# Analysing gravitational wave data for black hole echoes

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We repeat the analysis of Abedi, Dykaar and Afshordi (ADA) from arXiv: 1612.00266.

We use the same model templates as ADA but a modified background estimate from arXiv: 1612.05625.

### Our combined significance estimate for these signals is $\sim 1.3\sigma$ (p-value 0.104).



### It is an interesting possibility

- Gravitational waves are ideal for near horizon, strong field effects.
- Longer, horizon scale, wavelengths compared to EM tests.
- Null result would still imply interesting constraints on models.
- We should be open to the unexpected.
- The communication with non-LIGO scientists has worked well and inspired new ideas.

### Using the LOSC open data

- LOSC URL: https://losc.ligo.org/
- ADA originally used only 16 seconds out of 4096 seconds available for each event.

|           | SNR of main event | SNR of echoes | p-value of<br>echoes |
|-----------|-------------------|---------------|----------------------|
| GW150914  | 23.7              | 4.13          | 0.24                 |
| LVT151012 | 9.7               | 4.52          | 0.06                 |
| GW151226  | 13.0              | 3.83          | 0.48                 |

### **Consistency of SNR analysis**

We verify that using ADA methods, ADA results for SNR are reproduced.



### **Recovering injections**

We verify known signals injected by software in simulated data can be found.



### **Accounting for the differences**

- How to get from their 2.5 sigma to our 1.3 sigma Their p-value 0.011 to our p-value 0.104.
- Background estimated in more data and wider spaced. Accounts for factor ~3 in p-value.
- Widened window to originally searched window.
  Accounts for factor ~3 in p-value.
- Recovered values of gamma and t0 rail against their allowed ranges. Need a new physical model to go above gamma = 0.9.

### More data for background

We run on more of the LOSC open data to improve background estimation



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### Window of peaks is widened to originally searched size



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#### Recovered parameters cluster against range boundaries



γ

#### **Effect of wider priors on SNRs**



### Conclusions

- There is not sufficient evidence to claim the existence of echoes in the LIGO data.
- Our significance estimate is  $\sim 1.3\sigma$  (corresponding p-value 0.104).
- Even without sufficient evidence, searching for horizon modifications remains relevant.
- It is likely that the physical template models for echoes will be improved and more refined search methods can be applied.

### Thank you

### LVT151012 background values

On its own, LVT151012 has the lowest echoes p-value of the three events.



#### LVT151012 SNR^2



### **Issues not covered**

- The posteriors of final mass and spin parameters are not sampled for the original waveform used to build the template.
- The estimation of the PSD does not use all available techniques. Low frequency noise and spectral leakage is a possibility.
- The combining of data from two detectors is non-coherent.
- Parameter estimation is done over a fixed grid. Full Bayesian inference is not used to estimate parameters or models.
- Templates could be different. Super-radiance could cause the time between echoes to evolve over time.