Silence past the peak

Archisman Ghosh
Nikhef, Amsterdam

8^{th} Belgian-Dutch Gravitational Waves Meeting
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PHYSICAL REVIEW D **98,** 104020 (2018)

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

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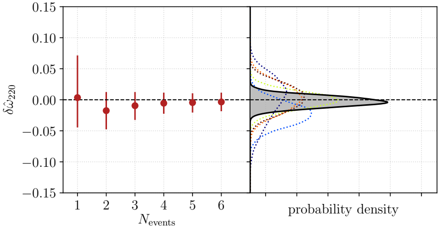
- Start with GR templates with ringdown. Add systematic QNM deformations:

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

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

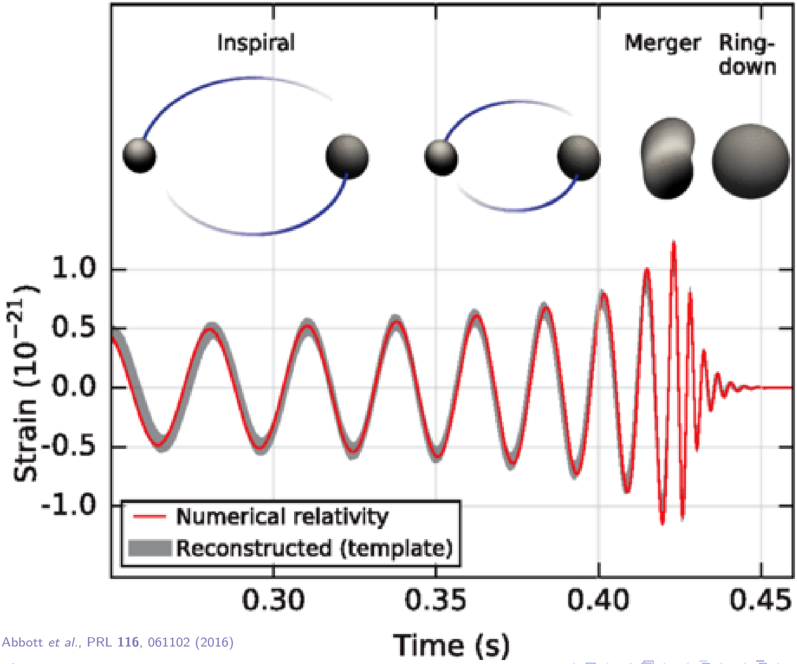
- With $\mathcal{O}(5)$ BBH sources similar to GW150914, the systematic departures can be measured with an accuracy of $\sim 1.5\%$ by the Adv LIGO-Virgo at design sensitivity.

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!



A morphology-independent search for gravitational wave echoes in data from the first and second observing runs of Advanced LIGO and Advanced Virgo

Ka Wa Tsang[1,2], Archisman Ghosh[1], Anuradha Samajdar[1], Katerina Chatziioannou[3], Simone Mastrogiovanni[4], Michalis Agathos[5], and Chris Van Den Broeck[1,2]



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, fuzzballs, . . .

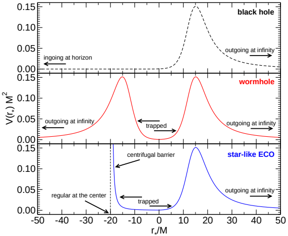
Three "complementary" ways in three different regimes:

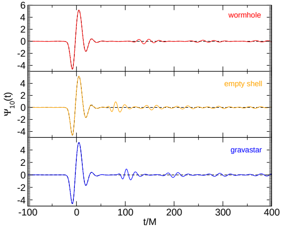
- Finite size effects during inspiral.
- No-hair conjecture with **ringdown** quasinormal modes. ~~THIS TALK~~
- Search for post-merger oscillations or **"echoes"**. THIS TALK

Search for "echoes" after the merger

In a large class of exotic compact objects,

Cardoso *et al.* (2016)





Horizon-scale corrections ⇒ secondary bursts of radiation.

Modulated and distorted train of "echoes".

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

n=8: wornholes

n=4: empty shell

n=6: thin-shell gravastars

Planck-scale corrections can appear relatively soon.

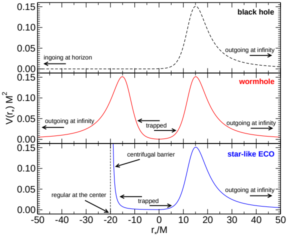
For an event like GW150914, $\Delta t = \mathcal{O}(100\,\mathrm{ms})$, at aLIGO design can hope to see first few echoes.

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)

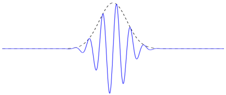


- Time difference between subsequent echoes.
- A "damping" at each reflection.
- A "phase-shift" at each reflection.
- Some change of the frequency content: "widening". *Zachary et al. (2017)*

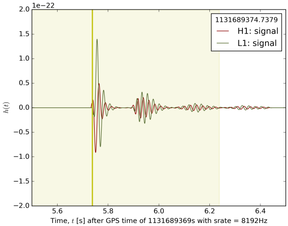
Model-agnostic search and characterization using BayesWave

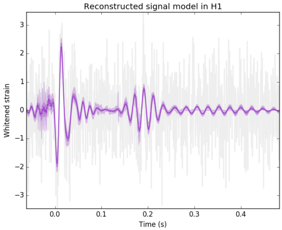
- BayesWave: Morlet-Gabor wavelet reconstruction: Cornish & Littenberg (2015)

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



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





BayesWave: model selection

detector strain = signal + glitch + gaussian noise

signal model: $F^{+}_{\text{detector}}(\theta,\phi,\psi)h_{+}(t-t_{\text{arr}}) + F^{\times}_{\text{detector}}(\theta,\phi,\psi)h_{\times}(t-t_{\text{arr}})$

glitch model: independent sum of wavelets in each detector

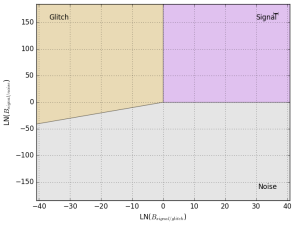
noise model: gaussian noise of given (or measured) PSD

Bayesian Occam's razor

Favours signal over glitch since it is modelled by fewer parameters.

Evidence for Signal

log(Evidence_signal / Evidence_glitch) = 36.3 ± 0.4
log(Evidence_signal / Evidence_noise) = 166.9 ± 0.3



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

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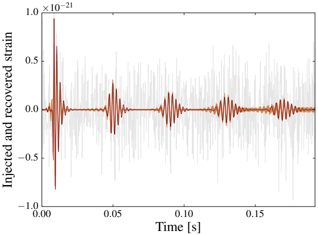
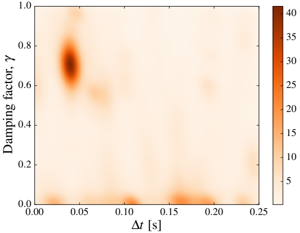
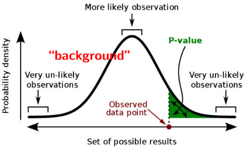
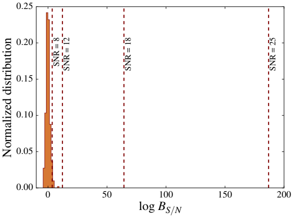






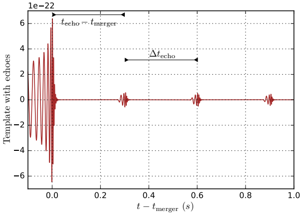


Results on detections: Prologue

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

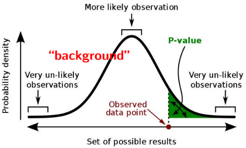
Echoes from the abyss: Tentative evidence for Planck-scale structure at black hole horizons

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 from the Abyss: A highly spinning black hole remnant for the binary neutron star merger GW170817

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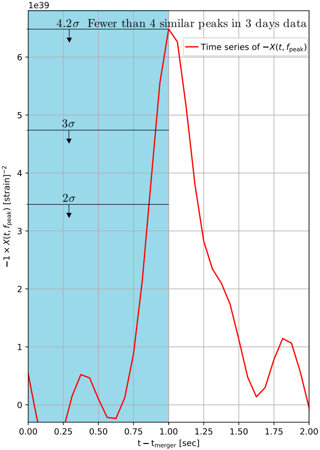

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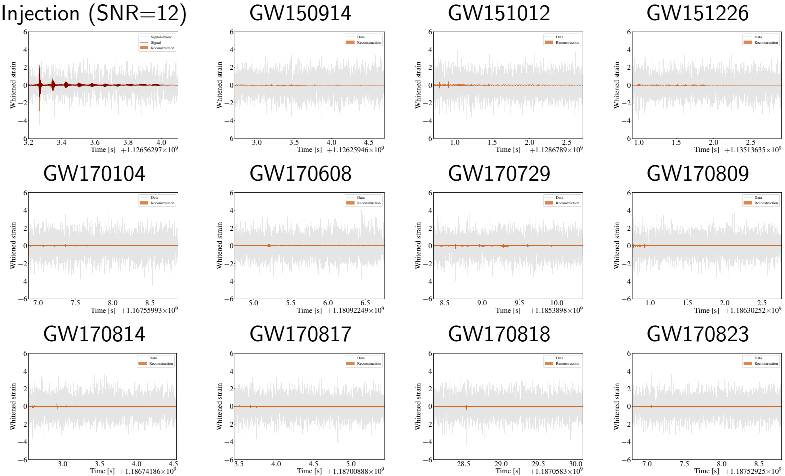
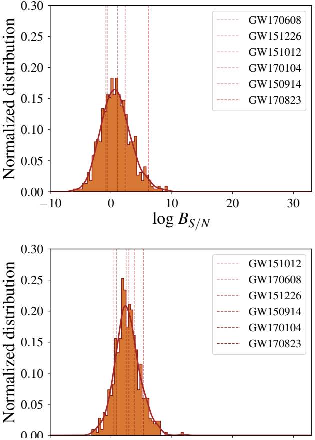
arXiv:1906.11168v1 [gr-qc] 26 Jun 2019

Reconstructions from injection and all GWTC-1 detections

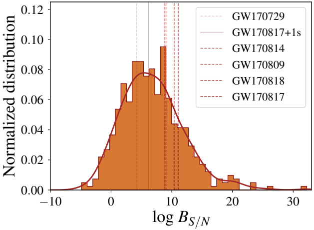


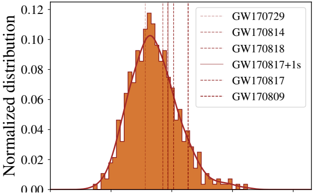
2-detector observations



Event	log $B_{S/N}$	$p_{S/N}$	log $B_{S/G}$	$p_{S/G}$
GW150914	2.32	0.26	2.95	0.43
GW151012	-0.59	0.70	0.35	0.88
GW151226	-0.67	0.72	2.48	0.53
GW170104	1.09	0.44	3.80	0.28
GW170608	-0.90	0.75	0.90	0.82
GW170823	6.11 2.1-σ	0.03	5.29	0.11
Combined		0.34		0.57

3-detector observations



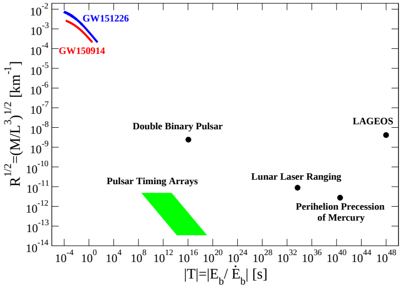


Event	log $B_{S/N}$	$p_{S/N}$	log $B_{S/G}$	$p_{S/G}$
GW170729	4.24	0.67	5.64	0.62
GW170809	9.05	0.31	12.69	0.09
GW170814	8.75	0.33	8.54	0.34
GW170817	11.05	0.19	10.30	0.20
GW170817+1s	6.19	0.52	9.39	0.27
GW170818	10.39	0.23	9.36	0.27
Combined		0.47		0.22

Summary and Outlook

Yunes *et al.* (2016)

Windows of extremely strong-field gravity.



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

Postmerger echoes is one possible observable GW signatures . . .

No convincing signatures yet . . .   but exciting new physics may show up soon!