Ringdown and echoes as probes of strong-field dynamics of GR

Archisman Ghosh
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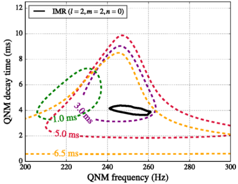
Michalis Agathos, Vitor Cardoso, Gregorio Carullo, Katerina Chatziioannou, Otto Hannuksela, Tjonnie Li, Tyson Littenberg, Lionel London, Jeroen Meidam, Peter Pang, Laura van der Schaaf, Ka Wa Tsang, Chris Van Den Broeck

Tests of GR in O1 run of Advanced-LIGO

Overview by Walter Del Pozzo

♣ First measurements of orbital dynamics beyond leading order in v/c.

♣ Consistency of observed signal with that expected from binary black holes mergers as predicted by GR: residuals; consistency between inspiral and merger-ringdown; ring-down consistent with least-damped quasinormal mode of a remnant Kerr black hole.



♣ Expect constraints to become stronger with subsequent detections.

Probing the nature of the compact objects

Are they really black holes, or exotic compact objects?

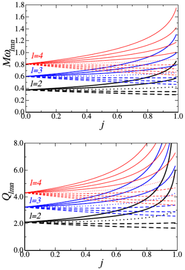
"Complementary" ways in different regimes:

- ♣ Tidal effects during inspiral.
- ♣ No-hair theorem with quasinormal modes.
- ♣ Search for post-merger oscillations or "echoes".

This talk: no-hair theorem with quasinormal modes, and search for post-merger oscillations.

Testing the no-hair theorem with quasinormal modes

No-hair theorem: A stationary black hole in Einstein's general relativity is described only by its mass and spin.



Berti *et al* (2006)

During ringdown, the quasinormal mode frequencies and damping times will depend only on the mass and spin of the remnant black hole, which can be obtained from linearized Einstein equations on Kerr background.

Test for dependences $\omega_{lmn}(M_f, J_f)$, $\tau_{lmn}(M_f, J_f)$.

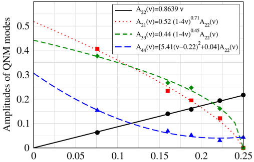
Testing the no-hair theorem with quasinormal modes

Even where it is not possible to measure the ω_{lmn} and τ_{lmn} directly, by combining information from multiple events, systematic departures from their GR values ($\delta\omega_{lmn}$ and $\delta\tau_{lmn}$) can be constrained.

$$\omega_{lmn} = \omega_{lmn}^{GR}(1+\delta\omega_{lmn}),\ \tau_{lmn} = \tau_{lmn}^{GR}(1+\delta\tau_{lmn})$$

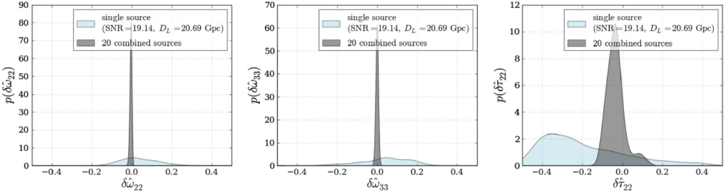
à la parameterized deformations

NR fits: Kamaretsos *et al* (2012)
Implementation: Gossan *et al* (2012)



$$\{\delta\omega_{220}, \delta\omega_{330}, \delta\tau_{220}\}$$

ET, 20 sources, masses: 500–1000 $M_\odot$, ringdown SNR $\sim$ 20:

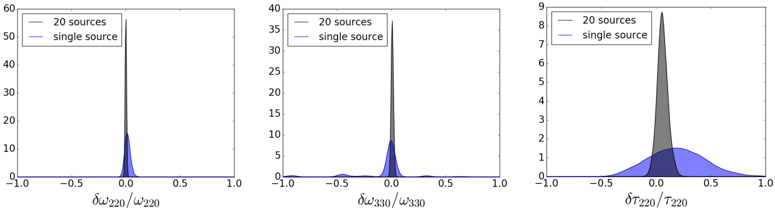


Results from: Meidam *et al* (2014)

Possible even with Advanced-LIGO!

GW150914-like source at aLIGO design, will have a ringdown SNR > 20.

aLIGO design, 20 sources, masses: 50–100 $\mathrm{M}_\odot$, ringdown SNR ~ 20:

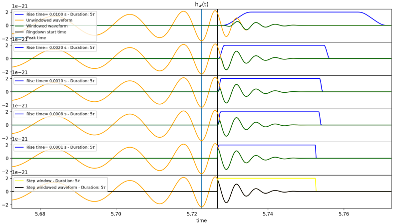


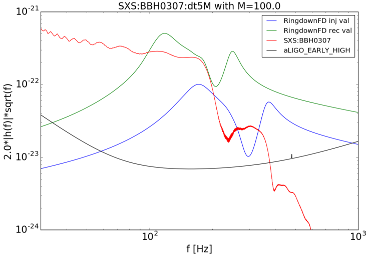
injection same as recovery template

Caveats

♣ Ringdown template occasionally tries to latch onto the pre-merger part.

♣ Cut at appropriate time; window with proper steepness.





Relative phase offsets between modes not correctly included in existing implementations.

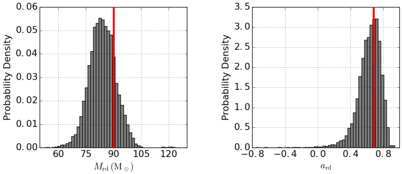
Improved models available

London *et al* (2012)

- Systematic errors in previous models.

"Multi-mode ringdown" model: *Talk by Lionel London*

- Inclusion of subdominant modes.



"Multi-mode ringdown" model gives better ringdown parameter estimates.

van der Schaaf, Carullo, Pang, Tsang, Hannuksela, Meidam, Agathos, AG, London, Li, Van Den Broeck

Post-merger oscillations or "echoes"

Cardoso *et al* (2016)

Horizon-scale corrections $\Rightarrow$ secondary bursts of radiation.

A large class of exotic compact objects.

Modulated and distorted train of "echoes".

$$\Delta t = nM \log(M/l)$$

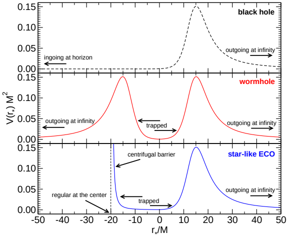
n=8: wormholes

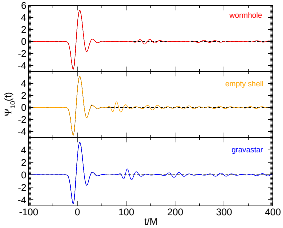
n=4: empty shell

n=6: thin-shell gravastars

Planck-scale corrections can appear relatively soon.

For an event like GW150914, $\Delta t = \mathcal{O}(100\,\text{ms})$, at aLIGO design can hope to see first few echoes.



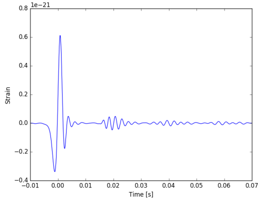


Talks by Jahed Abedi and Alex Nielsen, and poster by Julian Westerweck on modelled searches.

Model-independent search for echoes

- Form of echoes not sufficiently modelled.
- Exotic objects not envisaged in literature.

Search for repeating bursts of radiation immediately following the binary-merger detection.



Independent of detailed models: look for coherence between multiple detectors and between the subsequent bursts.

Results from BayesWave (placeholder).