Review: "Theory-agnostic searches for non-gravitational modes in black hole ringdown"

by

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In this work, multi-mode ringdown tests are studied in theories of gravity which are perturbatively close to General Relativity with additional minimally coupled scalar or vector fields for final compact objects perturbatively close to Kerr black holes. The main addition to 'standard' multi-mode 'intrinsic' ringdown tests is specifically the search for modes at frequencies associated to minimally-coupled scalar or vector modes around a Kerr black hole. The authors perform a Bayesian analysis using *PyCBC Inference* for several LIGO events as well as Fisher-matrix forecasts for future detectors. It is found that there is currently no evidence for such additional modes in the ringdown (for the considered events, see below) and that ET and CE (resp. LISA) could constrain the relative amplitude of these modes compared to the gravitational 220 mode to roughly $\lesssim 0.02$ (resp. $\lesssim 0.003$) (examples associated to ringdown SNR 150 (resp. 1000) for final dimensionless spin of about 0.9).

In my opinion, the work is interesting and concise but I would kindly ask clarification on the following points before recommending it for publication:

1. While the test proposed by the authors is not entirely model-specific, it is also not entirely theory-agnostic or 'generic'. Therefore, I would first ask if the authors agree with my reading summarized above that the tests are appropriate for "theories of gravity which are perturbatively close to General Relativity with additional minimally coupled scalar or vector fields for final compact objects perturbatively close to Kerr black holes". Second, I would then propose for the discussion to try to delineate more clearly when the authors believe these tests would be appropriate. See also the following point for classes of examples which seem to not be mentioned in the manuscript.

2. After motivating ringdown tests in the introduction as (page 1, left-column, last paragraph): "This provides opportunities for conducting multiple null-hypothesis tests of gravity [15,16] and investigating the nature of the remnant [17-19]", the emphasis of the manuscript seems decidedly on tests of gravity with additional degrees of freedom non-minimally coupled to gravity as opposed to the nature of the remnant. On the other hand, it seems to me that various theories with additional degrees of freedom minimally coupled to gravity may have the same signature depending on the nature of the remnant.

   Consider General Relativity coupled to an electromagnetic field. If the remnant has a charge which is not too big compared to the mass, there are clear gravitationally-led modes perturbed from Kerr as in the first line of (3) of the manuscript and electromagnetically-led modes behaving as the second line of (3), with approximately the free vector QNM frequencies. A similar setup giving rise to scalar-led mode contributions, which to leading order would have a gravitational piece with free scalar frequencies, could occur for minimally-coupled scalar fields with self-interactions for a remnant with scalar hair. Do the authors agree and have they considered this?

   Clearly, there would be other ways to look for such a final charged or otherwise hairy remnants but without being more specific about the model, it is not clear from the analysis in the manuscript that the same could not be said for many non-minimally coupled examples as well.

3. In Appendix D, it is not entirely clear to me what is meant by "indistinguishably" in "Our ability to indistinguishably observe a secondary mode ..." . From $\rho_{\rm res}$, I would infer that it

is meant to imply the secondary mode is distinguishable from the fundamental gravitational 220 mode, is that correct?

4. A key point emphasized in the manuscript is how different the scalar or vector modes are in frequency from the gravitational, Kerr modes in order to be "distinguishable" (see previous point). Here, the focus seems to be on the comparison between the fundamental gravitational mode and other modes: "At variance with overtones, the frequency of the (220) scalar or vector mode is always well separated from that of the fundamental gravitational mode (and hence more easily resolvable from the latter)" (page 3, end of section II). First, this seems to ignore the degeneracy of scalar, vector, and gravitational (220) modes as $\chi_f \to 1$. Second, in the context of tests of black holes in General Relativity, I would be more concerned about misidentifying another gravitational, Kerr mode or quadratic QNM with a scalar or vector mode. Why are the authors not more concerned about such confusion? More generally, one may worry that the proposed test only becomes interesting at ringdown SNR where several other modes, currently neglected, should be included in the analysis.

5. Currently three events are considered for the real data. For each of the event, some motivation is given for why they are an interesting choice in the beginning of Section III but do the authors have a more systematic selection mechanism (say ringdown SNR)? Why not?

6. On page 4, right-column (main text, below the figure), Jeffreys' scale criterion is invoked with reference to his book "The theory of Probability"from 1939. Some more recent references within the domain of gravitational wave tests of General Relativity such as [1, 2, 3] may be more appropriate to interpret the results in addition to the historical reference, whose thresholds could be considered arbitrary in the context of the manuscript.

7. It seems the amplitude-ratio $A_{R,220}$ is currently defined in the caption to table I. If so, I would also define it in the main text.

8. On page 2, left-column, last paragraph it is written that: "Namely, we propose to look for extra modes in the ringdown signal, which are not related to deformations of the Kerr ones". Perhaps it is not necessary to emphasize this, but they are not related in frequency directly to deformations of the *gravitational* Kerr ones.

References

[1] W. Del Pozzo, J. Veitch, and A. Vecchio, "Testing General Relativity using Bayesian model selection: Applications to observations of gravitational waves from compact binary systems," *Phys. Rev. D* **83** (2011) 082002, `arXiv:1101.1391 [gr-qc]`.

[2] S. Gossan, J. Veitch, and B. S. Sathyaprakash, "Bayesian model selection for testing the no-hair theorem with black hole ringdowns," *Phys. Rev. D* **85** (2012) 124056, `arXiv:1111.5819 [gr-qc]`.

[3] J. Calderón Bustillo, P. D. Lasky, and E. Thrane, "Black-hole spectroscopy, the no-hair theorem, and GW150914: Kerr versus Occam," *Phys. Rev. D* **103** no. 2, (2021) 024041, `arXiv:2010.01857 [gr-qc]`.