Black-hole ringdown and their progenitors: from numerical relativity to tests of GR

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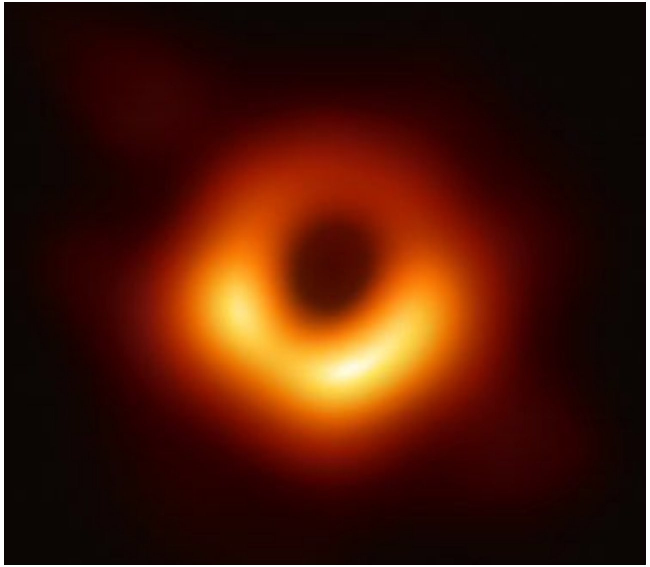
Pacilio+ (2024) arXiv: [2408.05276]

PYTHON software available at:
https://github.com/cpacilio/postmerger

Kerr Black Holes



EHT Collaboration (2019),
arxiv 1906.11238

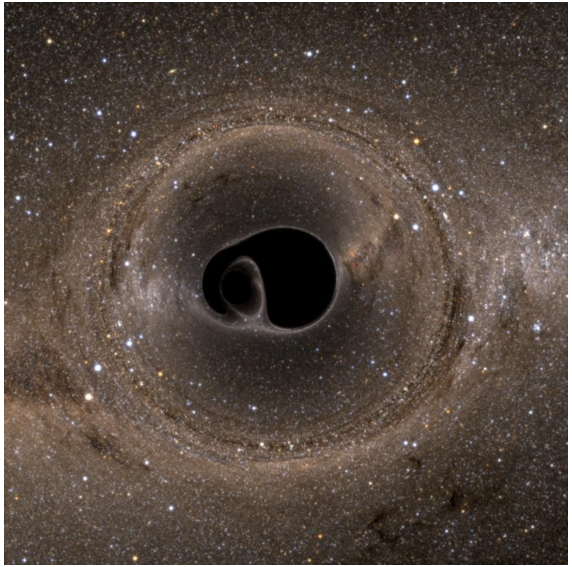
Uniqueness Theorem

Stationary black holes in vacuum in GR are uniquely described by the Kerr spacetime metric

$$
\begin{aligned}
ds^2 \; &= \; -\left(1 - \frac{2Mr}{\Sigma}\right) dv^2 + 2dvdr + \Sigma d\theta^2 \\
&\quad + \frac{(r^2 + a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma} \sin^2\theta d\bar{\phi}^2 \\
&\quad - 2a \sin^2\theta dr d\bar{\phi} - \frac{4Mra}{\Sigma} \sin^2\theta dv d\bar{\phi} \, .
\end{aligned}
$$

Roy P. Kerr
Phys. Rev. Lett. 11, 237 (1963)

Quasi-normal modes



Simulation by The SXS (Simulating eXtreme Spacetimes) Project

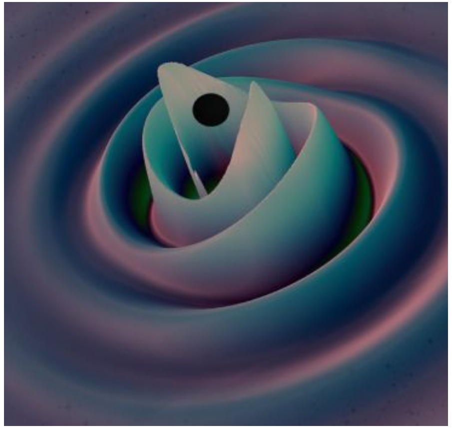
Black-hole perturbations

Linear perturbations about black holes are described by Teukolsky's equations

Black-hole spectrum

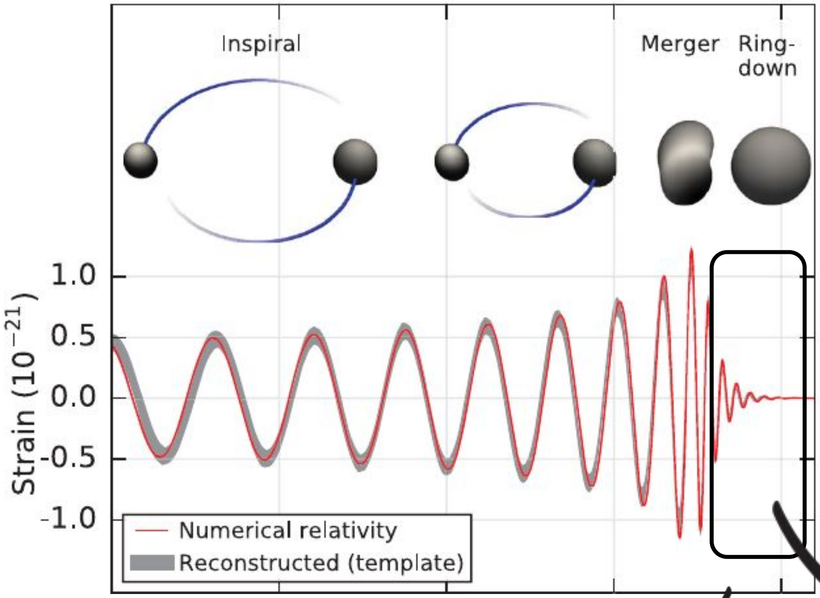
A perturbed black hole emits gravitational waves with a characteristic frequency spectrum

Teukolsky 2014, arxiv 1410.2130
Berti+ (2009), arxiv 0905.2975
Pani (2013), arxiv 1305.6759



Simulation by Georgia Tech, MAYA Collaboration

Quasi normal modes and the no-hair theorem



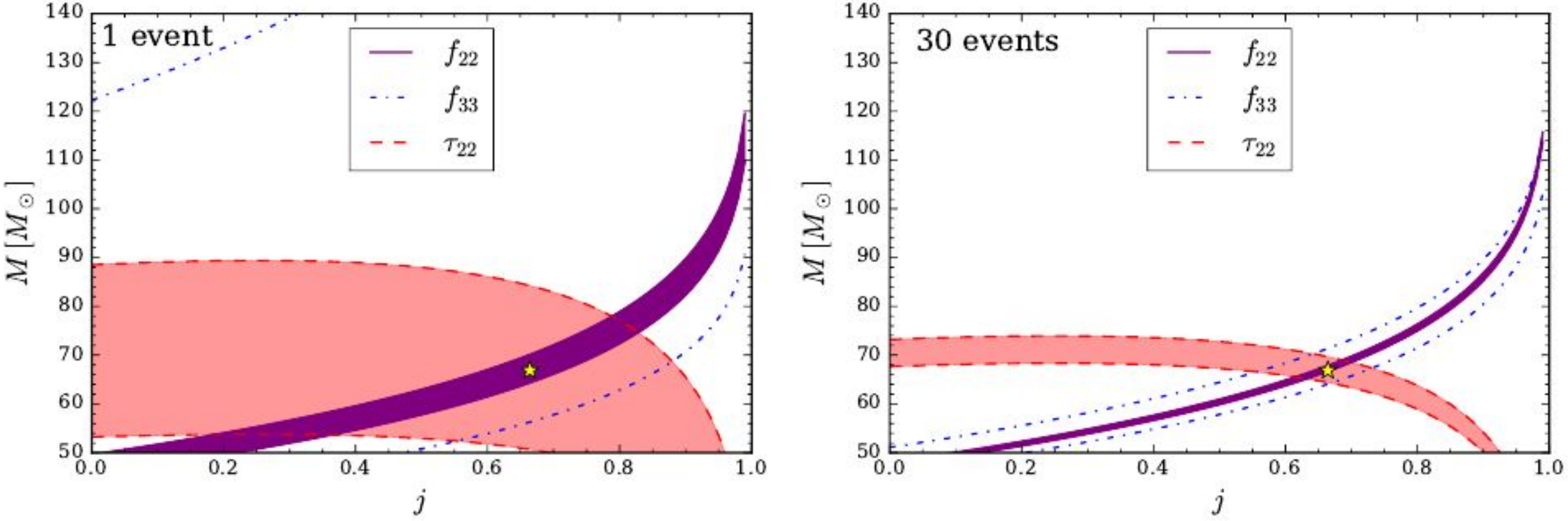
Black Hole Spectroscopy

As a consequence of the no-hair theorem, **the quasi normal modes depend only on the mass and spin** of the BH remnant

$$f_{lmn} \equiv f_{lmn}(M, \chi)$$
$$\tau_{lmn} \equiv \tau_{lmn}(M, \chi)$$

Black hole spectroscopy

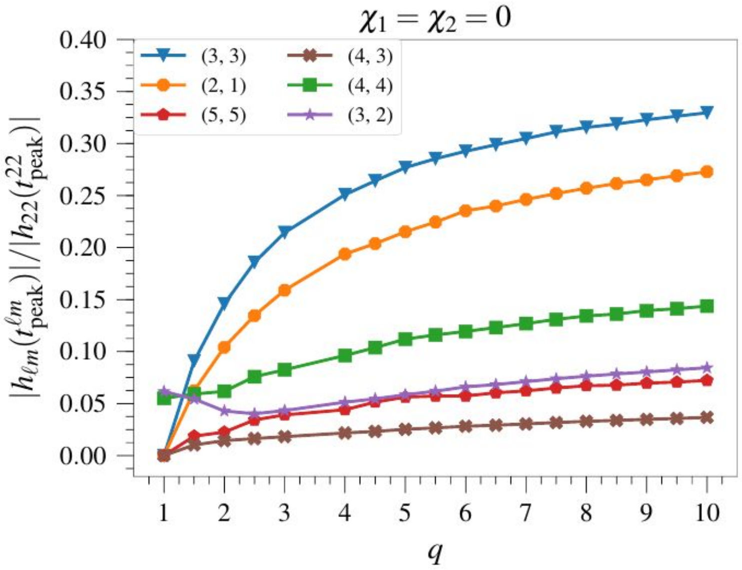
Measure **at least two** quasi-normal modes
Check that they are consistently inverted into mass and spin



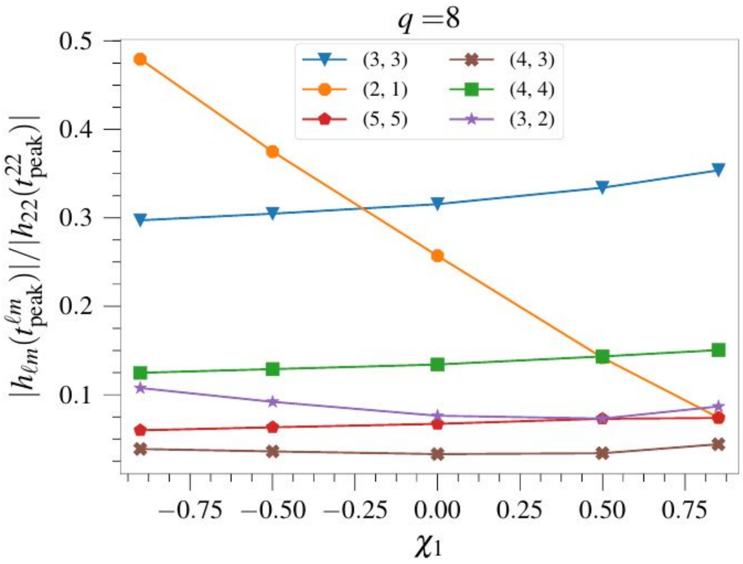
Brito+ (2018) [1805.00293]

Ringdown excitation amplitudes

The activation of QNMs is determined by their amplitudes



Cotesta+ (2018) [1803.10701]



Amplitudes depend on the intrinsic parameters of the progenitors

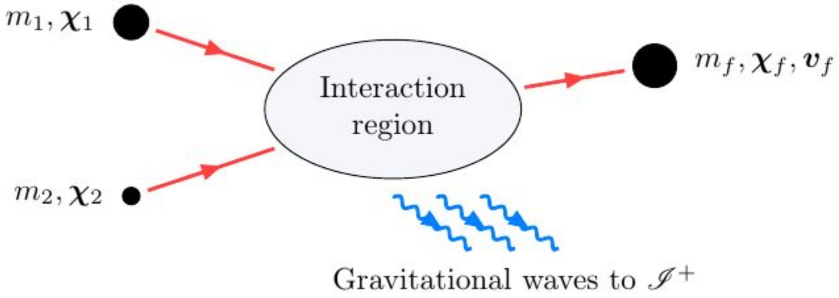
Kamaretsos+ (2012) [1207.0399]

Surrogates for ringdown amplitudes

Multipole fits for the ringdown amplitudes

Kamaretsos+ (2012) 1207.0399
London (2018) 1801.08208
Forteza+ (2022) 2205.14910
Cheung+ (2023) 2310.04489

The are all in closed form



Gaussian Process Regression (GPR)

- Parametric-free: does not did ansatze
- Outputs also uncertainties over predictions

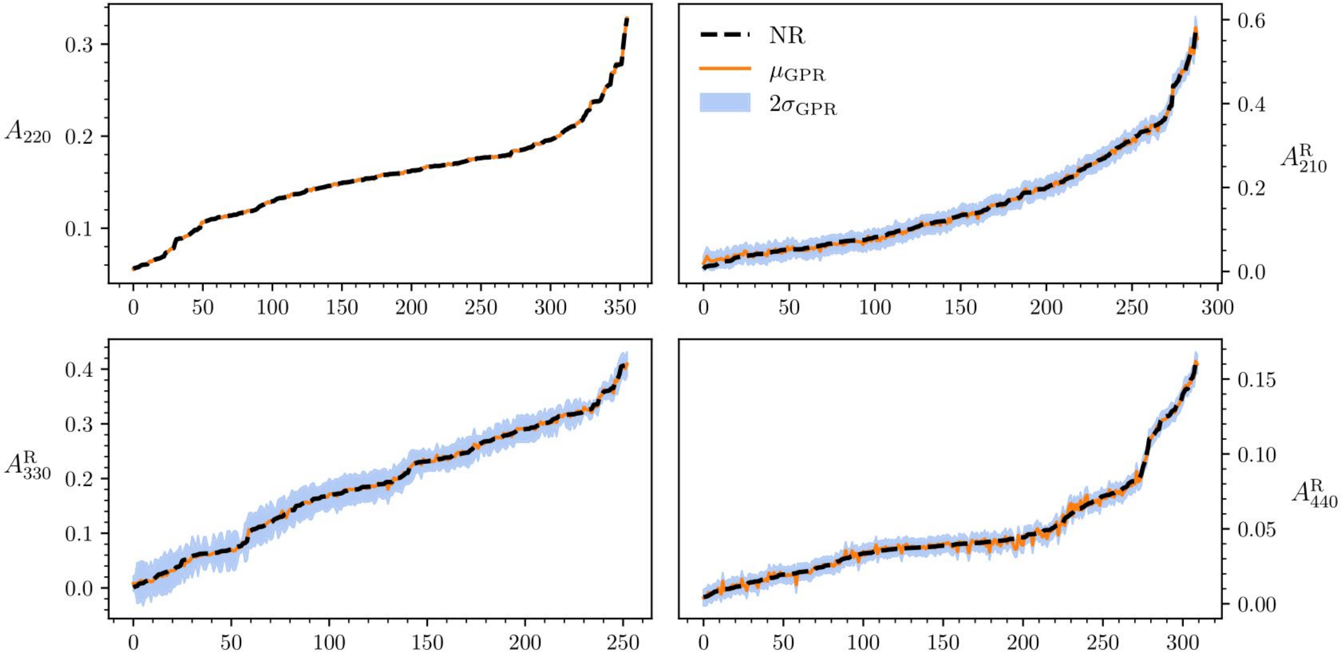
GPR used to build the most accurate surrogate fon final mass and spin

Varma+ (2018) 1809.09125
Boschini+ (2023) 2307.03435

We extend the surrogate to ringdown amplitudes of **non-precessing quasi-circular** binaries

See also Zertuche+ (2024) 2408.05300

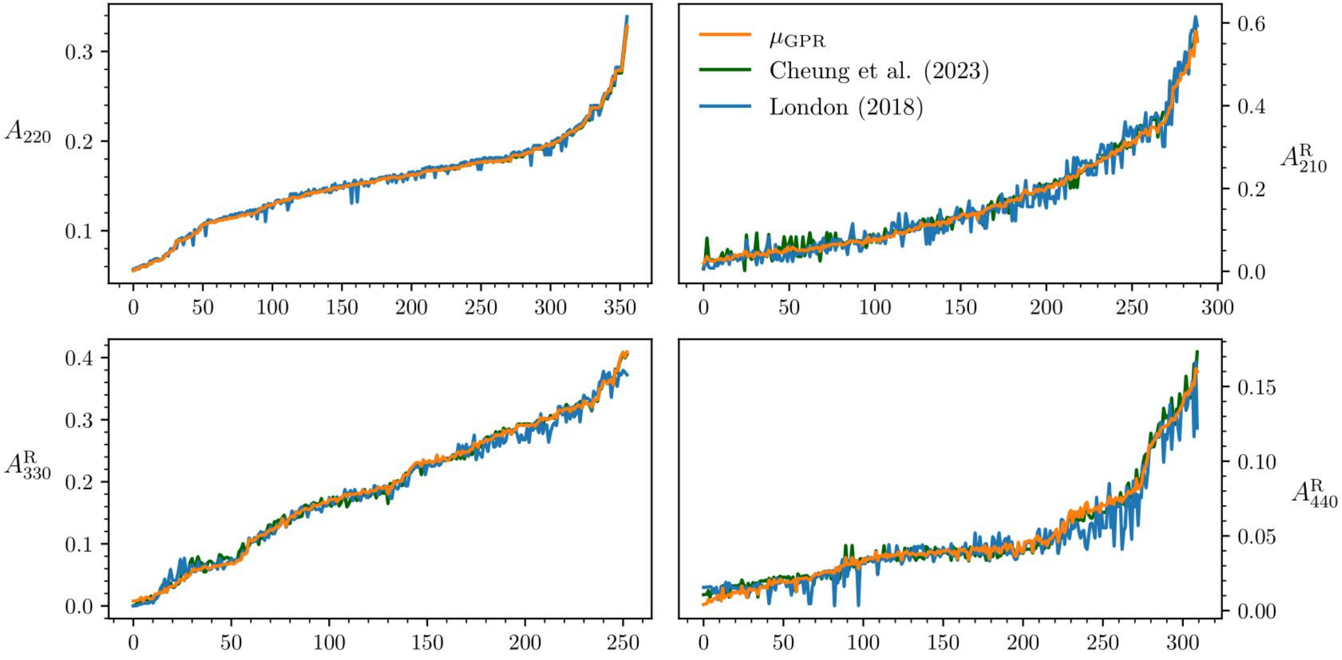
Results: comparison with NR data



Deviation of mean GPR predictions from NR data is order 10E-3

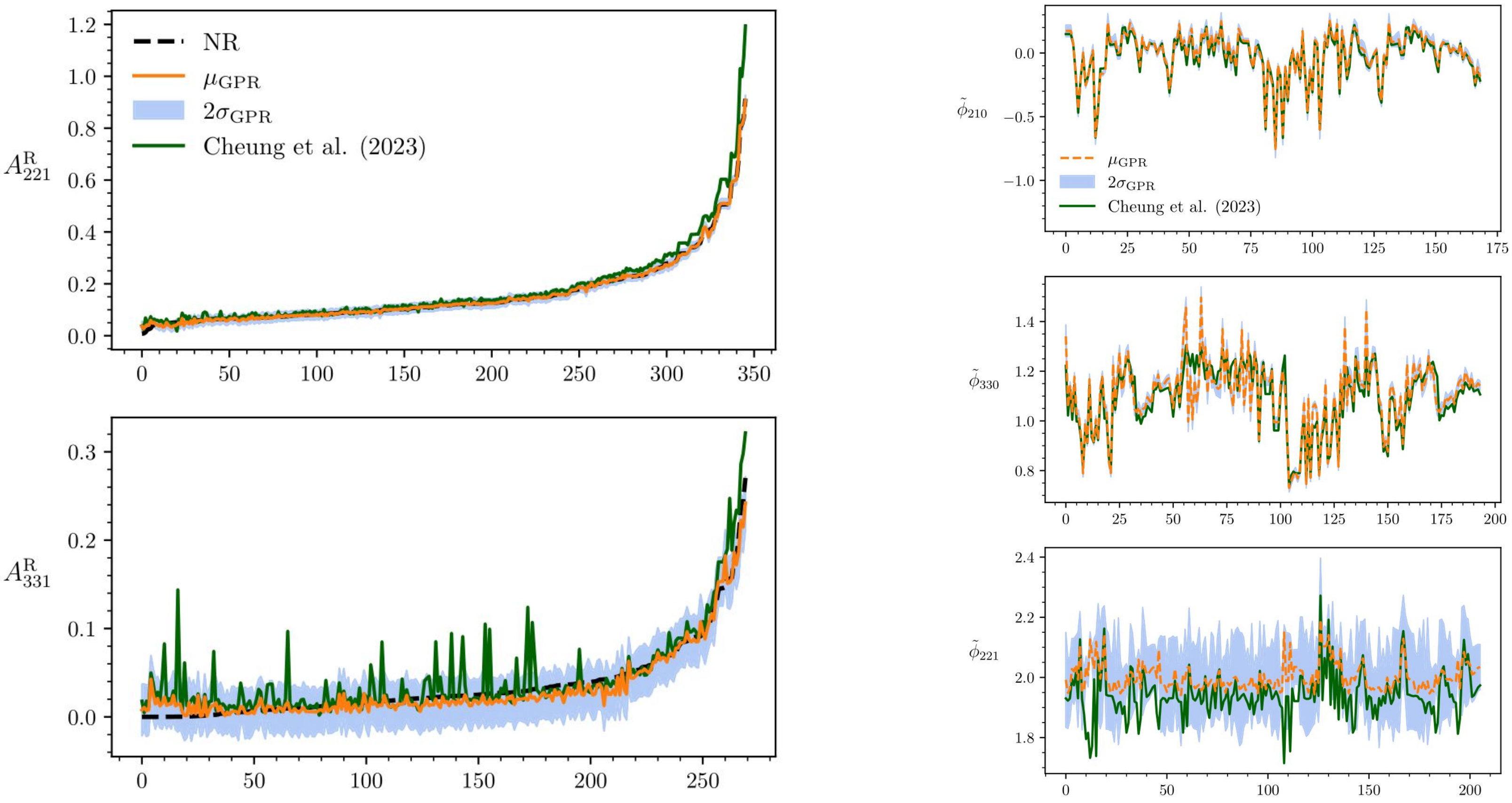
NR data are comprised within ~1 GPR standard deviations

Results: comparison with previous fits (I)

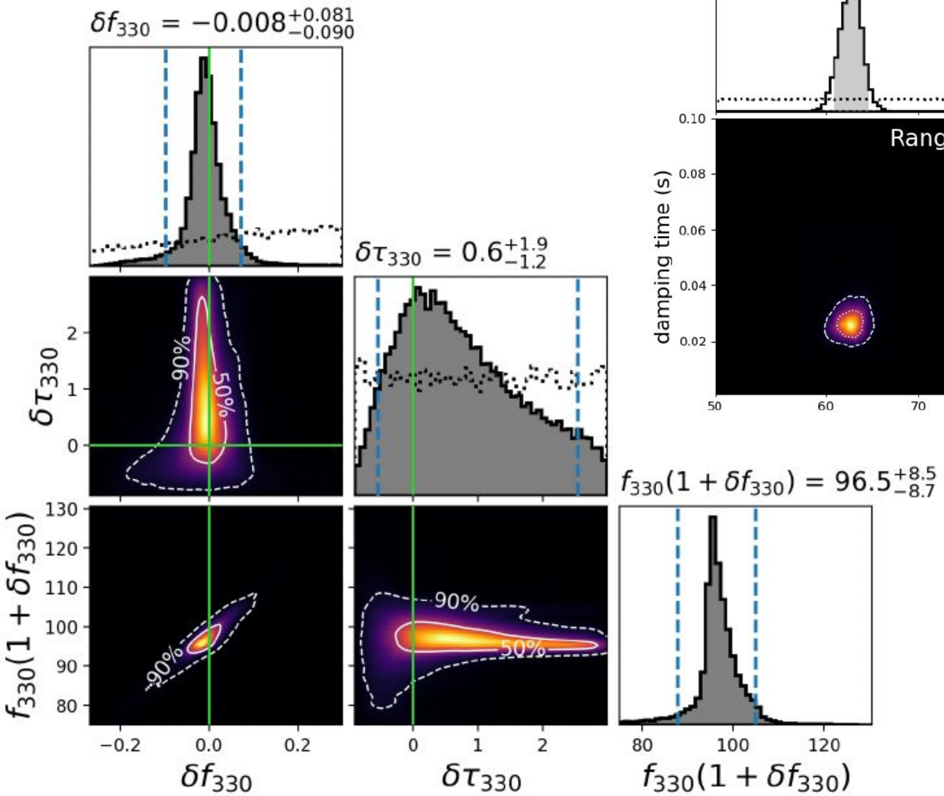


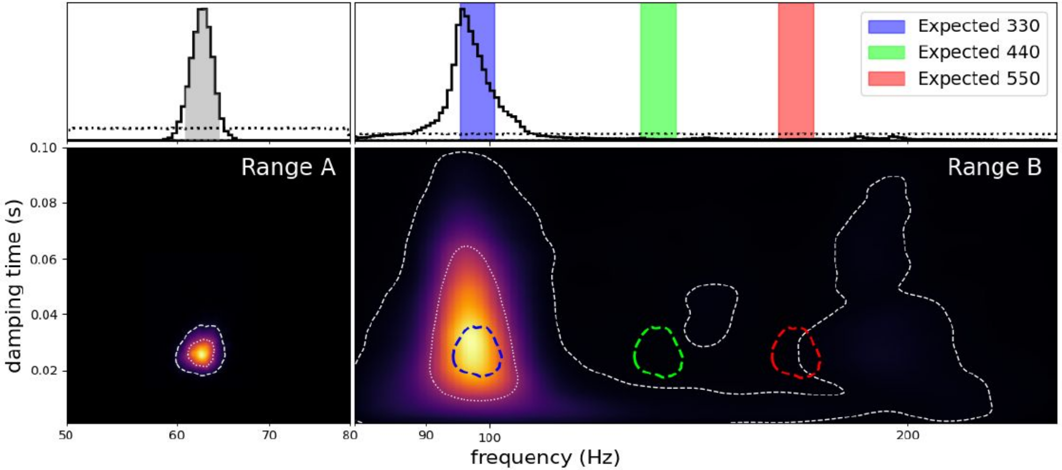
Overall agreement with the most updated fits: London (2018) and Cheung et al. (2023)

Results: comparison with previous fits (II)



GW190521: a case study for LVK





Deviation in the subdominant frequency (3,3,0) within 10%

Capano+ (2021), [arxiv 2105.05238](https://arxiv.org/abs/2105.05238)

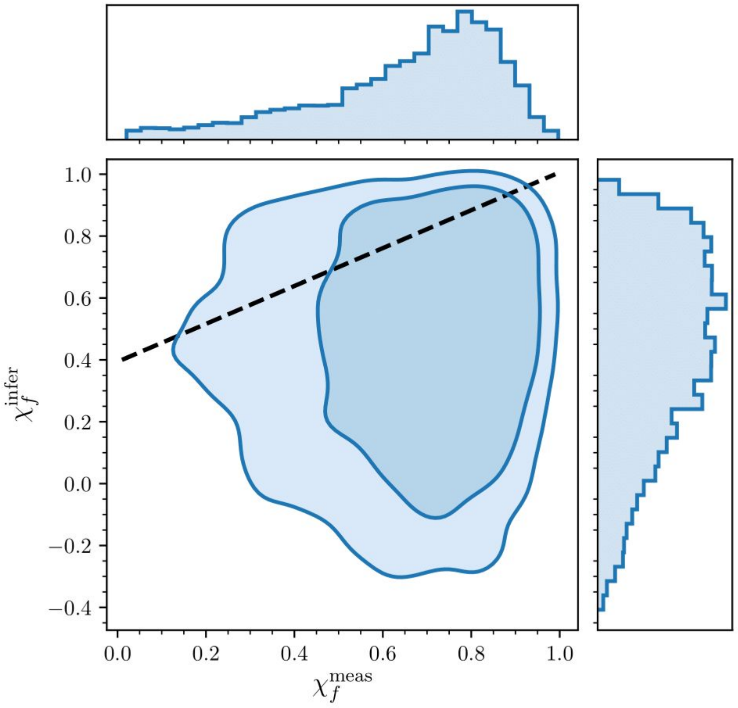
GW190521: amplitude-spin consistency

GR is a deterministic theory

- *Final spin and ringdown amplitudes* are determined by the same initial params
- We *have surrogate fits for both* final spin and ringdown amplitudes

Amplitude-spin consistency

- Measure amplitudes and final spin as independent parameters in ringdown
- Map amplitudes to initial params
- Map initial params to final spin
- Compare with measured final spin



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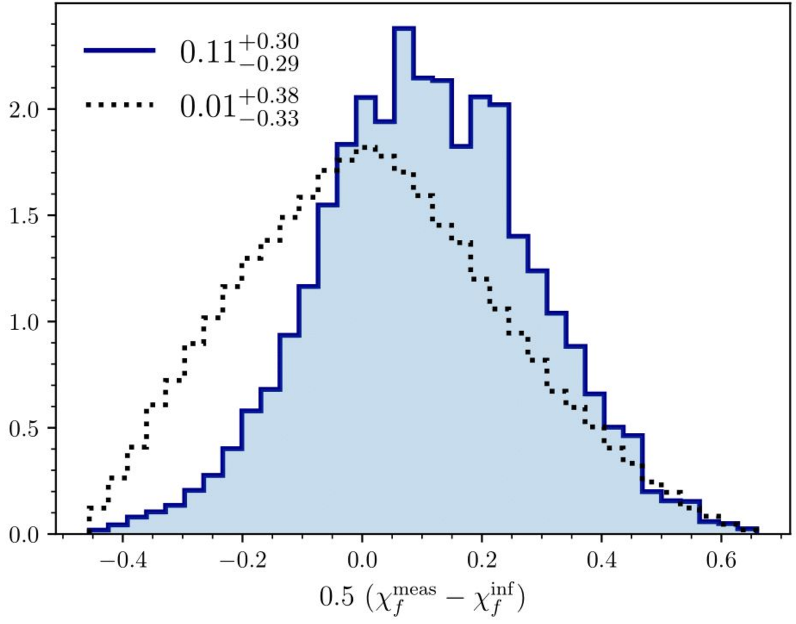

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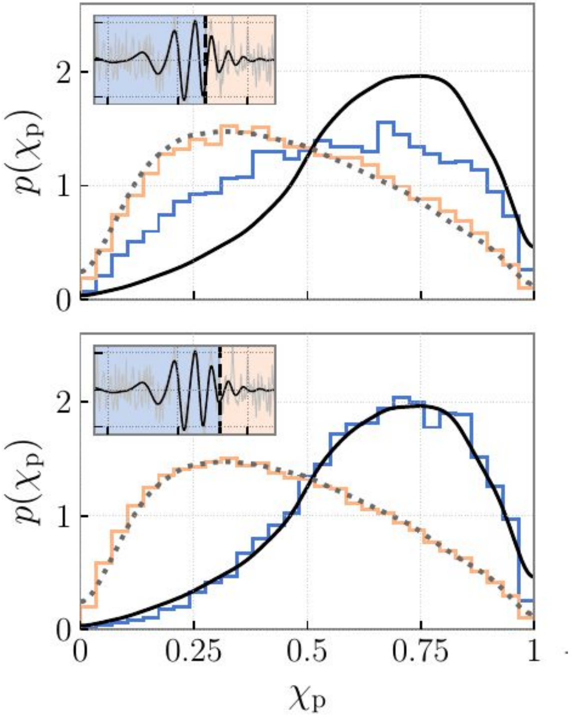
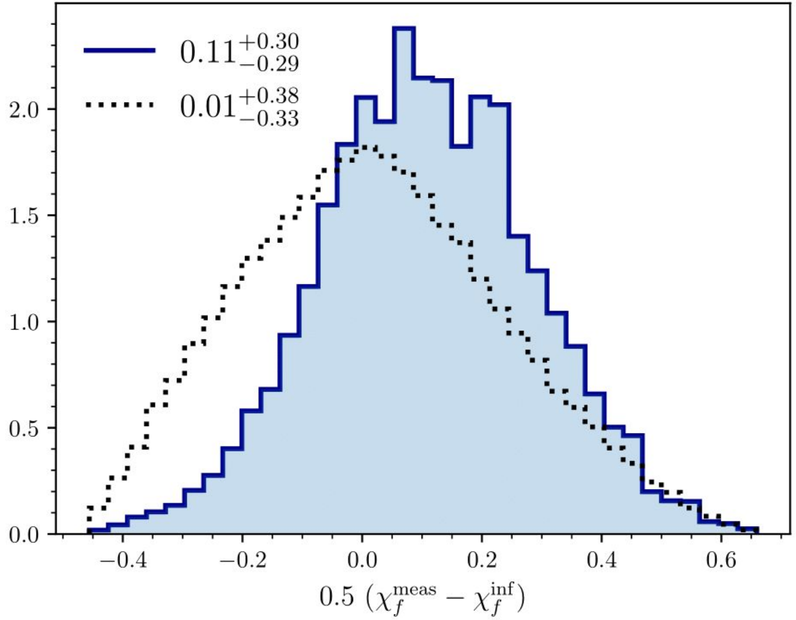
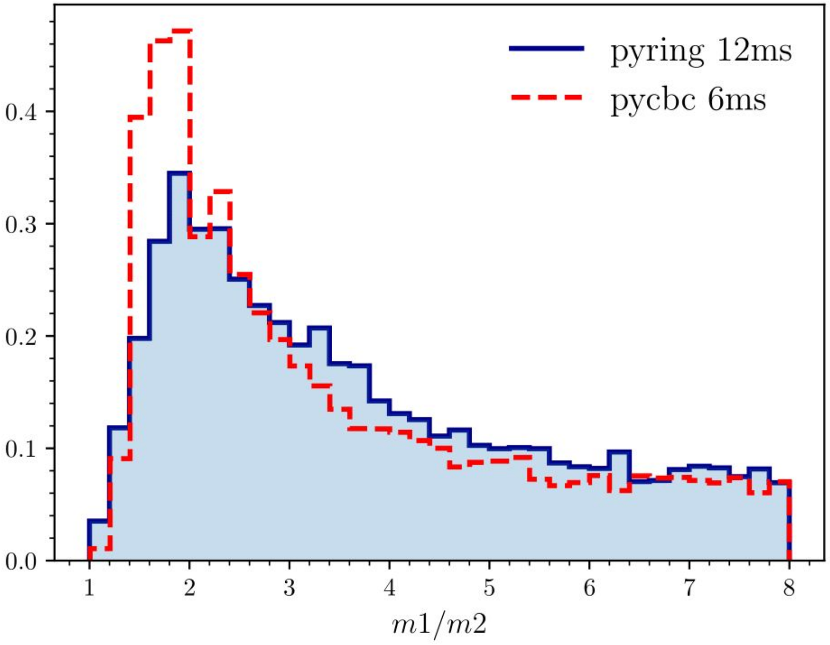
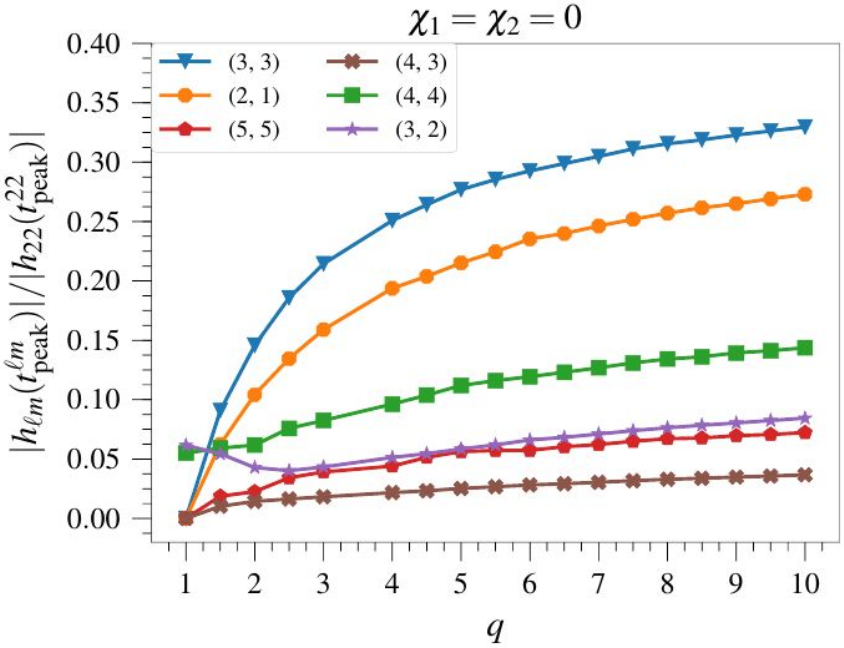




Miller+ (2021), [2310.01544]

GW190521: mass-ratio from A330/A220





Cotesta+ (2018) 1803.10701

Conclusions

PYTHON software available at:
https://github.com/cpacilio/postmerger

State of the art:

- Surrogate of NR ringdown from the SXS public catalog
- **Only quasi-circular and non-spinning**

Improving the model:

- Flexible **machine learning regression**: easier to extend than closed-form ansatzes
- Extension to eccentricity [see Carullo 2024] and precession [see Zhu+ 2023] is ongoing

Extend consistency tests:

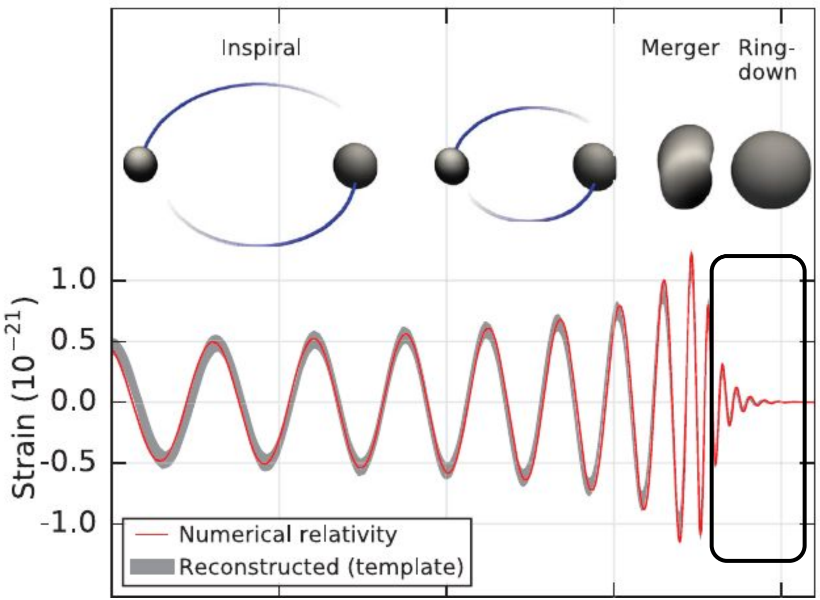
- Switch to a NR-informed template
- Relax consistency between initial parameters and final mass/spin

$$h = \sum_{l,m,n} A_{lmn} e^{-i\omega_{lmn}(t-t_0)}$$

Thank you!

Backup

Testing no-hair with black hole spectroscopy



BH spectroscopy: measuring the frequency and damping times of a BH from its GW signal

GR test: check that there is no "third" independent frequency or damping time

Berti, Cardoso, Will (2006), arxiv gr-qc/0512160

Berti+ (2016), arxiv 1605.09286

Baibhav+ (2023), arxiv 2302.03050

Gossan+ (2011), arxiv 1111.5819

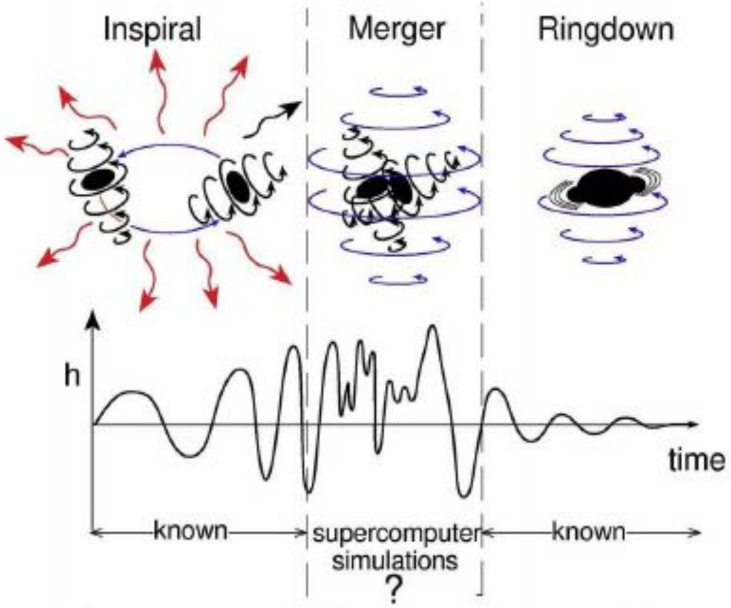
Meidam+ (2014), arxiv 1406.3201

Even if the background is Kerr, no-hair is violated if the perturbation dynamics differ from Teukolsky's

Barausse & Sotriou (2004), arxiv 0803.3433

Tattersall+ (2017), arxiv 1711.01992

Quasi normal modes and the no-hair theorem



If no-hair is violated, you have dependence from (at least one) further scale

Recent progresses in computing modified spectra:

Cano+ (2023) [arxiv 2304.02663]

Ghosh+ (2023) [arxiv 2303.00088]

$$f_{lmn} \equiv f_{lmn}(M, \chi, \alpha)$$
$$\tau_{lmn} \equiv \tau_{lmn}(M, \chi, \alpha)$$

Relation to black hole uniqueness

Uniqueness theorem – Stationary black holes are axisymmetric and are described by a member of the Kerr family

Kerr hypothesis – a black hole formed from gravitational collapse or from a binary merger will asymptotically settle to a member of the Kerr family, by emitting all charges except mass and angular momentum (aka the ‘no hair’ theorem) [as reviewed e.g. in Teukolsky 2014 https://arxiv.org/abs/1410.2130]

Assuming the Kerr hypothesis, the quasi-normal mode spectrum follows from Teukolsky’s equation and depends only on the final mass and the final spin of the black hole [as reviewed in e.g. Berti+2009 https://arxiv.org/abs/0905.2975]

$$\omega_{lmn} \equiv \omega_{lmn}\left(M_f, \chi_f\right)$$

What black hole spectroscopy tests (1)

Ringdown tests probe general relativity in the strong field regime

Quasi-normal modes can be approximated by the frequency and damping times of perturbed light rays at the innermost stable circular orbit for null geodesics (aka the ‘photon sphere’) [Cardoso+2009 https://arxiv.org/abs/0812.1806 and ref.s therein]

Higher order WKB methods refine this approximation and reinforce the physical connection between quasi-normal modes and the photon sphere

Black hole spectroscopy tests the BH structure in the vicinity of the photon sphere

What black hole spectroscopy tests (2)

The **uniqueness theorem** holds in several gravitational theories beyond GR. Examples: shift-symmetric Horndeski

However, the dynamics of perturbations is different, hence **the quasi-normal modes are different**

Here you only test the dynamics of the theory but not the metric of the asymptotic solution

Some gravitational theories beyond GR admit black hole solutions **different from Kerr**. Examples: Einstein–dilaton–Gauss-Bonnet, dynamical Chern-Simons

Here, you test the structure of the black hole in the vicinity of the photon sphere* and the dynamics of the perturbations at the same time

*In modified gravity, the connection with photon sphere is still under study, especially for rotating black holes [see Yagi 2022 https://arxiv.org/abs/2201.06186 and ref.s therein]