Digging deeper: finding sub-threshold compact binary merger events in LIGO data

LIGO Caltech SURF Program 2019 Project Proposal

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INTRODUCTION/BACKGROUND:

The LIGO and Virgo detectors have collected gravitational wave (GW) data from three separate observation runs since 2015, with the third run presently collecting data. There have been 10 signals from binary black hole (BBH) mergers and one binary neutron star (BNS) merger detected from the first two observation runs and several more from the third run. These detections were all confirmed due to high confidence in their signal-to-noise ratio (SNR); however, there are likely many more unconfirmed signals in the data due to lower SNRs. Initial PyCBC and GstLAL pipeline searches have flagged potential GW events as triggers based upon matched-filtering and threshold values **[1]**. Since the visible volume scale for binary black hole mergers is approximately $V \propto M^{2.1}$, higher mass mergers are easier to detect than those of lower mass **[2]**. Current CBC searches do not adequately differentiate GWs of lower confidence from inherent noise. Bayesian model comparison of coherence may be a way to effectively discriminate whether a trigger, a flagged event from the pipeline searches, is likely a GW signal or instrumental noise from the detectors. Coherence requires that the strain signals in multiple instruments share a phase evolution consistent with a single astrophysical source, represent a well-described compact-binary-coalescence (CBC) waveform, and be temporally coincident **[3]**. Instrumental noise transients (glitches) are not expected to fully meet these requirements, whereas GWs are; therefore, allowing the distinction to be made.

The data from these signals contain valuable untapped information to understanding gravitational waves and the characteristics from merging black hole and neutron star systems in the distant universe. Being able to collect and analyze the data from the weaker signals will help fill in the gaps of our understanding of CBC populations.

OBJECTIVES:

A Bayesian coherence ratio (BCR) compares the odds between the hypotheses that the data comprises coherent CBC signal or incoherent instrumental features. This calculation factors in the evidence of the signal in pure gaussian noise, non-gaussian noise fluctuations that are not coherent between detectors, and the coherent signal in gaussian noise. Priors, such as the BBH merger rate and mass range, will be determined through trial and error and be used to compute the evidence parameters in the BCR calculation. The two weighted terms (α and β) in the BCR calculation are priors that affect the separation between the background and foreground populations and will be adjusted to produce useful BCRs. A predetermined surrogate glitch hypothesis will be used and an assumption for the gaussian noise evidence is of a perfect measurement of the detector noise power-spectral-density (PSD) **[3]**.

We want to calculate the BCR for triggers produced in all observing runs to detect weak GW signals and potentially define empirical probability distributions that would allow us to obtain likelihood ratios to use for trigger classification. For now, we will compute and apply the BCR to Observation 2 background triggers in effort to reject any glitches. This will allow an updated false alarm rate (FAR) to be used for Observation 3 event analysis. A BCR < 1 would allow for the rejection of that trigger as a GW event because it would favor the odds of the hypothesis that the data is comprised of incoherent instrumental noise.

APPROACH:

The principal steps for this project will be to become familiar with the data and learning how to set up and run multiple (Bilby) jobs on a computer cluster. I estimate this part of the project to take up to three weeks because there will be a learning curve when learning new techniques to handle data. The following step will be to determine appropriate priors, such as the weights (α and β) which minimize the overlap between the signal and noise trigger **[3]** to calculate accurate BCRs. We will also need to determine a signal duration limit that we want to initially evaluate and providing us with a chirp-mass range. We will use standard ranges to restrict parameters on mass ratio, spin magnitude, luminosity distance, etc. This step should take about 1-2 weeks. Following the BCR calculations, we will compare the background selection to the foreground triggers by plotting a histogram of survival function against $\log_{10}$BCR and plotting BCR vs SNR distributions. This process should only take a couple weeks to produce useful plots. The next step is to identify any likely GW events and/or reject any likely triggers due to instrumental noise, which should be completed in the same time frame as the previous step. This will allow us to calculate a new FAR that we will apply to Observation 3 events, improving our confidence in those events. The final step for this project would be to select new parameters, signal time duration limit, and compute BCRs for Observation 3 triggers. After running through the same sequence of steps, we can work on making any improvements/adjustments to method of distinguishing signal from noise. This portion of the project should last around five weeks.

To complete this project, I will need access to the data files of all flagged triggers from the LIGO observing runs. The results from this project are reliant upon properly flagged triggers from the initial pipeline search of the data.

PROJECT SCHEDULE:

- **Become familiar with workspace and handling data (Weeks: 1-3)**
    - Get workspace set-up
    - Learn how to properly set-up/run multiple (bilby) jobs on a computer cluster
- **Calculate BCR (Weeks: 3-5)**

- **Travel to LIGO Livingston, LA (Week 4)**
- Determine appropriate priors (trial and error)
    - Mass range, luminosity distance, BBH merger rate, weighted terms (α and β), etc.
- Computing the Evidence terms
    - Select signal duration limit
    - Select appropriate ranges for parameters (i.e. component masses, mass ratio, spins)
- Produce template waveforms using IMRPhenomP

- **Compare BCR from background selection to foreground triggers (Weeks: 5-6)**
    - Plot histograms of survival function against $\log_{10}$BCR
    - Plot BCR vs SNR distributions
- **Identify any likely GW events and/or reject any likely triggers due to instrumental noise (Weeks: 5-6)**
    - Calculate new FAR to apply for Observation 3 events
- **Select new parameters, signal time duration limit, and compute BCR for Observation 3 events (Weeks: 6-9)**
    - Run multiple Bilby jobs on Observation 3 triggers
    - Work on any improvements/adjustments to method of distinguishing signal from noise
- **Prepare final paper and present a 15-minute talk on project/results (Weeks: 9-10)**
    - Gather and organize all results, plots/graphs, data
    - Put together a PowerPoint presentation
        - Background/Introduction, Objectives, Methodology, Analysis, Results, Conclusion
        - Include appropriate plots, images, data, equations, etc.
    - Practice presentation
    - Continue to work on final paper **(Due: Late October)**
        - Keep in touch with mentors and new results
        - Submit by deadline

REFERENCES:

[1] Abbott et al., GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs, 2018, arXiv:1811.12907 [astro-ph.HE]

[2] Fishbach M., Holz D. E., Where Are LIGO's Big Black Holes?, 2017, Astrophys. J. Lett., 851, L25

[3] Isi et al., Enhancing confidence in the detection of gravitational waves from compact binaries using signal coherence, 2018, arXiv:1803.09783 [gr-qc]

[4] Thrane E., Talbot C., An introduction to Bayesian inference in gravitational-wave astronomy: parameter estimation, model selection, and hierarchical models, 2019, arXiv:1809.02293 [astro-ph.IM]