Black-hole ringdown parameter estimation

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Introduction

After the coalescence of two compact objects, the final black hole settles down to equilibrium in the ringdown phase. For astrophysical Kerr black holes, the ringdown spectrum is characterized by the mass and the angular momentum of the black hole. General relativity describes the late stages of the ringdown as a superposition of quasi-normal modes (QNM), with the shape of an exponentially damped sinusoid. The central frequency and the decay time are characteristic of the intrinsic parameters of the black hole.
Observations of the QNM spectrum could be used to verify the black-hole nature of the final object, and to further test the theory of general relativity. Using a parameter estimation code recently developed in PyCBC [1], which currently incorporates the Markov Chain Monte Carlo (MCMC) Python packages kombine [2] and emcee [3], we aim to resolve at least two modes of the black-hole ringdown.

Test on GW150914

As a test of this new method one would want to be able to reproduce the results obtained for GW150914 [4]. We use a simple ringdown waveform model

$$h(t) = A \exp^{-t/\tau} \cos(2\pi f_0 t + \phi_0)\,,$$

and let the parameter estimation vary over the central frequency f_0, damping time τ, amplitude A, and phase ϕ_0. Here we show the results for f_0 and τ at a fixed time of approximately $10M$ after merger time (t_M), $t = t_M + 3$ ms.

The posterior distribution of f_0 and τ in our parameter estimation is consistent with the results published in [4]

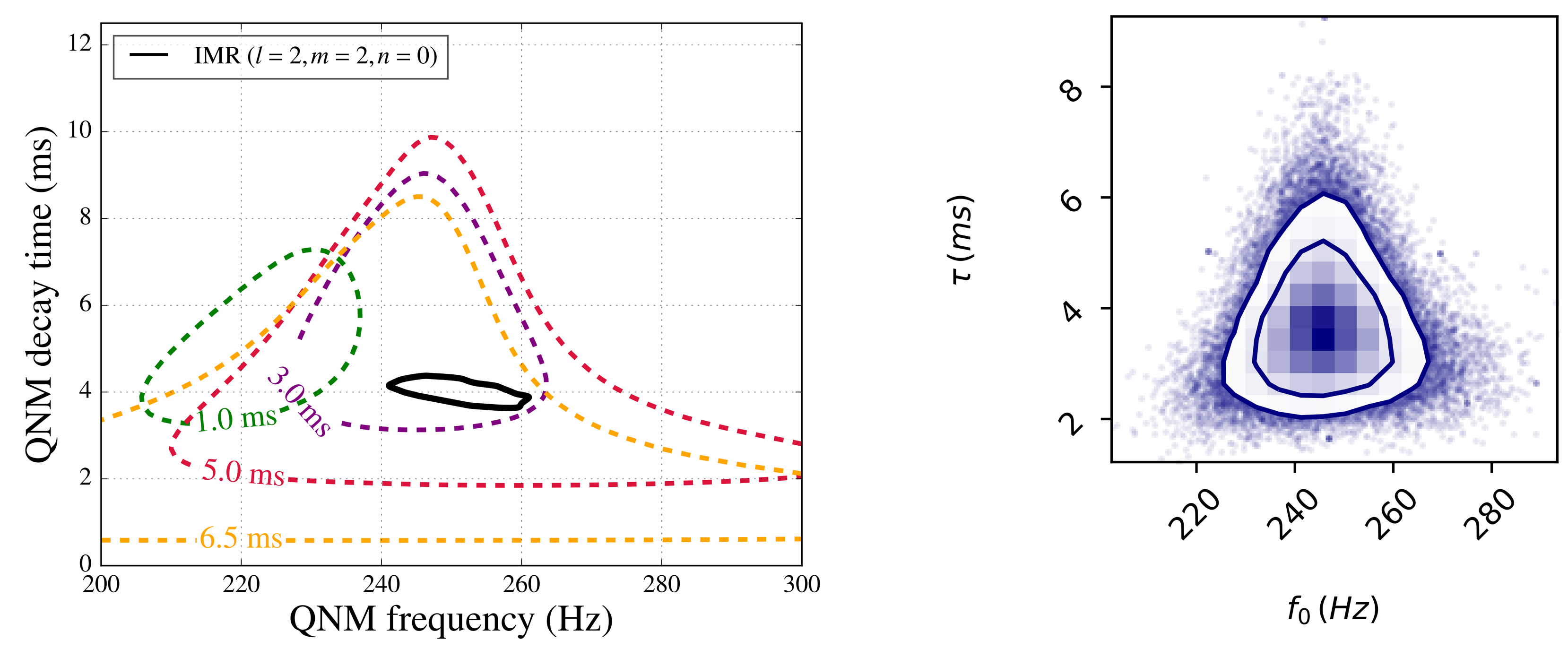


Fig. 1: *Left*: Results published for GW150914 [4] at different run times, with the contours showing the 90% confidence level. *Right*: Results obtained with PyCBC at $t = t_M + 3$ ms, with the outer contour showing the 90% confidence level.

GW150914 mass and spin from the ringdown

One can also model the ringdown waveform in terms of the intrinsic parameters of the black hole [5, 6]. Thus, information about the mass and the spin of the final Kerr black hole can be obtained from the ringdown stage of the coalescence, without knowledge about the inspiral. Here we show the results obtained for GW150914 at a fixed time of approximately $10M$ after merger time, $t = t_M + 3$ ms. The mass from our results is the detector-frame mass, which was quoted to be $M_f^{detector} \simeq 67 M_\odot$ in [7].

The posterior distribution of M_f and S_f in our parameter estimation is consistent with the values quoted for the detector-frame mass and final spin in [7].

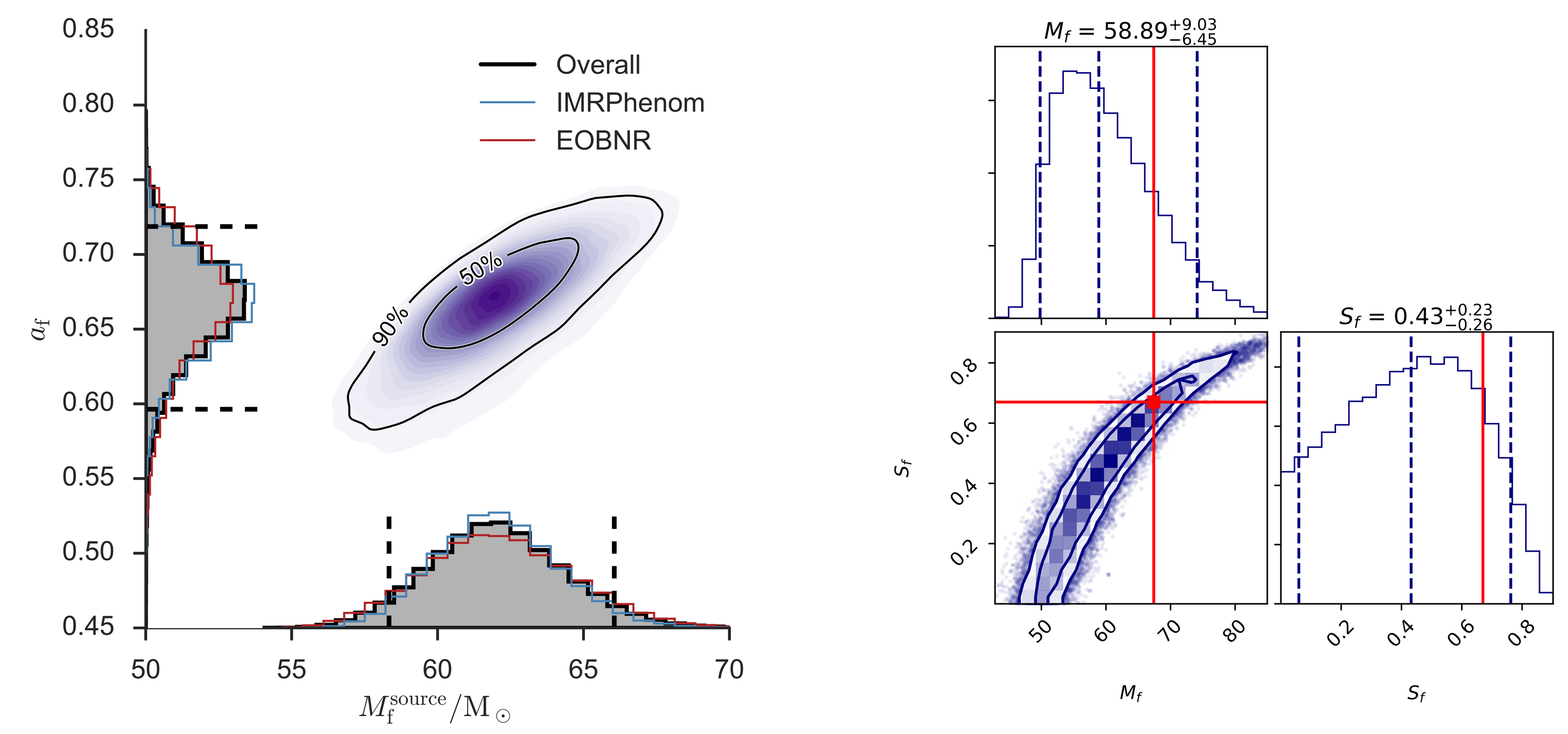
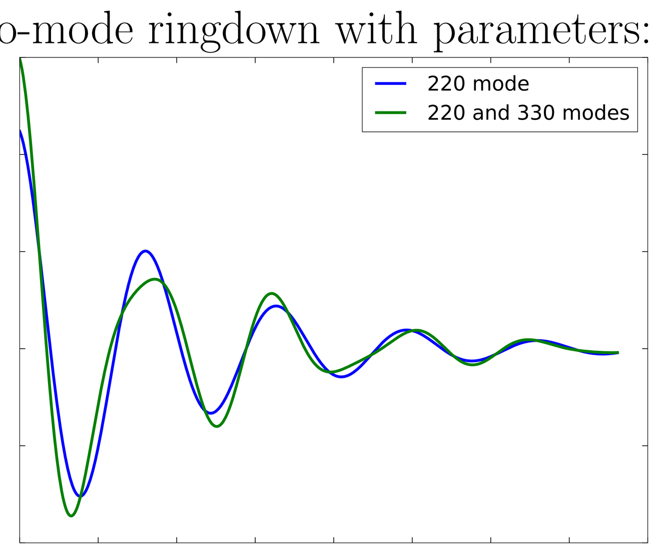


Fig. 2: *Left*: Results published for GW150914 in [7], for comparison. Note that here the source-frame mass is shown. *Right*: Results obtained with PyCBC at $t = t_M + 3$ ms. The dashed lines on the histograms show the 90% confidence interval and the median value. The outer contour is the 90% confidence interval and the red cross marks the parameters quoted in [7].

Injecting a two-mode ringdown

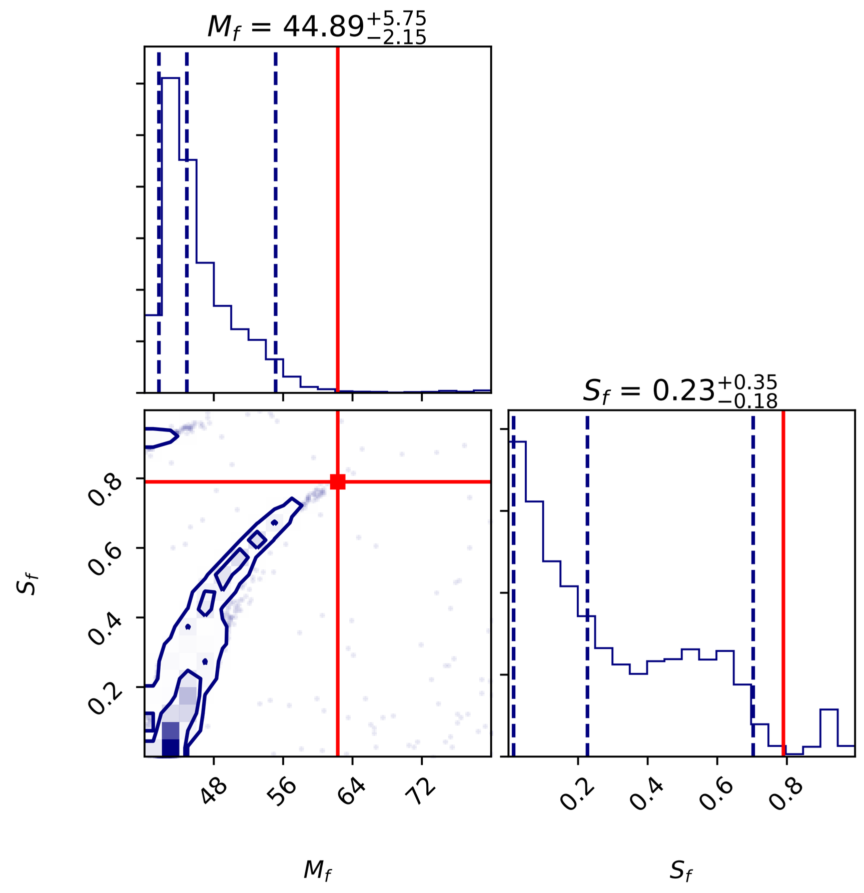
We perform a parameter estimation analysis, both with a single-mode ringdown waveform and with a multi-mode ringdown, on a simulated two-mode ringdown with parameters:

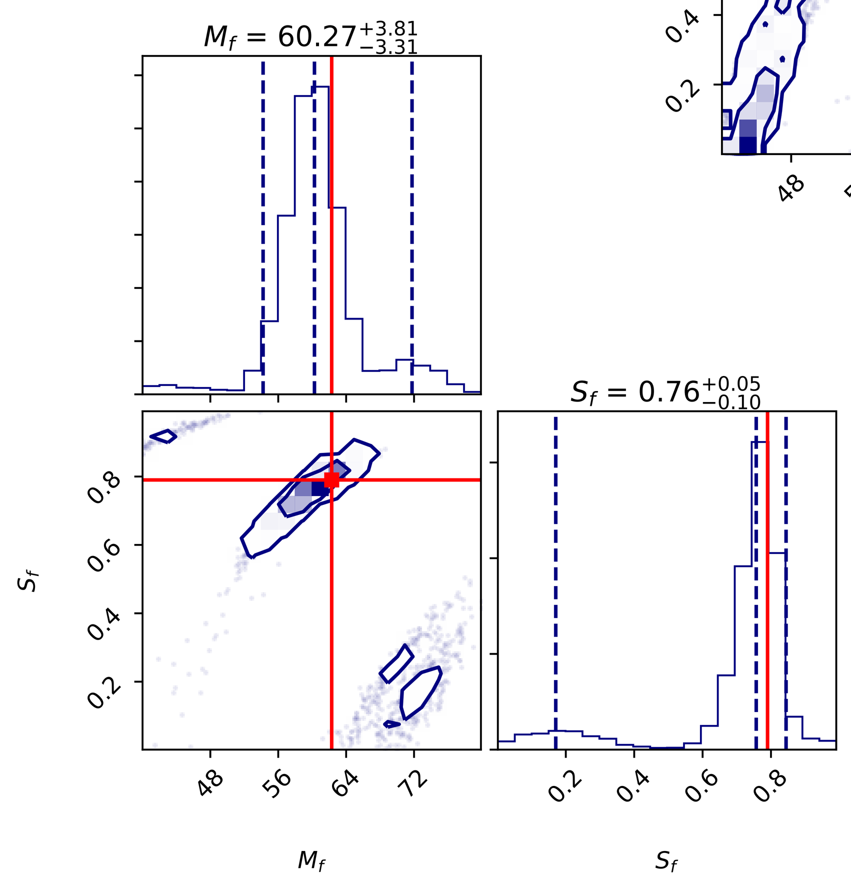
- Two modes: 220 and 330
- Amplitude of the subdominant mode: $A_{330} = \frac{1}{3} A_{220}$.
- Mass: $M_f = 62.3 M_\odot$
- Spin: $S_f = 0.79$
- Simulated Gaussian noise with O1 PSD



For a loud enough subdominant mode, a bias is introduced in the intrinsic parameters of the black hole and the single-mode analysis cannot recover the expected values.

Single-mode (220) analysis on multi-mode ringdown injection: recovered parameters are biased.





Multi-mode (220 and 330) analysis on multi-mode ringdown injection: real parameters within posterior distribution.

Fig. 3: Results of both a single-mode (top) and a multi-mode (bottom) ringdown analysis on a multi-mode injection. The red cross marks the parameters of the simulated ringdown.

Conclusions and future work

Parameter estimation on the ringdown part of a gravitational-wave signal provides a method for estimating the mass and the spin of the final black hole without requiring knowledge of the inspiral phase. **Our results on the mass and spin of GW150914 are consistent with the values published in [7].**
The multi-mode analysis results indicate that observations of the QNM spectrum of black holes might be possible in the near future, as detector sensitivity improves. Such observations will allow us to verify the Kerr nature of the final black hole, and test the no-hair theorem.

Future work

- Perform multi-mode ringdown parameter estimation on full compact binary coalescence waveform models that include higher modes (e.g. numerical relativity waveforms).
- Compute statistical evidences for different ringdowns to infer what model describes the final object with highest probability.
- Extend our ringdown waveform up to the merger using analytical fits [8] to gain SNR in the ringdown phase.
- Study what SNR of the ringdown is necessary for multi-mode detection with this method in different sensitivity curves.
- Perform ringdown analysis with higher modes on real gravitational-wave signals.

References

[1] PyCBC pipeline: https://github.com/ligo-cbc/pycbc/.
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[4] LIGO Scientific and Virgo collaborations, *Physical Review Letters* **116**, 221101 (2016).
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