Title: Improvements on the methods for searching echoes

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Abstract: The recent detections of merging black holes allow for observational tests of the nature of these objects, such as searching for the GW echo signals proposed in some models. Tentative evidence for these was presented, found in an analysis based upon methods for GW data analysis as demonstrated on the Ligo Open Science Center. We present the results of characterising these method's behaviour when applied to the specific form of the echo signals, and address problems and improvements based on our findings.

Outline

- Difference in significance estimates
- Recapitulate the model and search procedure
- Compare significance estimation procedures
- Concerns about methods
- Noise stability
- Short transient noise
- Different event combinations

Significance estimation for the evidence for black hole GW echoes

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November 8, 2017

Different significance estimates for ADA and AEI analyses

- Combining the first three events:
  - Abedi et al. find p-value of **0.011** in support of echoes.
    $\rightarrow$ Higher SNR in **1%** of random noise tests.
  - We find **0.02**.

- GW150914 alone:
  - Abedi et al. find p-value **0.11**.
  - We find **0.23**.

- Other event combinations show p-value up to **0.2**.
  $\rightarrow$ Higher SNR in **20%** of random noise tests.

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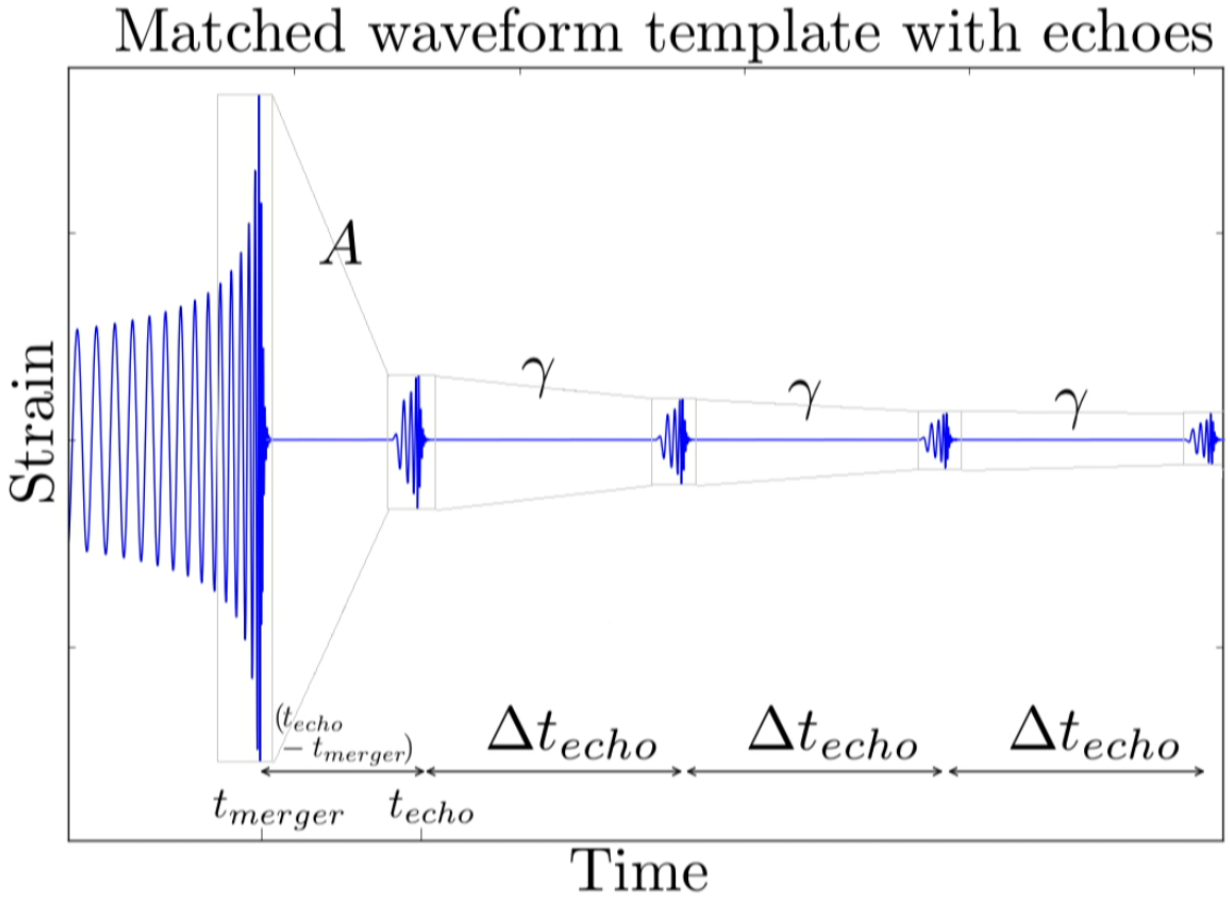
Echo model for analysis



Analysis for echo model - search procedure

1. LOSC waveform + methods, find best-fit template for event.
2. Produce **pure** echo template for given echo-parameters.
3. Produce template bank, evenly spaced grid in parameters.
4. Matched filtering for echo templates; event removed.
   $\rightarrow$ Sensitive to waveform model!
5. Maximise of SNR^2 over all parameters for each x.
   Combining events: Sum SNR^2 for each x.
6. Parameters varying between events:
   A, Δt_{echo}
   kept the same for all events:
   $x = (t_{\mathrm{echo}} - t_{\mathrm{merger}})/\Delta t_{\mathrm{echo}}$, $t_0/\Delta t_{\mathrm{echo,\ theory}}$ and γ (and $\Delta\phi$).

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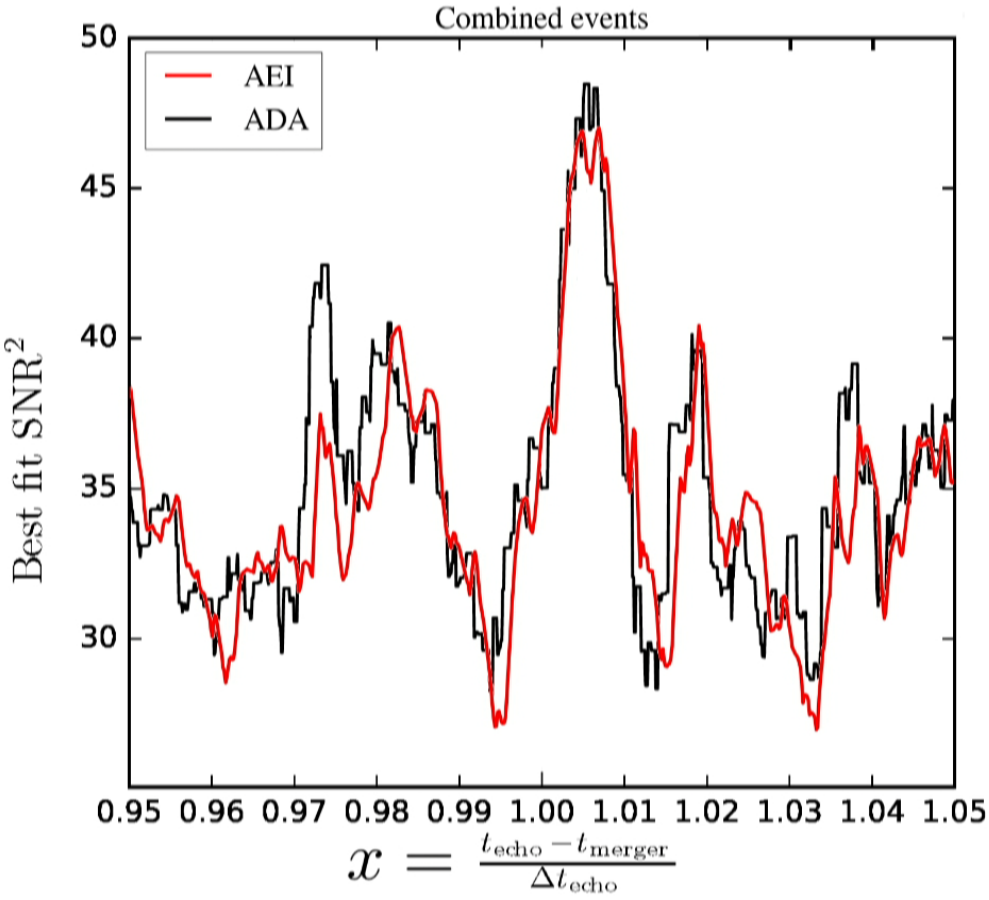
Analysis for echo model - result

AEI implementation closely reproduces ADA's result in SNR^2.



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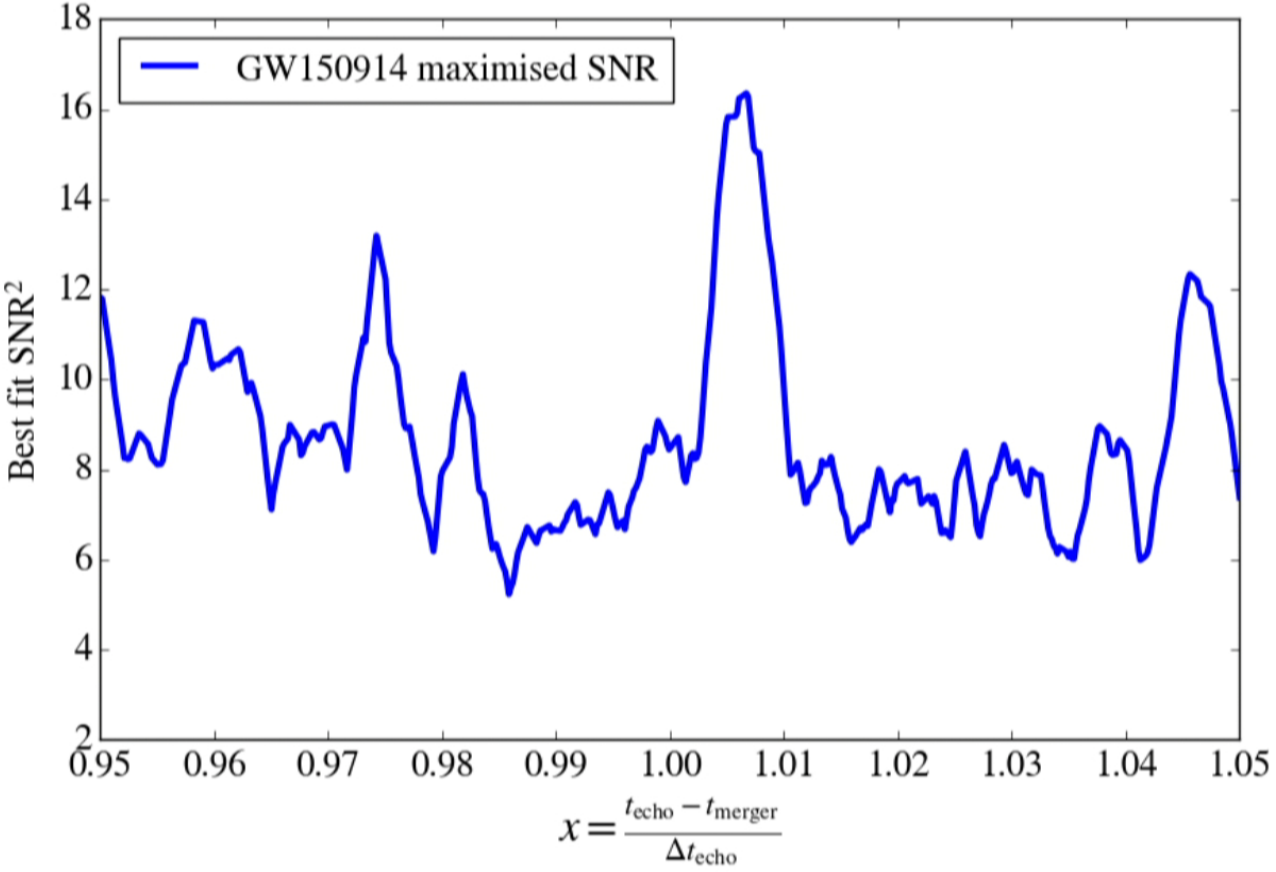
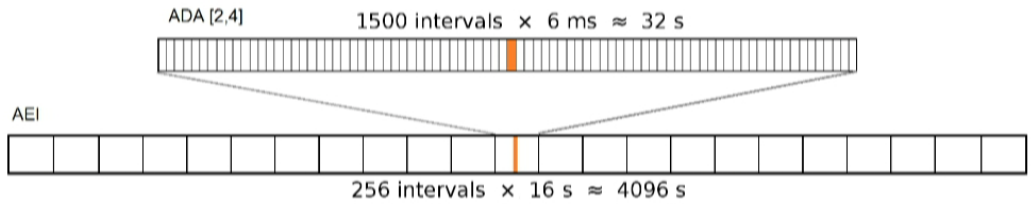


Significance estimate - ADA method

1. Find maximum SNR^2 in range $x \in (0.99, 1.01)$.
2. Calculate SNR^2 again in range $\frac{t_{\mathrm{echo}} - t_{\mathrm{merger}}}{\Delta t_{\mathrm{echo,theory}}} \in (9, 38)$.
   $\rightarrow$ Slightly adapt maximisation for this region.
3. Divide region into 2% segments in $\frac{t_{\mathrm{echo}} - t_{\mathrm{merger}}}{\Delta t_{\mathrm{echo,theory}}}$
   $\rightarrow$ 1480 segments.
4. No. segments with higher peak SNR / total no. segments
   $\rightarrow$ p-value.

Significance estimate - AEI method

1. Find maximum SNR^2 in range $x \in (0.99, 1.01)$.
2. Divide all available data into 32 second / 16 second segments (length of template).
3. Perform echo analysis on each, identical to event dataset.
4. No. segments with higher peak SNR / total no. segments $\rightarrow$ p-value.



Concerns about ADA method

- *Independent* noise samples required for significance estimate.
- Samples of detector data have no overlap.
- But samples of the maximised SNR have to be independent
  $\rightarrow$ Need independent samples for this analysis method.
- Used echo templates are much longer than the segments
  $\rightarrow$ SNR for one segment also uses data from another!
- Time right after the event may be contaminated by further echoes, if present.

Concerns about AEI method

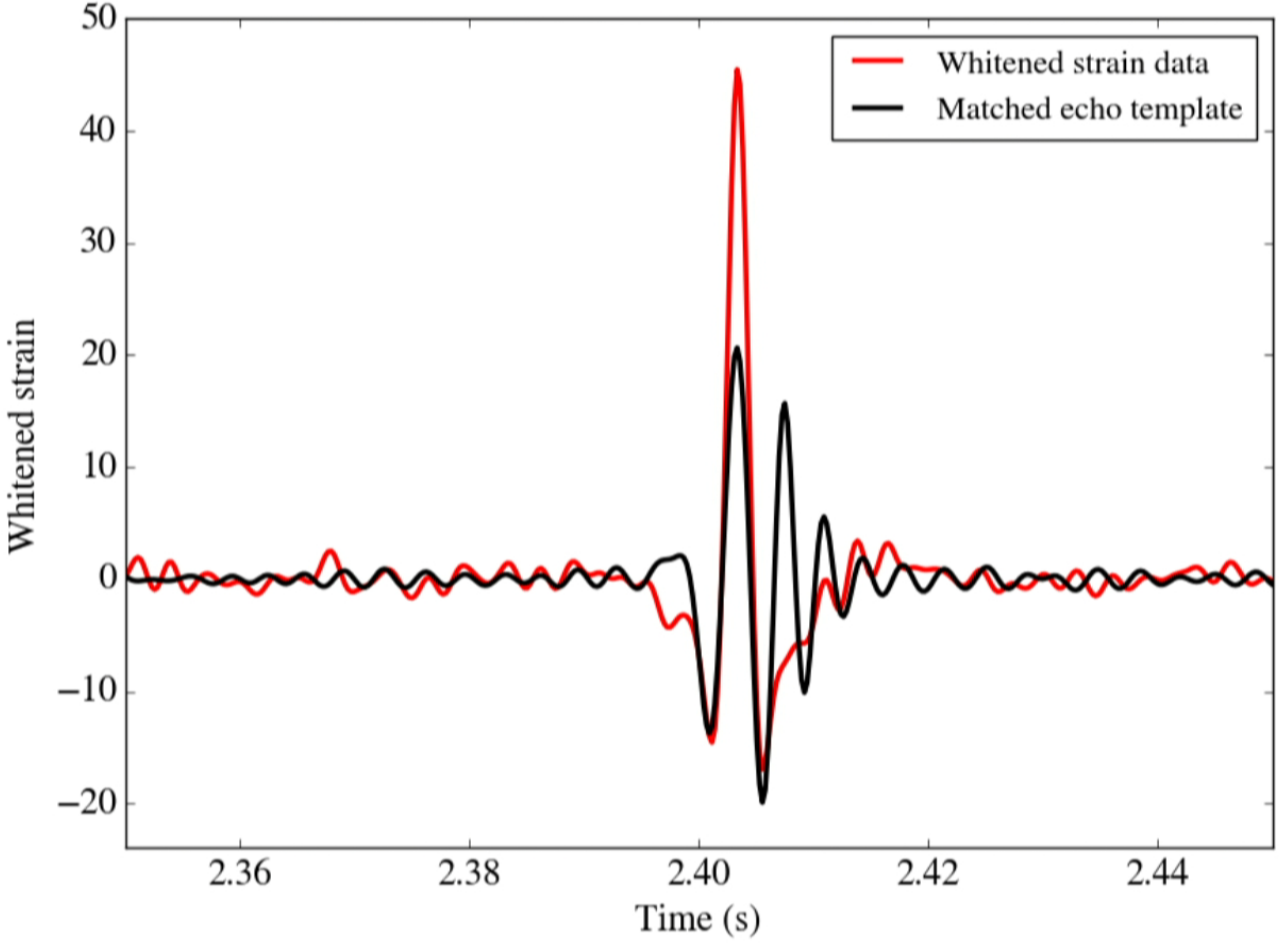
- Time separation of event and background datasets larger than for method 1.
- Detector noise not stationary over long times.
- Instantiations of the same noise are required for significance estimation.

Benefits:

- Overlap cannot occur. Templates never move across dataset boundaries.
- Rate of noise triggers is not strongly affected by expected slight PSD variations in LIGO noise

Beware of short transient noise

Short templates fit short transient noise well.



Results for significance

Event	ADA	original priors 16s (32s)	widened priors 16s (32s)
GW150914	0.11	0.199 (0.23)	0.705 (0.365)
(1,2,3)	0.011	0.02 (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)

Analysis for echo model - result

Fixing phase change $\Delta\phi$ to model assumption: