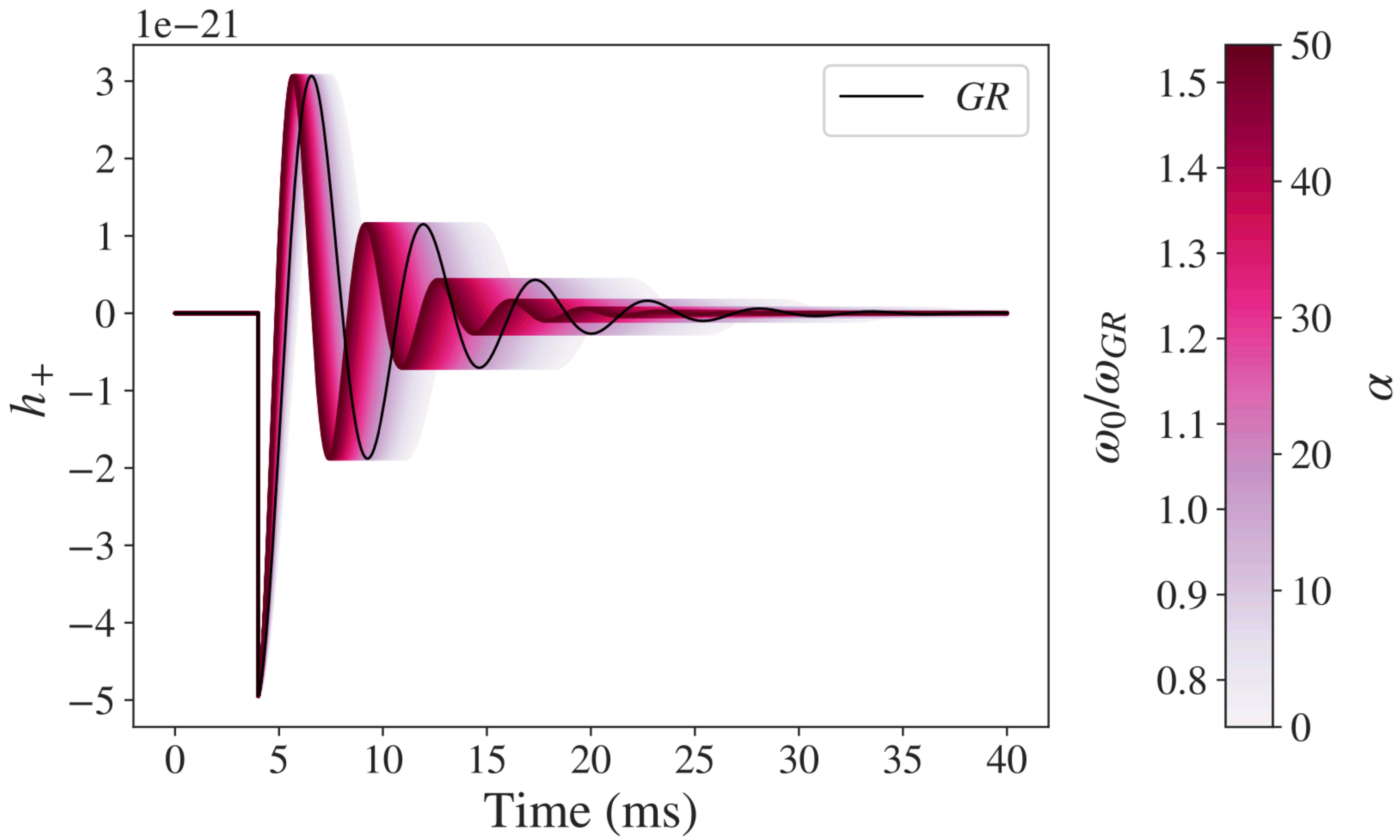
Carullo et al, arXiv:2109.13961

Constraints on BH charge



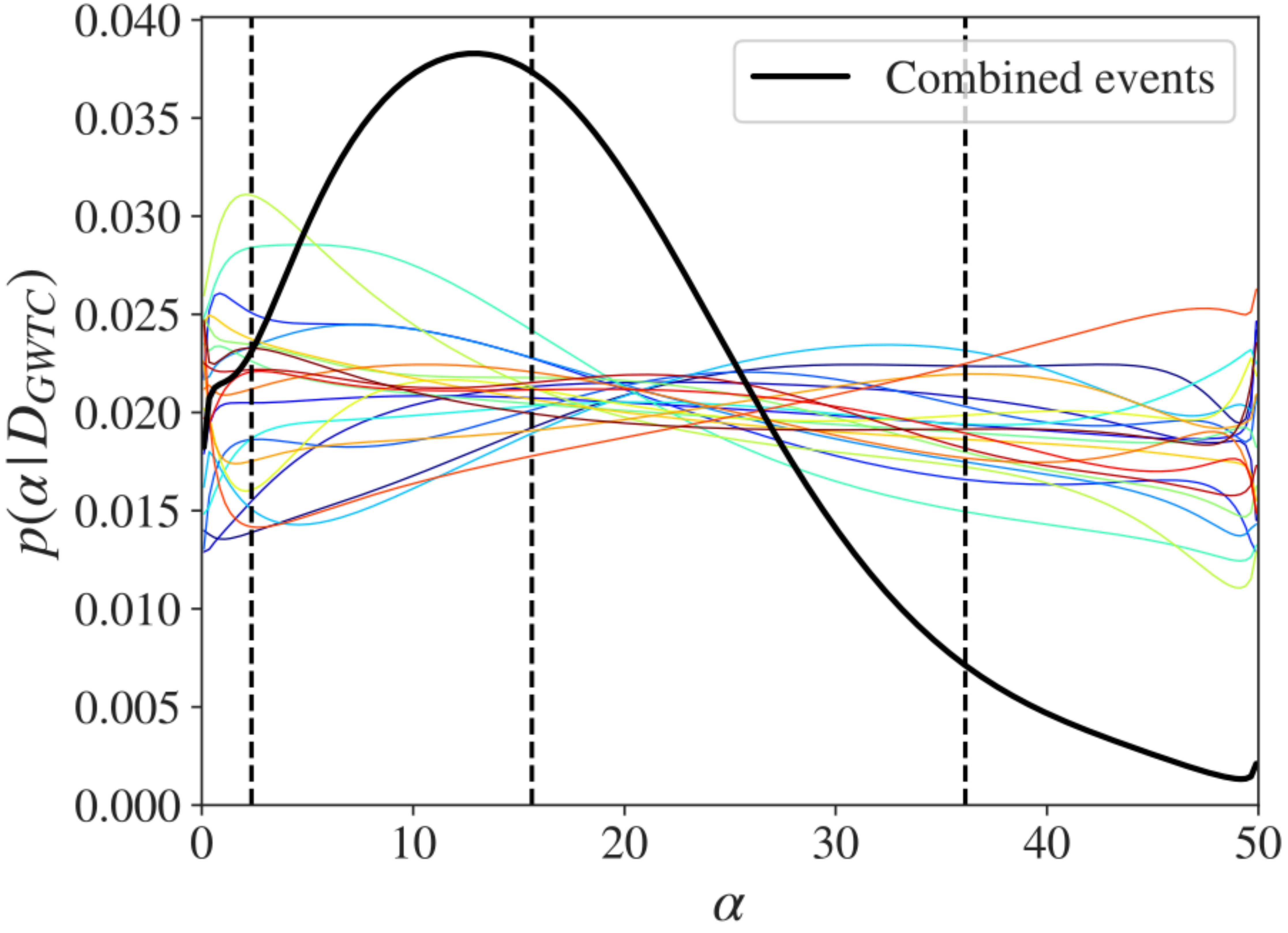
Carullo et al, arXiv:2109.13961

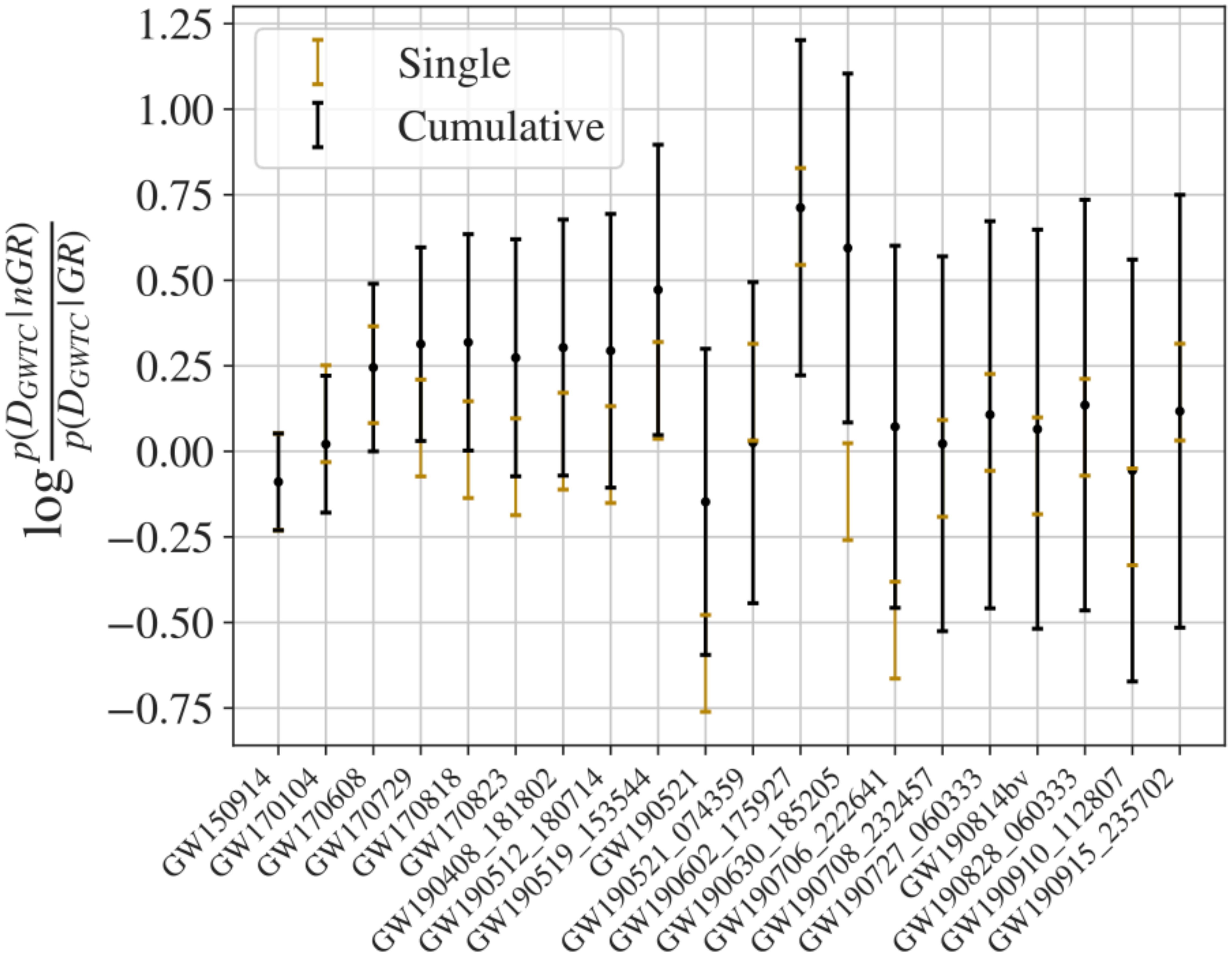
Quantum black hole spectroscopy



Laghi, Carullo, Veitch, Del Pozzo, arXiv:2011.03816

Quantum black hole spectroscopy





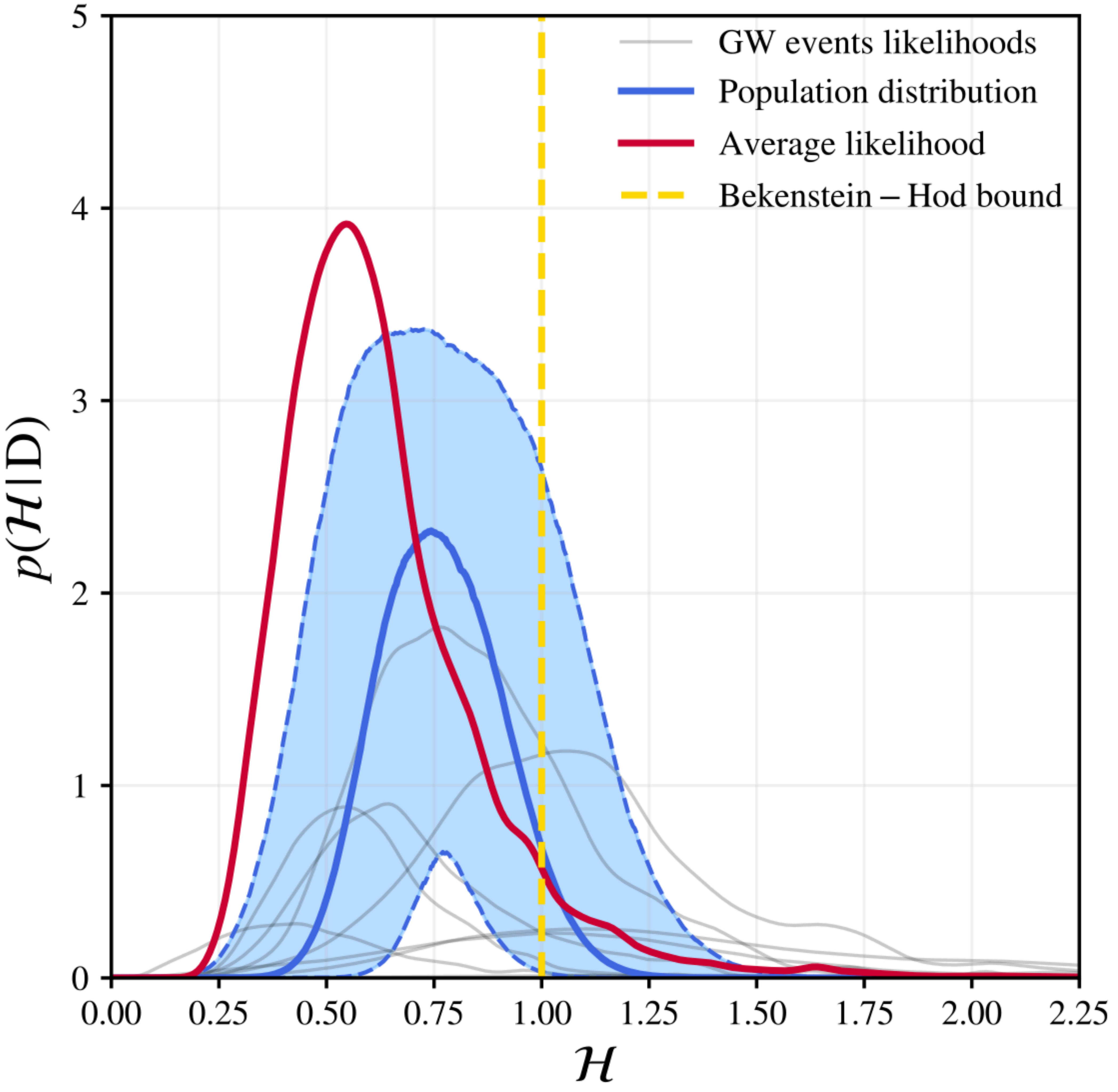
Laghi, Carullo, Veitch, Del Pozzo, arXiv:2011.03816

BHs obey the Bekenstein-Hod bound

- Rate of information emission is limited from above, in *any* system

$$\mathcal{H} := \frac{1}{\pi} \cdot \frac{\hbar \omega_I}{k_B T} \leq 1$$

- From ringdown emissions in GWTC-2, the bound is obey at the 91% credible level



Carullo et al, arXiv:2103.06167

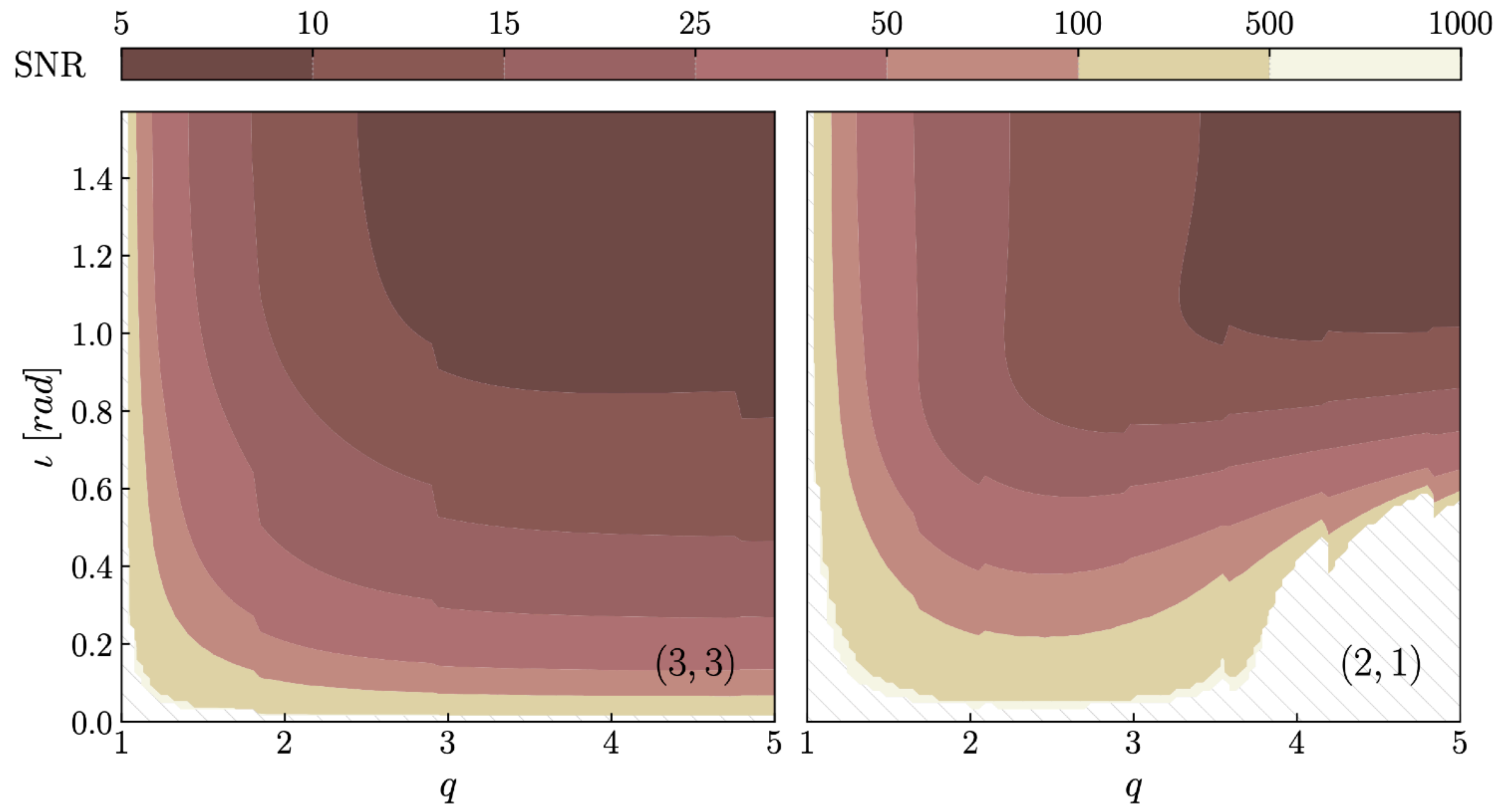
Higher order angular modes

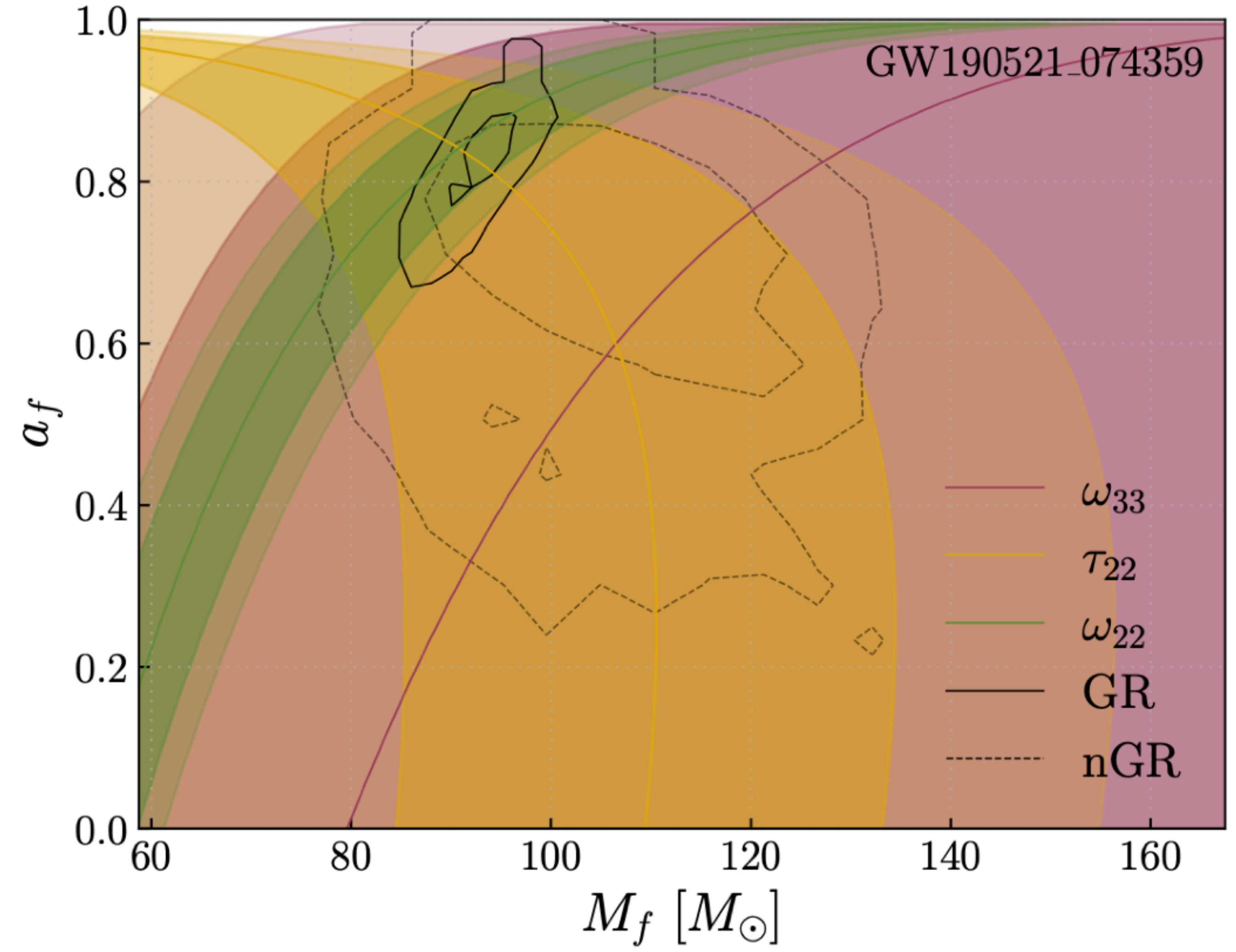
Gennari, Carullo, Del Pozzo, arXiv:2312.12515

- As the number of detected events will increase, so will the possibility of detecting $l > 2, \quad m \neq 2$ modes

- Multi-mode BH spectroscopy

  - Smoking gun for violations of BH uniqueness theorems





Conclusions

- To date (and in our limited sensitivity):
  - **BBHs and GW behave just like GR predicts**
- Many more and louder detections in the future
  - Improved sensitivities to tiny violations of GR
  - Better constraints on violation parameters
- Next few years will concretise BH spectroscopy
  - Are the merger remnant GR BHs?