BLACK HOLE SPECTROSCOPY HORIZONS
FOR CURRENT AND FUTURE GRAVITATIONAL WAVE DETECTORS

LIGO-VIRGO OPEN DATA WORKSHOP #4

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ABSTRACT

In the final stage of a binary black hole merger, gravitational waves are emitted in the form of damped sinusoids (quasinormal modes), whose spectrum is characterized by the properties of the remnant black hole. Black hole spectroscopy is the proposal to use the detection of two or more quasinormal modes to test the no-hair theorem. For current and future gravitational wave detectors, we obtain the black hole spectroscopy horizons: the maximum distance up to which two or more modes can be detected in the ringdown of a binary black hole merger.

BACKGROUND

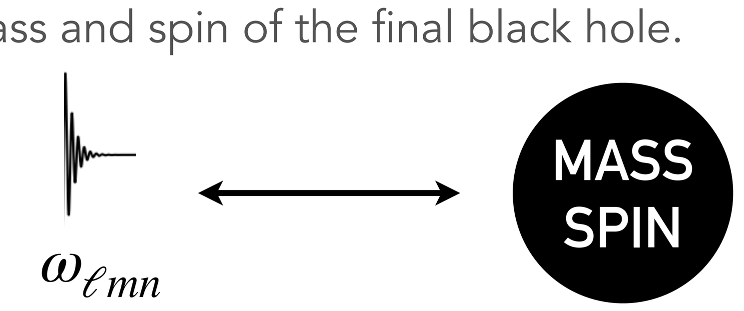
- The gravitational wave emitted during the final phase (ringdown) of a binary black hole merger is well approximated by *quasinormal modes* (QNMs). The waveform of this stage can be written as

$$h_+ + ih_\times = \frac{M_f}{D_L}\sum_{\ell mn} A_{\ell mn} e^{i[\omega_{\ell mn}(t-t_i)+\phi_{\ell mn}]}\,{}_2S_{\ell m}(a\omega_{\ell mn}).$$

- The QNMs characteristic complex frequencies $\omega_{\ell mn} \equiv 2\pi f_{\ell mn} + i/\tau_{\ell mn}$encode information about the remnant black hole.

NO-HAIR THEOREM

- Astrophysical black holes (Kerr) are described by their mass and spin → QNMs frequencies depend only on the mass and spin of the final black hole.



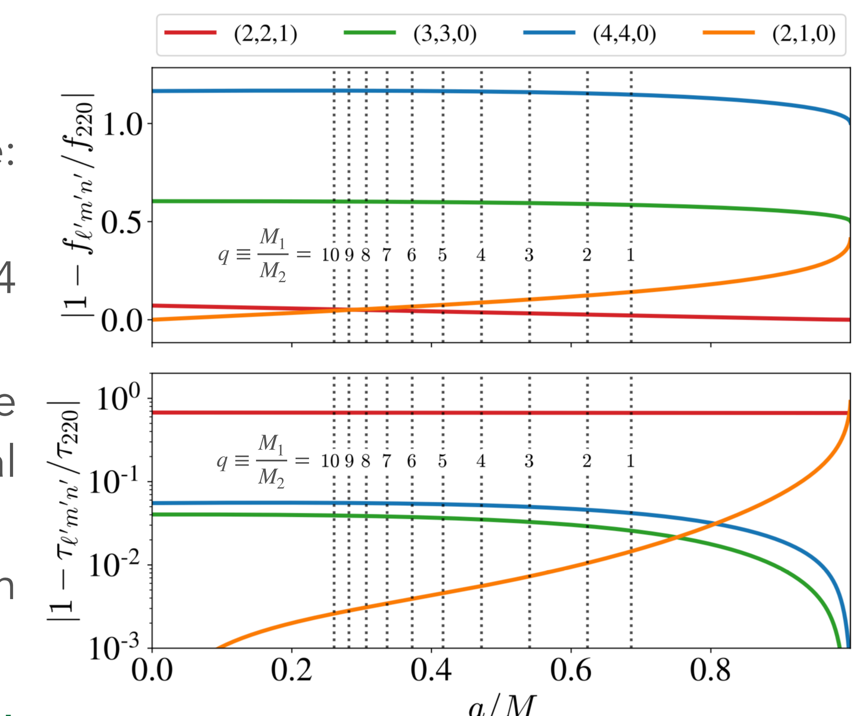
BLACK HOLE SPECTROSCOPY

- A single QNM frequency is needed to determine the mass and the spin.
- The detection of multiple QNMs can be used to make an independent test of the no-hair theorem: two or more modes should be consistent with the same final mass and spin [1, 2, 3].

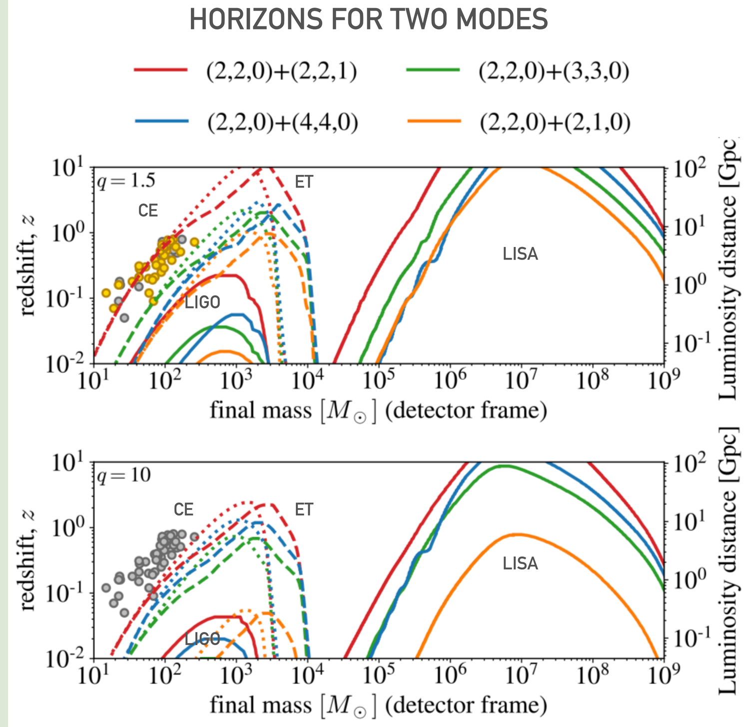
BLACK HOLE SPECTROSCOPY HORIZONS

QNMS IN THE RINGDOWN

- The dominant mode is the fundamental quadrupolar mode: $(\ell, m, n) = (2,2,0)$.
- The dominant mode was detected in the ringdown of GW150914 and other detections [4,5].
- The inclusion of sub-dominant QNMs in the analyses decreases the error in the determined mass and spin, but there is *no* statistical evidence for the detection of a second mode in the data [5, 6, 7].
- *Black hole spectroscopy horizon:* maximum distance up to which two or more modes can be detected.



BLACK HOLE SPECTROSCOPY HORIZONS FOR TWO MODES



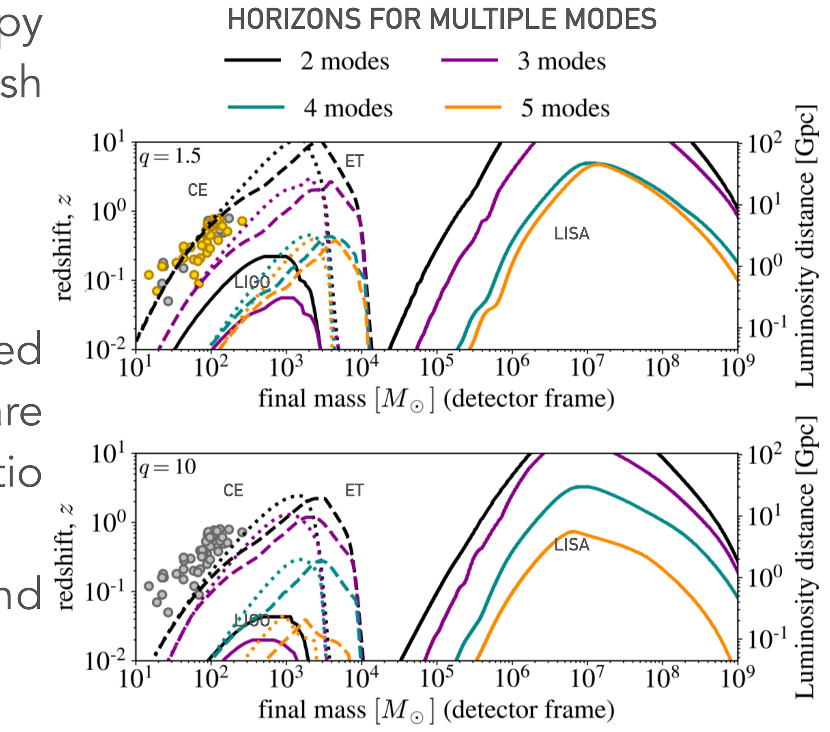
RESOLVABILITY: RAYLEIGH CRITERION

- To perform black hole spectroscopy we need to be able to distinguish two or more modes [2]:

$$|f_{\ell mn} - f_{\ell'm'n'}| > \max(\sigma_{f_{\ell mn}}, \sigma_{f_{\ell'm'n'}}),$$
$$|\tau_{\ell mn} - \tau_{\ell'm'n'}| > \max(\sigma_{\tau_{\ell mn}}, \sigma_{\tau_{\ell'm'n'}}).$$

- Measurement errors are computed using Fisher Matrix and they are valid for high signal to noise ratio (SNR) cases.
- Gives and either-or answer and permits no gradation.

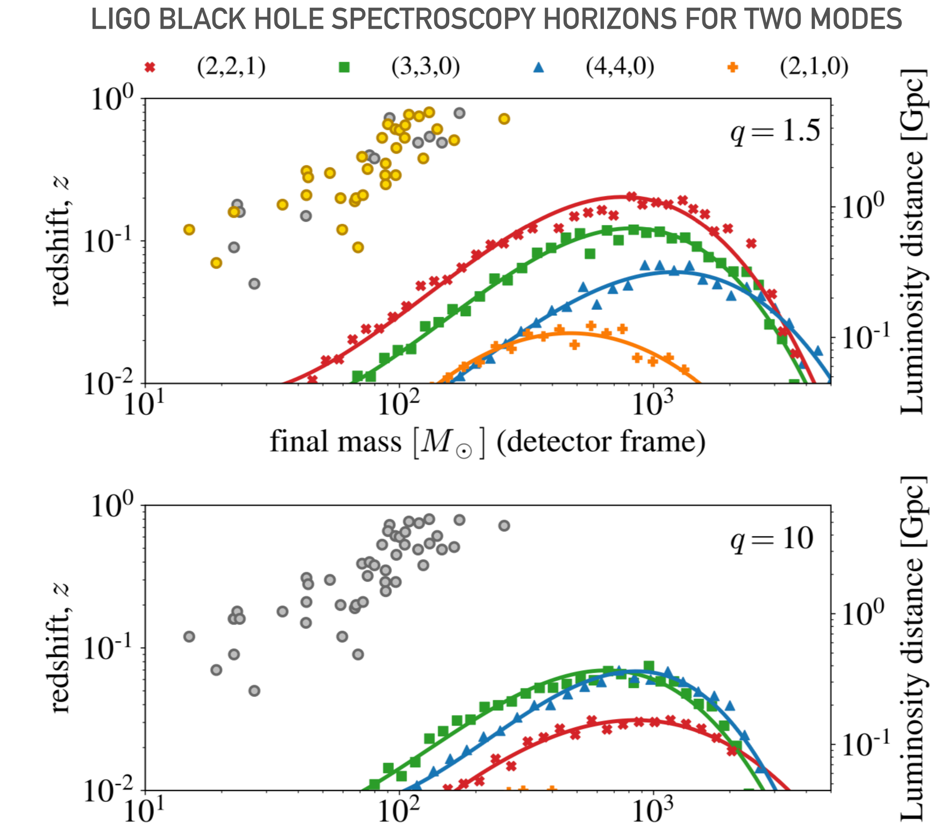
BLACK HOLE SPECTROSCOPY HORIZONS FOR MULTIPLE MODES



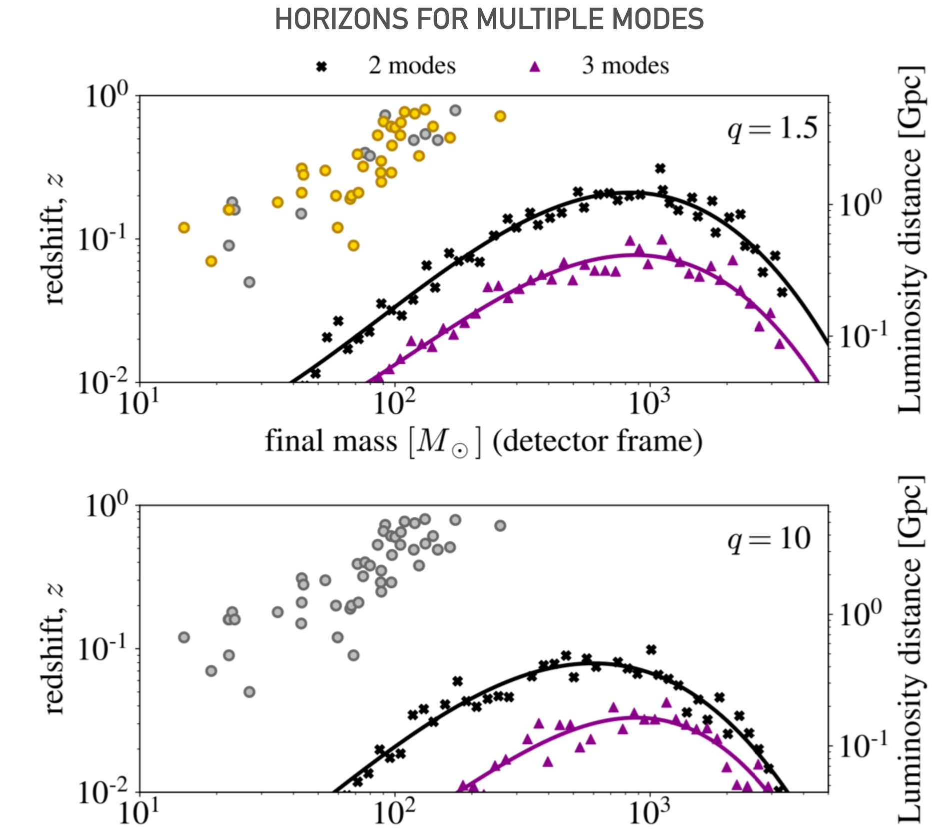
BAYESIAN INFERENCE AND MODEL COMPARISON (LIGO)

- Bayesian inference is used in parameter estimation of real data analyses.
- We require a Bayes factor $\log B^{\text{N modes}}_{\text{N-1 modes}} \geq 8$, where N = 2, 3, as evidence for an extra mode in the signal.
- Injected signals are informed by Numerical Relativity:
  - two-mode cases: $d = n + d_{220} + d_{\ell mn}$
  - multiple-mode cases: $d = n + d_{220} + d_{221} + d_{330} + d_{440} + d_{210}$

LIGO BLACK HOLE SPECTROSCOPY HORIZONS FOR TWO MODES



LIGO BLACK HOLE SPECTROSCOPY HORIZONS FOR MULTIPLE MODES



FINAL REMARKS

- There are exciting prospects for testing the nature of black holes with gravitational waves!
- Black hole spectroscopy provides an independent test of the no-hair theorem using information contained in the ringdown of a binary black hole merger.
- The first overtone is favored for binaries with more symmetric masses (q=1) and higher harmonics are favored for less symmetric masses (q = 10).
- Einstein Telescope and Cosmic Explorer will be sensitive enough to resolve events similar to the events detected so far.
- LISA black hole spectroscopy horizons are very big, but its sources are still uncertain.
- Closer sources will be needed to perform black hole spectroscopy with a single LIGO. Multiple detections analysis and mode stacking may compensate the low sensitivity.

REFERENCES

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