Probing the nature of compact objects using gravitational-wave ringdown and echoes

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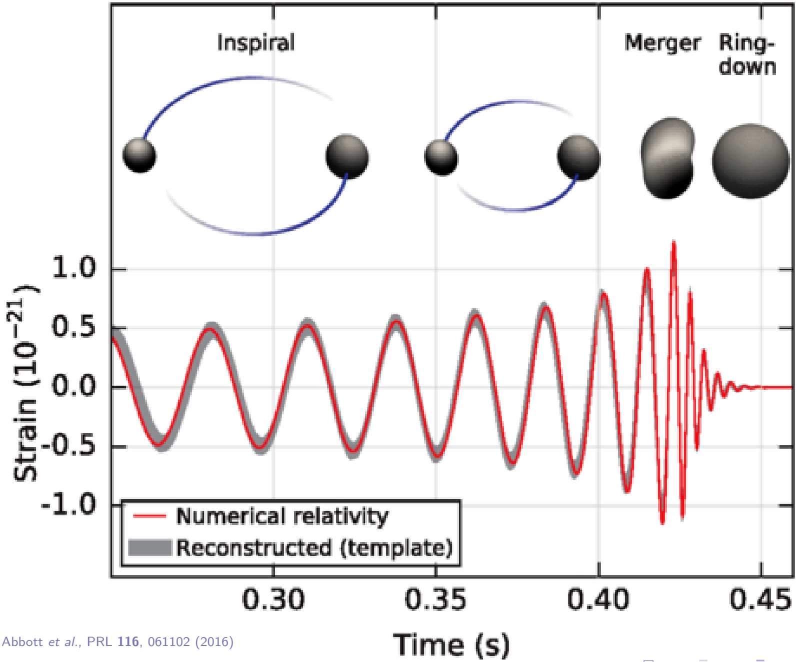


Abbott *et al.*, PRL **116**, 061102 (2016)

Probing the nature of the progenitor and remnant compact objects

Are they really black holes, or exotic compact objects mimicking black holes?

Boson stars, dark matter stars, gravastars, shells, wormholes, **non-local stars**, . . .

Three "complementary" ways in three different regimes:

- Finite size effects during inspiral. HINDERER
- No-hair conjecture with **ringdown** quasinormal modes. THIS TALK
- Search for post-merger oscillations or **"echoes"**. THIS TALK

Testing the no-hair conjecture

No-hair conjecture: *A stationary black hole in Einstein's GR is described only by its mass and spin.*

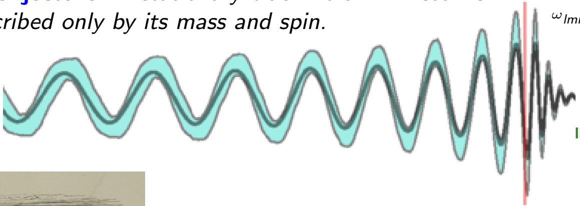
ringdown

quasinormal modes (QNM)

$\omega_{lmn}(M_f\,,a_f),\ \ \tau_{lmn}(M_f\,,a_f)$

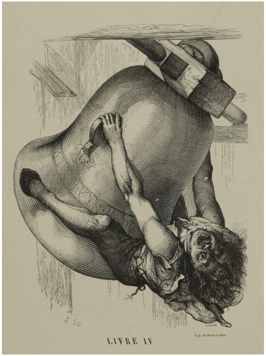
damped oscillations

"bell"



linear

non-linear



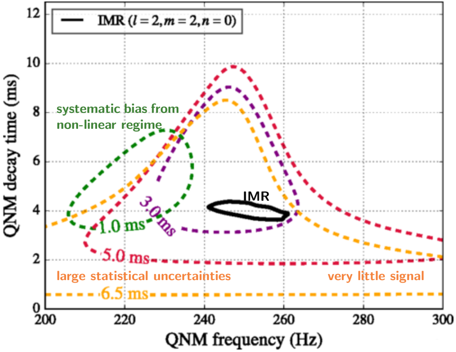
linear regime

damped sinusoids

Consistency of what we observe with a set of QNM frequencies / damping times?

Ringdown of GW150914

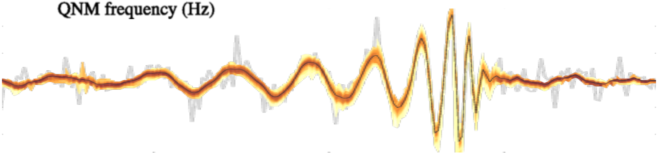
Abbott *et al.*, PRL **116**, 221101 (2016)



linear regime

damped sinusoids

Time after peak ampl.	SNR
1.0 ms	
3.0 ms	8.5
5.0 ms	6.3
6.5 ms	4.8



Difficult to measure leading QNM for GW150914.

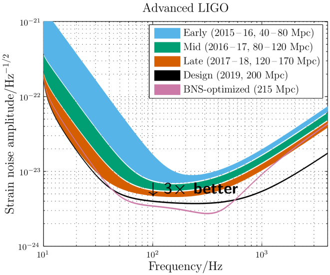
Expected improvement in the coming years

- Additional detectors.

  Loudness scales as $\sqrt{N_{\text{detectors}}}$.

- Accuracies scale with detector sensitivity.

  For same event 3× better at design sensitivity.



Abbott *et al.*, LLR (2016) 19:1

- Leading QNM of GW150914-like source should be clearly detectable.

Multipole modes are needed for a ringdown-only test of the no-hair conjecture

Algorithm for ringdown parameter estimation no-hair conjecture test

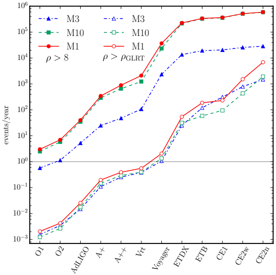
Testing the no-hair conjecture with ringdown quasinormal modes

Design sensitivity $\sim$ 3 times higher.

Need about 3$\times$ design sensitivity to isolate subleading QNM

Assumed populations . . .

Single event!



Berti *et al.* (2016)

Combine information from multiple detections:

- "Coherent mode stacking" — Yang *et al.* (2017)
- Parameterized deformations — Gossan *et al.* (2011), Meidam *et al.* (2014)

Testing the no-hair conjecture with ringdown quasinormal modes

- Even where one is not able to isolate the individual modes, one can look for **systematic** departures in the QNM frequencies and damping times from their GR values.

Gossan *et al.* (2011) Meidam *et al.* (2014)

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

- Sensitive to **generic** deformations.

- The general expectation was that such tests would become effective only for sources detected by third generation or space-based detectors.

A "recipe" for ringdown parameter estimation

- Ringdown-hunting is a sophisticated data-analysis problem.

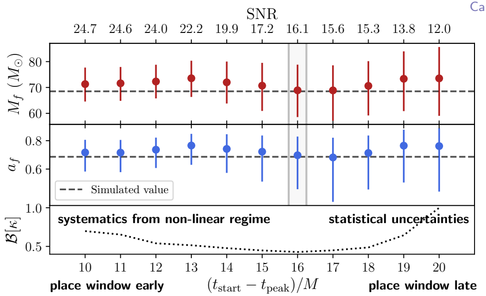
Ringdown template occasionally tries to latch onto the pre-merger part of the signal

A higher mode in ringdown template often tries to match leading order mode

GW150914: $10M \approx 3.3$ms

- Remove earlier detector data and search in $[10M, 30M]$ following peak of signal.

Carullo *et al.* (2018) with **AG**



- Effective criterion for "start of ringdown" from point of view of parameter estimation.

PHYSICAL REVIEW D **98,** 104020 (2018)

Empirical tests of the black hole no-hair conjecture using gravitational -wave observations

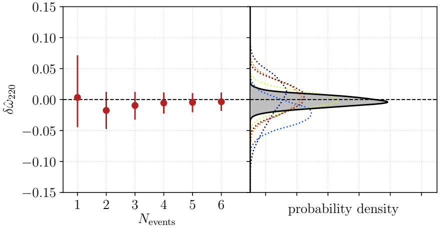
Gregorio Carullo,[1,2,*] Laura van der Schaaf,[2] Lionel London,[3] Peter T. H. Pang,[4] Ka Wa Tsang,[2] Otto A. Hannuksela,[4] Jeroen Meidam,[2] Michalis Agathos,[5] Anuradha Samajdar,[2] Archisman Ghosh,[2] Tjonnie G. F. Li,[4] Walter Del Pozzo,[1,6] and Chris Van Den Broeck[2,7]

- Start with GR templates with ringdown. Add systematic QNM deformations.

(2,2,0), (2,2,1), (2,1,0), (3,3,0), (3,3,1), (3,2,0), (4,4,0), (4,3,0), (5,5,0)
London *et al.* (2017)

- With $\mathcal{O}(5)$ BBH sources similar to GW150914, the systematic departures can be measured with an accuracy of $\sim 1.5\%$ by the Adv LIGO-Virgo at design sensitivity.

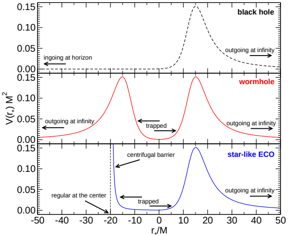
If we observe a 100 $M_\odot$-60 $M_\odot$ BBH tomorrow, we can use this algorithm to detect ringdown and start testing the no-hair conjecture!

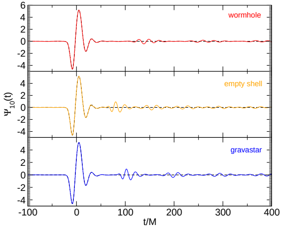


Search for "echoes" after the merger

In a large class of exotic compact objects,

Cardoso *et al.* (2016)





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

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.

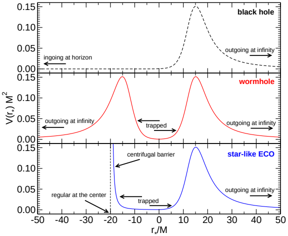
For an event like GW150914, $\Delta t = \mathcal{O}(100\,\mathrm{ms})$, at aLIGO design can hope to see first few echoes.

Can search for "echoes" immediately following the binary-merger detection.

Not sufficiently modelled; Exotic objects not envisaged in literature.

Robust features?

Cardoso *et al.* (2016)



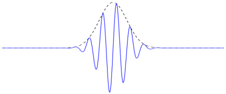
- Time difference between subsequent echoes.
- A “damping” at each reflection.
- A “phase-shift” at each reflection.
- Some change of the frequency content: “widening”.

Zachary et al. (2017)

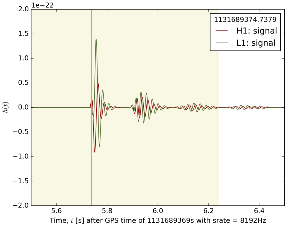
Model-agnostic search and characterization using BayesWave

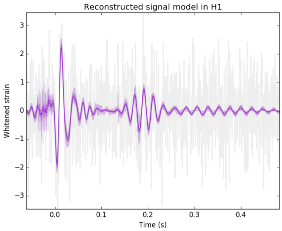
- BayesWave: Morlet-Gabor wavelet reconstruction: Cornish & Littenberg (2015)

$$h(t) = \sum_{j=0}^{N_s} \Psi(t; A_j, f_{0j}, \tau_j, t_{0j}, \phi_{0j})$$



$$\Psi(t; A, f_0, \tau, t_0, \phi_0) = A e^{-(t-t_0)^2/\tau^2} \cos\left(2\pi f_0 (t - t_0) + \phi_0\right)$$





A model-agnostic coherent search for echoes

- Use wavelets that are trains of sine-Gaussians to reconstruct the signal

$$\Psi(t; A_n, f_0, \tau, t_n, \phi_n) = \sum_{n=0}^{N_{\text{echoes}}} A e^{-(t-t_n)^2/\tau_n^2} \cos\left(2\pi f_0 (t - t_n) + \phi_n\right)$$

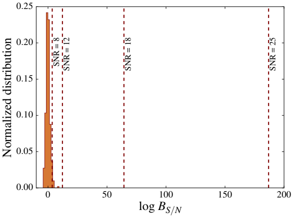
With:

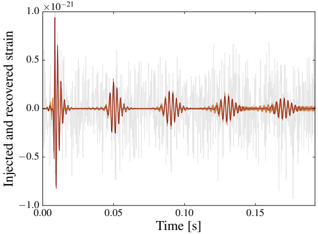
$A_n = \gamma^n A$	damping
$\tau_n = w^n \tau$	widening
$t_n = t_0 + n\Delta t$	time between subsequent echoes
$\phi_n = \phi_0 + 2\pi f_0 n\Delta t + n\Delta\phi$	phase shift subsequent echoes

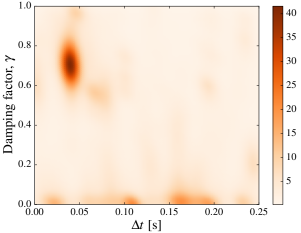
PHYSICAL REVIEW D **98,** 024023 (2018)

A morphology-independent data analysis method for detecting and characterizing gravitational wave echoes

Ka Wa Tsang,[1] Michiel Rollier,[1] Archisman Ghosh,[1] Anuradha Samajdar,[1] Michalis Agathos,[2]
Katerina Chatziioannou,[3] Vitor Cardoso,[4] Gaurav Khanna,[5] and Chris Van Den Broeck[1,6]





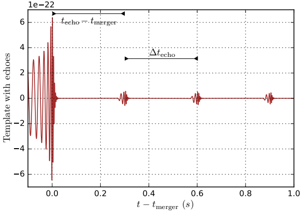


Results on detections: Prologue

PHYSICAL REVIEW D **96,** 082004 (2017)

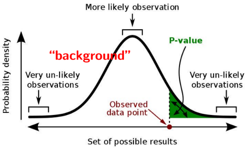
Echoes from the abyss: Tentative evidence for Planck-scale structure at black hole horizons

Jahed Abedi,[1,2,3,*] Hannah Dykaar,[4,5] and Niayesh Afshordi[3,5,†]



	Range	GW150914	Combined
$(t_{echo} - t_{merger})/\Delta t_{echo}$	(0.99,1.01)	1.0054	1.0054
γ	(0.1,0.9)	0.89	0.9
$t_0/\overline{\Delta t}_{echo}$	(-0.1,0)	-0.084	-0.1
Amplitude[a]		0.0992	0.124
SNR_{max}		4.21	6.96
p-value		0.11	0.011
significance		1.6σ	2.5σ

2.5-σ



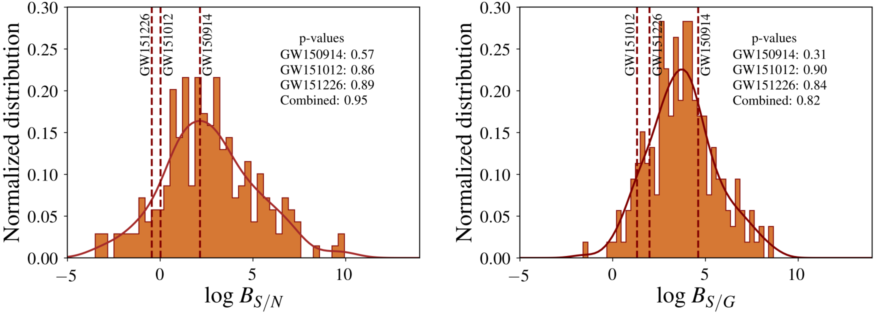
Event	[21]	original 16s (32s)	widened priors 16s (32s)
GW150914	0.11	0.199 (0.238)	0.705 (0.365)
LVT151012	-	0.056 (0.063)	0.124
GW151226	-	0.414 (0.476)	0.837
GW170104	-	0.725	0.757
(1,2)	-	0.004	0.36
(1,3)	-	0.159	0.801
(1,2,3)	0.011	0.020 (0.032)	0.18 (0.144)
(1,3,4)	-	0.199 (0.072)	0.9 (0.32)
(1,2,3,4)	-	0.044 (0.032)	0.368 (0.112)

1.3-σ

Westerweck *et al.* (2018)

Echoes search at O1 BBH detections - Bayesian evidences

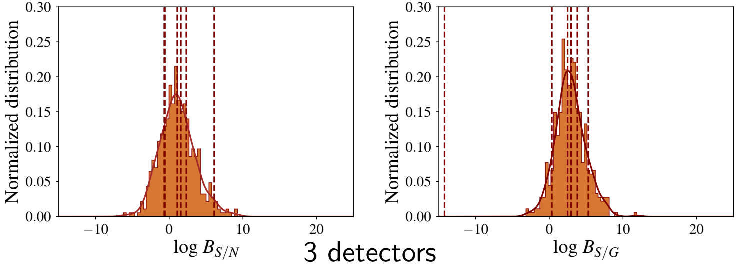
Background calculation:
Analyze $\sim$ 200 8s-segments from GPSTime 1126073529 to 1126075217



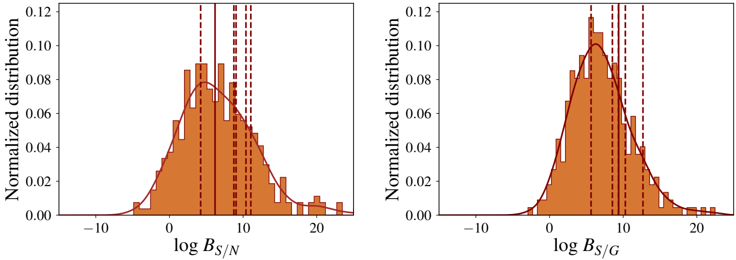
All three events are well within the background.

GWTC-1 results

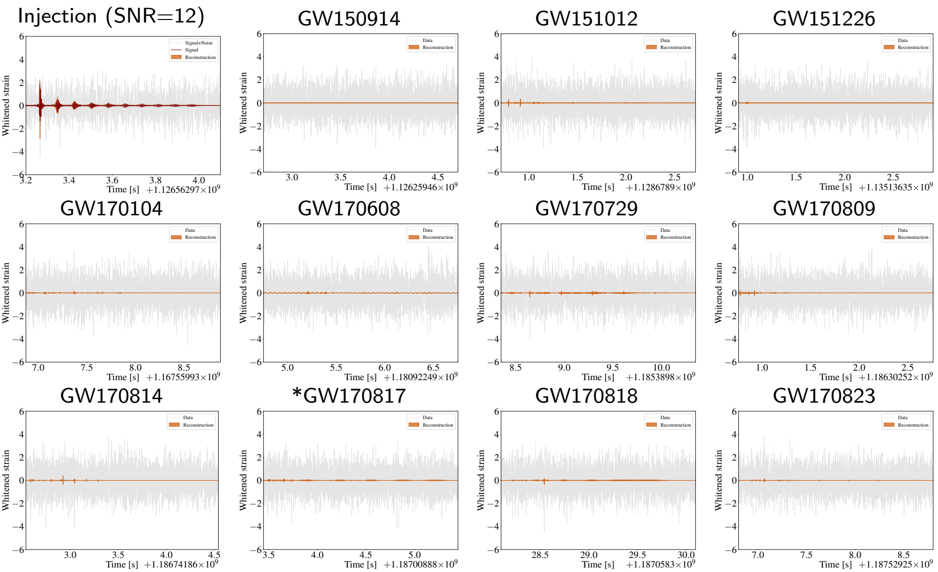
2 detectors



3 detectors



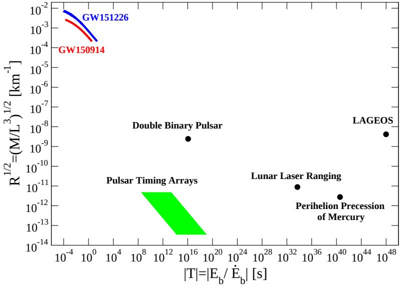
Reconstructions from injection and all GWTC-1 detections



Summary and Outlook

Yunes *et al.* (2016)

Windows of extremely strong-field gravity.



Probing length scales $r \sim 3M - r \sim 2M$.

Ringdown and echoes are two possible GW signatures . . .

Exciting new physics may show up soon!