Crowdsourcing GWs: Emergent Properties of Gravitational Wave Searches

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Determining whether a gravitational wave (GW) signal is of astrophysical origin or is caused by terrestrial noise still presents a challenge to the GW community. Current searches estimate the significance of events by calculating the false alarm rate (FAR) and p_{astro}, but these results are limited to a single search pipeline. In this work, we are going to investigate different ways of combining GW information to learn more about observed compact mergers. This will include investigating current searches, designing new methods of combining results from multiple pipelines, and testing whether they result in a meaningful estimate of astrophysical significance of events in realistic datasets.

I. INTRODUCTION

Since the first detection of gravitational waves (GWs) [1], the total number of GW candidates reported by LIGO-Virgo-KAGRA (LVK) Collaboration reached 90 [2] and continues to grow [3]. At the same time, determining whether a certain signal has astrophysical origin or is caused by terrestrial noise still remains a challenge, which leads to the uncertainty in the number of detected compact mergers [4].

Noisy local environments that are difficult to model, observations with multiple detectors, and inability to shield the instruments from GW signals result in the dependence of the estimated significance on a search analysis [5]. The main approach that is used to search for events is matching signals to the compact binary coalescence (CBC) waveform templates which is implemented in various ways by PyCBC [6], GstLAL [7], and IAS Search (IASS) [8] search pipelines. There are several technical differences between the searches, so they result in different estimates of noise background and probabilities of astrophysical origin for the same events. However, all pipelines are designed to search for the same compact binary mergers, so their estimates of event significance are not fully independent and should correlate.

In order to calculate significance of events, we introduce two quantities, false alarm probability and p_{astro}. False alarm probability is a probability of observing a coincidence or a "false alarm" with a signal-to-noise ratio (SNR) equal or higher than a certain value. As a result, to confirm the presence of a signal, one must show that the probability to obtain the observed event in a dataset that only contains noise is smaller than a given threshold [5]. It is also possible to convert false alarm probability into a related quantity called the false alarm rate (FAR), which is measured in yr^{-1} and is usually included in GW catalogs, e.g., [2].

On the other hand, p_{astro} is defined as a probability that a GW candidate has astrophysical origin and is not caused by terrestrial noise. It is calculated by combining the rates at which triggers – outputs of a search pipeline – are generated by both astrophysical and noise sources, i.e., both false and true alarm rates [9].

p_{astro} can be described in terms of Bayesian statistics as suggested in [10]:

$$p_{astro}(x) = \frac{p(S|x, \Phi_s, \Phi_n)}{p(S|x, \Phi_s, \Phi_n) + p(\varnothing|x, \Phi_n)}, \qquad (1)$$

where x is a trigger statistic, S is a signal hypothesis, $\varnothing$ is a noise hypothesis, and Φ_s and Φ_n are some signal and noise parameters. Thus, $p(S|x, \Phi_s, \Phi_n)$ and $p(\varnothing|x, \Phi_n)$ are posterior probabilities of signal and noise hypotheses, respectively.

Applying Bayes' theorem, one can rewrite equation (1) as follows:

$$p_{astro}(x) = \frac{\pi_s p(x|S)}{\pi_s p(x|S) + \pi_n p(x|\varnothing)}, \qquad (2)$$

where π_s and π_n are prior probabilities of having a signal or noise and $p(x|S)$ and $p(x|\varnothing)$ are the corresponding likelihoods of getting a trigger x in a dataset containing signal or only noise.

In order to write a similar expression for a unified p_{astro}, we define $\vec{x}$ as a vector of triggers from multiple pipelines and obtain

$$p_{astro}(x) = \frac{\pi_s p(\vec{x}|S)}{\pi_s p(\vec{x}|S) + \pi_n p(\vec{x}|\varnothing)}. \qquad (3)$$

It is important to note that, since pipelines are correlated, $p(\vec{x}|S)$ and $p(\vec{x}|\varnothing)$ are not independent and the relationship between them might need to be determined separately.

II. OBJECTIVES

The goal of this project is to develop a method of combining gravitational wave information from different sources to learn more about the observed compact mergers. It will include building an understanding of PyCBC, GstLAL, and IASS search pipelines in order to combine their FARs and calculate the unified astrophysical probability.

After developing our method and testing it on realistic data, we plan to come up with an updated list of GW candidates that will include an estimation of their astrophysical probabilities and other properties from multiple searches. In addition, we are interested in analysing the contribution of the IASS pipeline, which is developed outside of the LVK collaboration, to the results of internal PyCBC and GstLAL pipelines. This work will help to better understand the emergent properties of already detected candidates and provide insights for new GW detections in the O4 observing run.

III. CURRENT PROGRESS

Since the beginning of the program, I familiarized myself with the basics of existing GW data analysis techniques by completing the Gravitational Wave Open Data Workshop [11]. I learned how to access publicly available data, display it as time series, and perform two types of transformations from time domain to frequency domain, namely Fast Fourier Transform and Q-transform. In addition, I learned the basics of waveform generation, matched filtering, and parameter estimation. Most importantly, I gained some practical experience with PyCBC matched filtering and used it to generate SNR time series and estimate event significance given a simplified search.

For example, I was able to discriminate between a signal and two glitches in a given dataset by applying a χ^2-based signal consistency test and analysing re-weighted SNR time series.

The implementation of χ^2 test for gravitational waves is described by Bruce Allen [12] and can be briefly summarized by the following equation:

$$\chi_r^2 = \frac{1}{N}\sum_{i=0}^{p}(\rho_i - \rho/p)^2, \tag{4}$$

where p is the number of frequency bins, $N = 2p - 2$ is a number of degrees of freedom which serves as a normalization factor, ρ_i is SNR of an individual bin, and ρ is an expected fraction of the total SNR for each bin.

The χ_r^2 is an indicator of how well the template matches the data and will be close to unity for a good match. High values of χ_r^2 would indicate the domination of noise, wrong template, or the presence of a high-SNR glitch that does not match the model predictions.

The top part of Fig. 1 shows the example SNR series that include a signal and two glitches. To determine the significance of each peak, we calculate the χ_r^2 using the equation (4) for each data point and observe a minimum in the vicinity of 104 s in the time series in Fig. 2. After this, we computed the re-weighted SNR using the following equation:

$$\hat{\rho} = \frac{\rho}{\frac{1}{2}[1 + (\chi_r^2)^3]^{1/6}} \tag{5}$$

The resulting time series displayed in the bottom Fig. 1 only show one peak at 104 s, which indicates that it is a real signal and the rest two peaks in the top part of the figure are glitches.

Having identified the signal, it is helpful to calculate its significance or false alarm probability. It is more informative to calculate the significance of a real signal, so Fig. 3 shows the false alarm probability of a GW170814 Virgo detection (intersection of red lines) plotted together with the noise data points (black dots).

It is calculated as the number of noise samples with SNR equal or higher than the event SNR divided by the total number of samples. The false alarm probability calculated from the simplified model is 1.9%, whereas the reported value calculated by taking into account more background data is 0.3% [13]. This calculation illustrates the fact that false alarm probability is calculated mostly from the properties of noise with minimal assumptions based on astrophysical models and previous detections.

IV. NEXT STEPS

After completing the workshop and other introductory training, my next step is to explore different mathematical and statistical methods of combining false alarm rates or p-values both in context of gravitational waves and science in general, e.g., [14]. Doing this will help us to suggest a method that results in a single number describing the significance of events, but which is simple enough computationally to be used with multiple pipelines and realistic data. Next, I plan to learn more about specific technical details of how PyCBC, GstLAL, and IASS pipelines estimate the likelihood of signals and noise to understand how to combine them together.

Finally, we are going to calculate unified FARs and p_{astro} firstly for the combination of PyCBC and GstLAL and then for the combination of all three pipelines to analyse the contribution of the IASS specifically. Provided our method works well, we will then calculate unified p_{astro} for all catalogued events and analyse the results that we obtain.

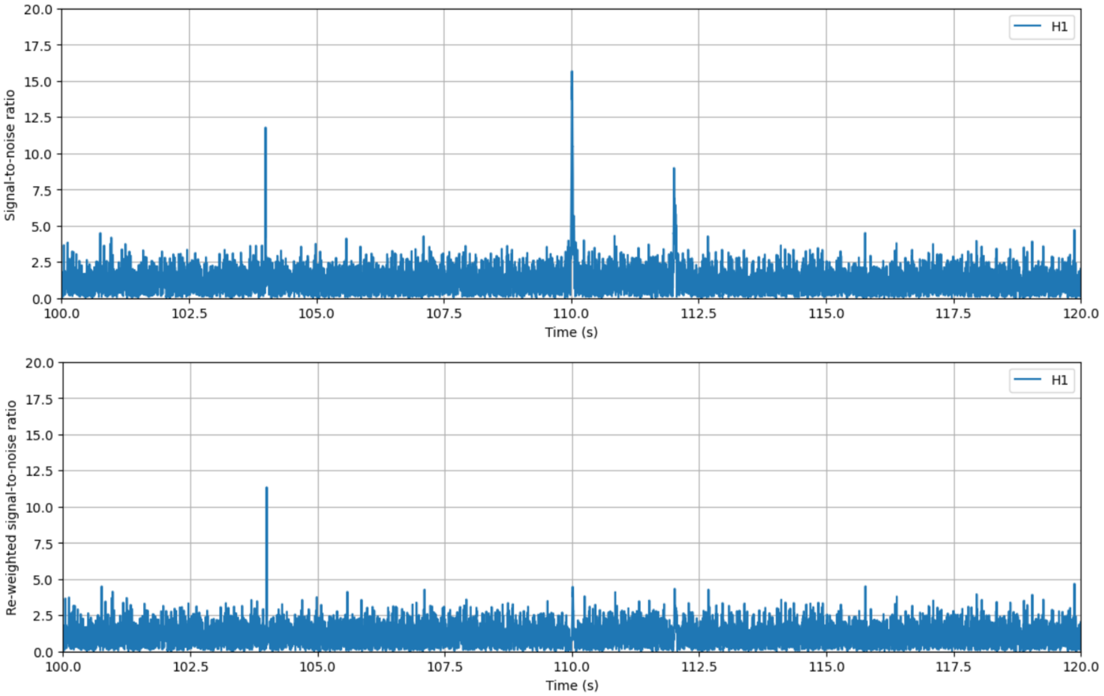

FIG. 1. Top: Signal-to-noise ratio time series that show one signal peak and two glitches, but no indication of which peak is the real signal. Bottom: Re-weighted signal-to-noise-ratio time series after the application of the χ_r^2 test that suppressed glitches and left only one peak at 104 s, which is the real signal.

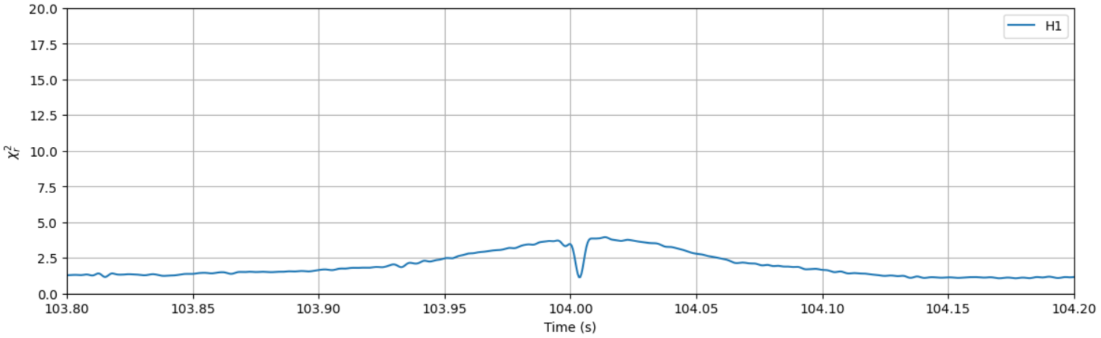

FIG. 2. Application of χ_r^2 test to signal-to-noise ratio time series that results in low values for a good match between a signal and a model and high values for a mismatch. The figure shows a good match at around 104 s, which led to the peak in the bottom part of Fig 1.

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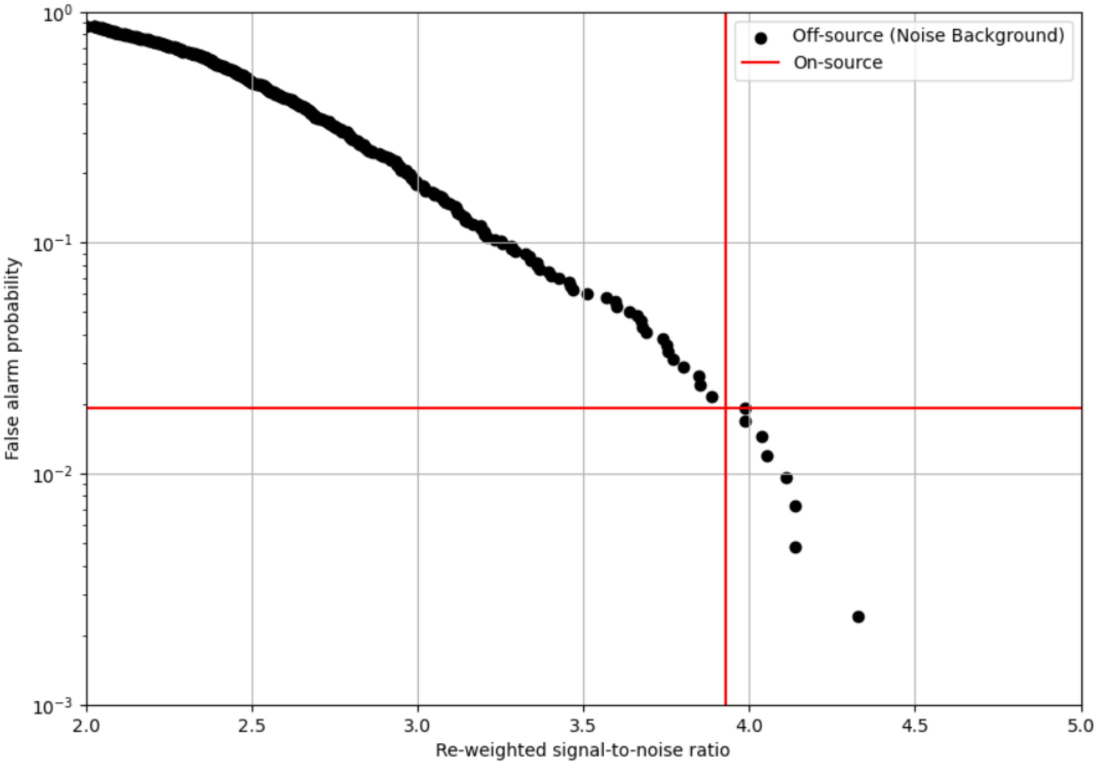

FIG. 3. False alarm probability for GW170814 Virgo detection that is calculated as the number of noise samples with signal-to-noise ratio (SNR) equal or higher than the event SNR. The probability value calculated for this event is 0.019, which is shown at the intersection of red lines as compared to the results for noise shown as black dots.

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