Testing the black hole no-hair conjecture with gravitational waves

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Background

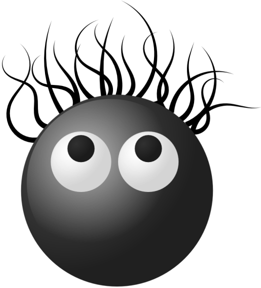
No-hair theorem

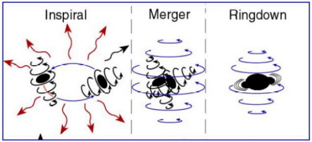
- *Stationary BHs are completely characterised by mass M, angular momentum J and charge Q.*

- With as many as 5 confirmed BBH source detections, GW astronomy has become quite routine with the advanced detector era.

- The current detector sensitivity and the parameters of the observed binaries has however not been enough to extensively probe the ringdown regime of GWs.

- Analyses of ringdown have focussed on target sources by 3$^{\text{rd}}$ generation of detectors like the *Einstein Telescope*.



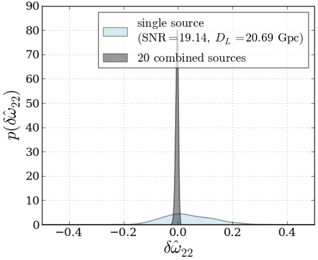


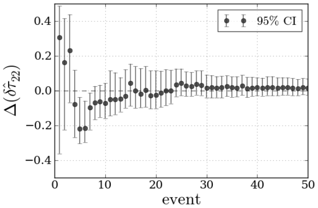
Characterisation of ringdown

- *Quasi-Normal Modes* emitted during ringdown resemble *damped* sinusoids:

$$h(t) = \frac{1}{D_L} \sum_{l,m>0} A_{lm} \mathrm{e}^{-t/\tau_{lm}} Y_{lm}(\theta, \phi) \cos(\omega_{lm} t + m\phi)$$

- $\omega_{lm}^{GR} = \omega_{lm}^{GR}(M, J)$
  $\tau_{lm}^{GR} = \tau_{lm}^{GR}(M, J)$
- Consistency test for No-hair theorem:
  - $\omega_{lm} = \omega_{lm}^{GR}(1 + \delta\hat{\omega_{lm}})$
  - $\tau_{lm} = \tau_{lm}^{GR}(1 + \delta\hat{\tau_{lm}})$





Meidam et al., Phys. Rev. D 90, 064009 (2014)

Highlights from current work

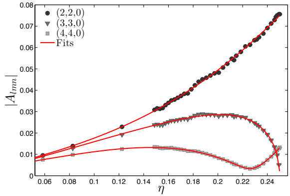
- Considering overtone index n beyond the fundamental mode ($n = 0$).
- Estimate parameters characterising ringdown from future 2^{nd} generation detectors (*design sensitivity*).
- As few as $\mathcal{O}(5)$ sources sufficient for constraining GR from a consistency test of the no-hair theorem.

Ringdown-only waveform model

- Considering non-spinning progenitors.
- Waveform model of the form:

$$h(t) = \frac{1}{D_L} \sum_{n,l,m} A_{lmm} S_{lmn}(\theta, \phi) \mathrm{e}^{i(\omega_{lmn} + i/\tau_{lmn})t}$$

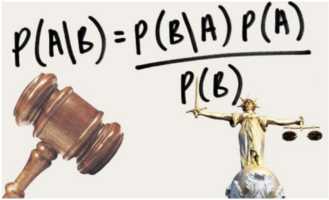
- Parameter space: $\{M_f, a_f, q, \alpha, \delta, \iota, \psi, D_L, t_c, \varphi_c\}$.
- The amplitudes A_{lmn} are given by NR simulation fits as series expansions in $\eta = \frac{m_1 m_2}{(m_1+m_2)^2}$.



London,Healy,Shoemaker, Phys. Rev. D 90, 124032 (2014)

Method

- Focus on Bayesian inference for all analyses.
- Using inference module `LALInference` in the LIGO data analysis software `LAL`.
- Choose conservative prior distributions on sampling parameters.
- Numerical relativity simulations from publicly available **SXS** catalogue being used.



Picture: The Guardian

Veitch et al.,2015
https://wiki.ligo.org/DASWG/LALSuite

Method · · ·

- Extracting ringdown-only signal from an NR simulation using *Planck window*:

$$f(t) = \frac{1}{1 + e^{\left(\frac{t_{end} - t_{start}}{t - t_{start}} + \frac{t_{end} - t_{start}}{t - t_{end}}\right)}}$$

- Window placement made $10 - 20M$ after the peak of the waveform.
- Optimal placement required to ensure being in the linearised regime and also have enough SNR in the signal.

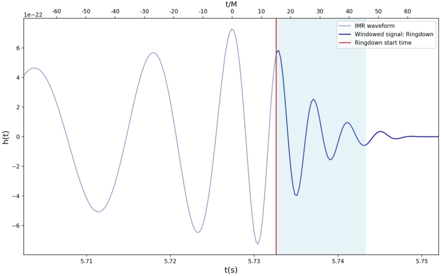


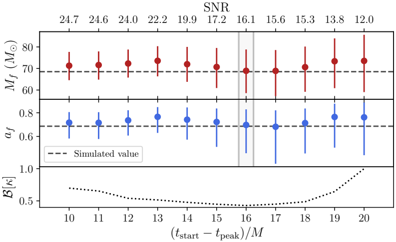
Figure courtesy: Gregorio Carullo

Sources simulated

- The component masses of the simulated sources lie between [50,90] $M_\odot$ and mass ratios $q \in [1, 3]$.
- Luminosity distances to the source are chosen such that the SNR of the full signal $\sim$ 100.
- This leaves a *ringdown-only-SNR* $\sim$ 15.

Parameter estimation

- The window is applied to the simulated signal *as well as* the template.
- The start-time of the window is varied from 10M to 20M after the peak of the waveform in steps of M.
- It was found that at 16M after the peak, the parameter estimates are most accurate, by minimising the following:



$$\mathcal{B}(\kappa) = \sqrt{\Delta\vec{x}(\kappa) \mathrm{C}^{-1}(\kappa) \Delta\vec{x}(\kappa) + \det \mathrm{C}(\kappa)}$$

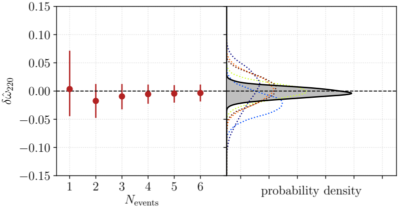
$$M_f = 68.5\, M_\odot, a_f = 0.686$$

$$\Delta\vec{x}(\kappa) = \left(\frac{\bar{M}_f(\kappa) - M_f}{M_\odot}, \bar{a}_f - a_f \right)$$

Carullo et al., arXiv: 1805.04760

Results on testing general relativity

- $\omega_{lmn}(M_f, a_f) \to (1 + \delta\hat{\omega}_{lmn})\omega_{lmn}(M_f, a_f)$
  $\tau_{lmn}(M_f, a_f) \to (1 + \delta\hat{\tau}_{lmn})\tau_{lmn}(M_f, a_f)$
- Parameterisation is agnostic to a particular nature of violation of the no-hair theorem.
- Damping times and frequencies depend only on M_f and a_f; independent measurement of three paramaters sufficient to constrain the conjecture.
- Least damped mode ($n = 0$) most informative.



Carullo et al., arXiv: 1805.04760

Future avenues

- Extend analyses to using spin-aligned progenitor sources.
- Use the method on the BBH detections made so far.
- Extend to higher mass ratio q.