Optimizing Gravitational Wave Searches For Intermediate Mass Black Hole Binaries

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Introduction

Our goal is to improve sensitivity to gravitational waves (GWs) hidden in LIGO data, generated by intermediate mass black hole binary mergers by improving the quality of groupings in the search procedure.

In order to find GWs in the noise, the data is filtered through a large bank of GW templates, and a signal-to-noise ratio (SNR) is calculated for all time. If the SNR is high enough, a chi-squared (χ^2) statistic is also calculated for this trigger. A low chi-squared means the trigger is a good fit to the GW template. Triggers that only appear in one of the LIGO instruments are assumed to be noise, while triggers that appear in both detectors within a light travel time are GW candidates. The likelihood ($\mathcal{L}$) that a GW candidate is a real signal is calculated from the SNR and χ^2 values for a given trigger according to:

$$\mathcal{L} = \frac{\mathrm{p}(\rho_\mathrm{d}, \chi^2_\mathrm{d} | \theta, \mathrm{signal})}{\mathrm{p}(\rho_\mathrm{d}, \chi^2_\mathrm{d} | \theta, \mathrm{noise})}$$

The numerator is the probability that this combination of SNR and χ^2 was produced by a signal, and the denominator is the probability that it was produced by noise. The denominator is constructed by using the density of noise generated triggers from each detector. In Fig. 1, we sketch what the density of noise generated triggers from a single detector might look like in black dots. If a GW candidate falls within the populated area of the PDF, it is likely just a false alarm; if the candidate falls outside of the main cluster, it is likely a signal.

Motivation

In Fig. 1, we plot a GW candidate in red. Since there are no black noise triggers in its vicinity, it is very difficult to calculate its statistical significance. To better resolve the tails of these distributions, we combine noise triggers from similar templates together when constructing the denominator of L. (This is shown in Fig. 1 as black + grey dots).

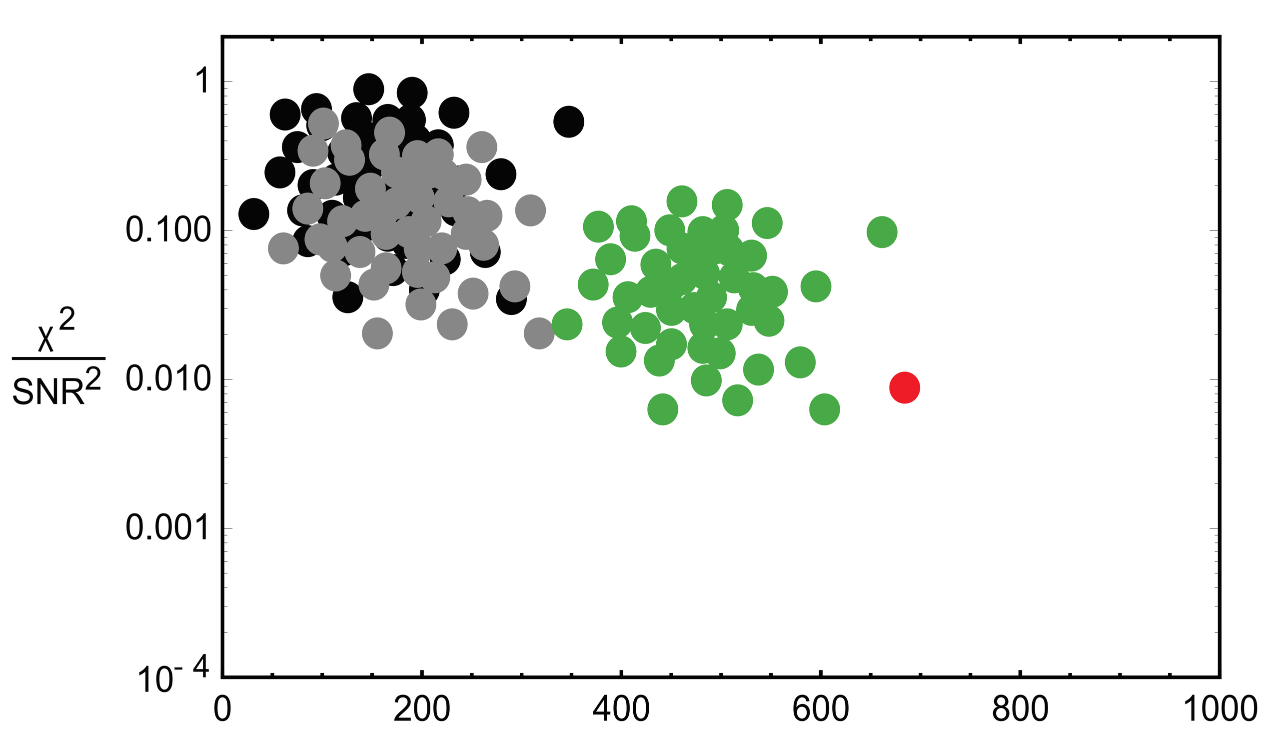
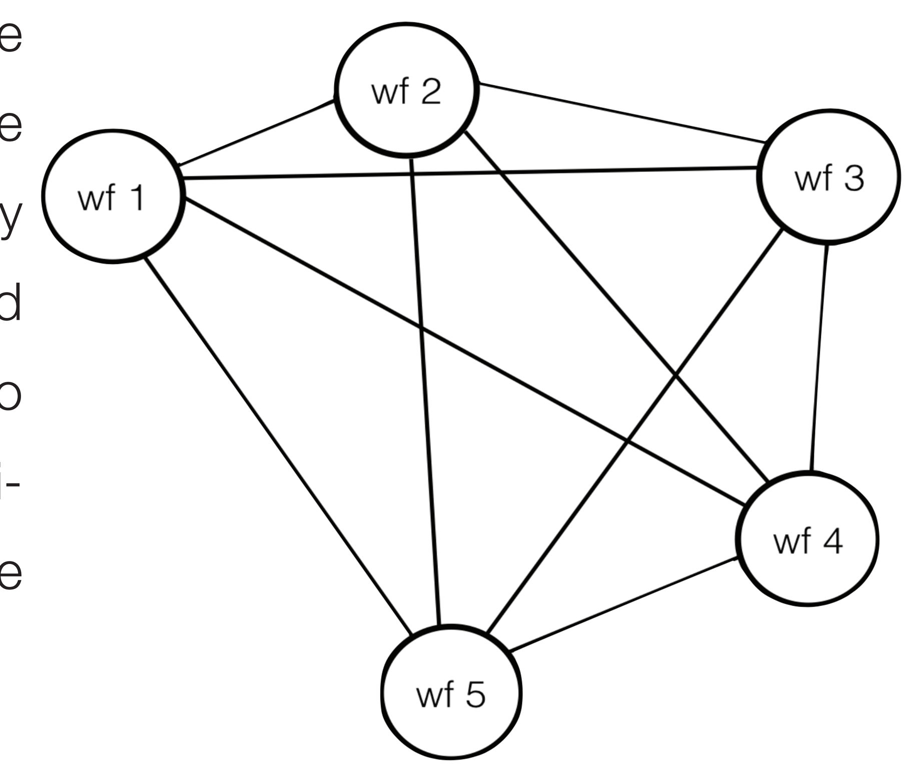


Fig. 1

However, if we group waveforms whose clusters are too different (green dots in Fig. 1), we can see that the GW candidate in red will no longer have a high significance. For this reason, we should be able to increase our sensitivity to GW signals by optimizing our template groupings.

Algorithms

We used graph theory to tackle the problem of grouping like waveforms. Mapping every waveform on to a vertex, and the similarity of waveforms to weighted edges between vertices, we formed a complete graph.



Walktrap

Walktrap utilizes the principle that a walk along a weighted graph is more likely to stay within tightly knit communities.

Default

Default bins the templates by chirp mass. This is the current way LIGO groups templates, and is based solely on chirp mass ($\mathcal{M}$), a very crude proxy for similarity. Chirp mass is given by:

$$\mathcal{M} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$$

where m_1, m_2 are the component masses of the binary system. There are some problems with this method, so we set out to find a better one.

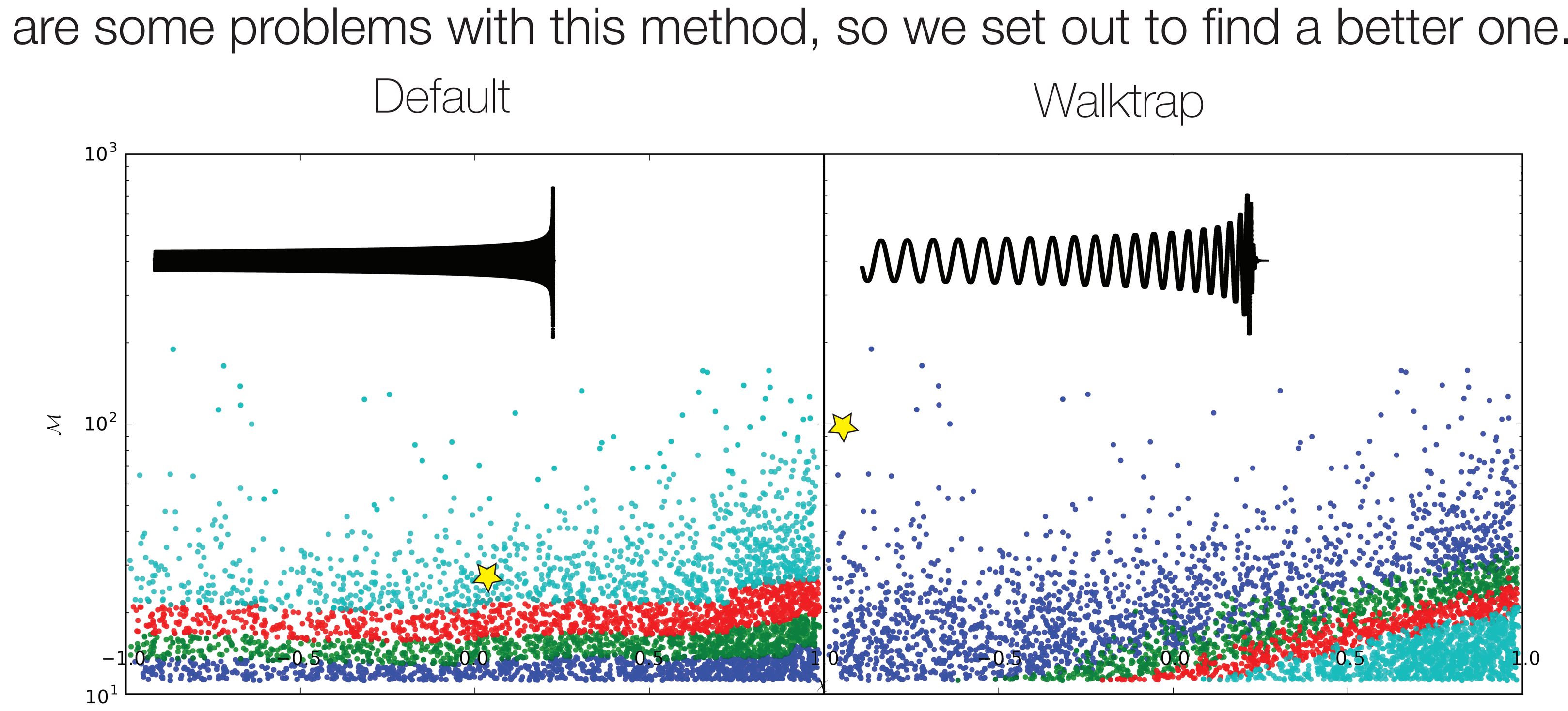


Fig. 2

Results

We found that the walktrap method of waveform clustering improves overall search sensitivity versus the default method of binning. The walktrap method of binning improved the signal sensitivity most in the intermediate to larger mass range of inspiral waveform signatures – the most difficult to detect due to their short durations.

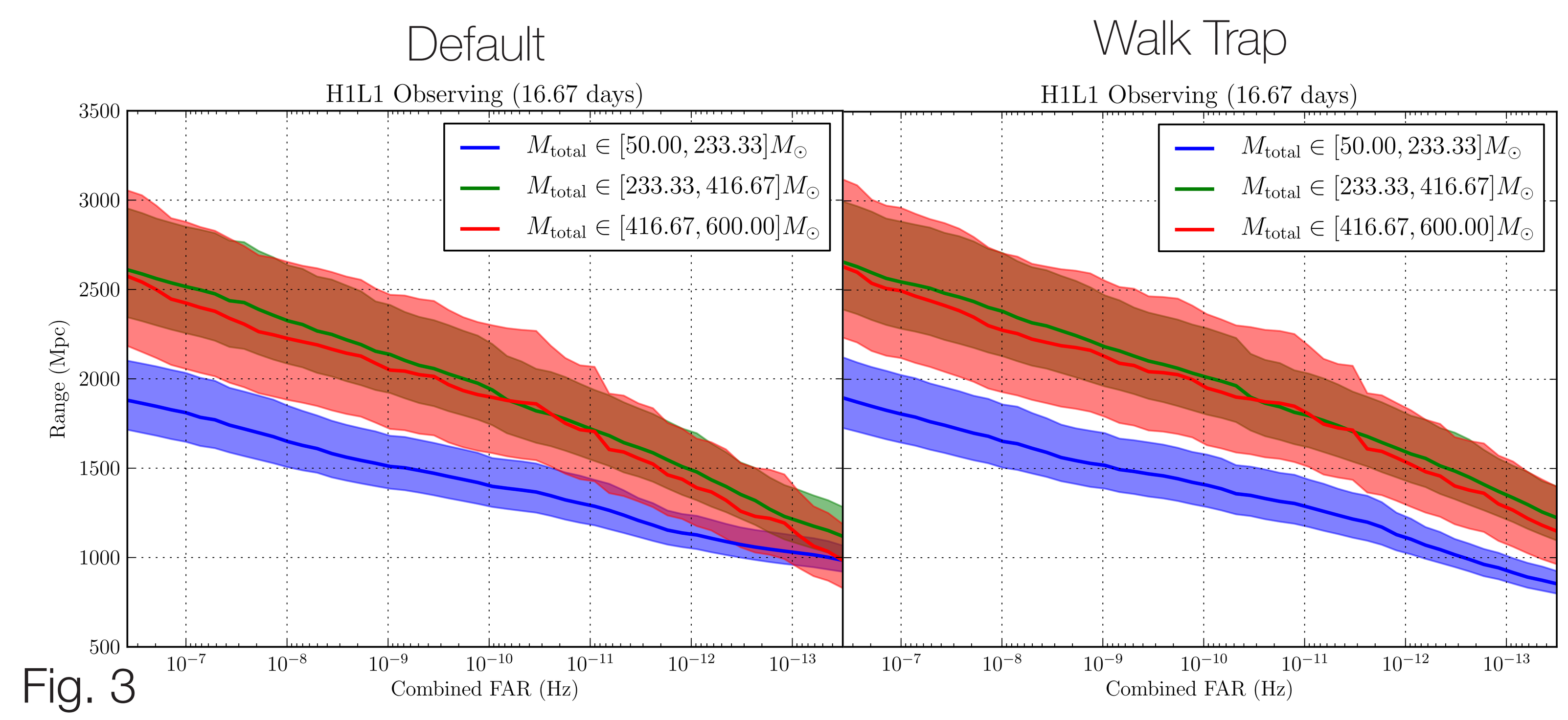


Fig. 3

We suspect the gains in sensitivity in the high mass ranges are due to the fact that the default method of binning groups solely by chirp mass. We can see this in the 'default' graph as a part of Fig. 2. The groupings are horizontal lines, constant in chirp mass with the default binning method. Waveform duration varies in chi, and this variation is not taken in to account with the default binning method.

Walktrap, however, forms more representative groupings, dividing the waveforms in to groups that vary in chirp mass, taking chi values in to account.

Future Work

We explored several other binning algorithms not presented here over the summer. One of those methods led to very unexpected and unintuitive results, which warrant further investigation.

Acknowledgments // References

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