Analyzing Causes of Gravitational Wave False Alarms

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Abstract

The prompt discovery of gravitational wave events is performed by a variety of matched-filtering search pipelines. Due to the non-Gaussian nature of the Advanced LIGO detector, these pipelines often react to transient noise sources, commonly referred to as glitches, and mistake them for gravitational wave events. Analyzing the properties of these glitches and a pipeline's reaction to them is thus crucial to improve pipeline efficiency and event validation accuracy. In this study, we perform such an analysis on one of these pipelines, GstLAL, with the intent of providing a battery of tests and models by which a given gravitational wave candidate may be evaluated against to provide a higher degree of confidence in the identification of the event origin in addition to offering a valuable perspective on the responsiveness of this pipeline to instrumental noise.

Gravitational Waves & LIGO

- Gravitational waves were first predicted by Einstein's theory of General Relativity in 1916
- These "ripples" in spacetime are commonly caused by merging binary systems (black hole and neutron star pairs)
- First detection of gravitational waves was made by LIGO in 2015
- At the beginning of O3, more than 90 events had been discovered by a global network of detectors

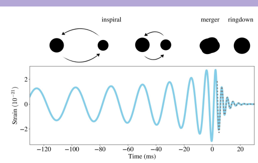


Figure 1: Expected waveform from a binary inspiral broken into its three phases [1]

Figure 2: An aerial view of LIGO Livingston (LIGO Caltech, 2015)

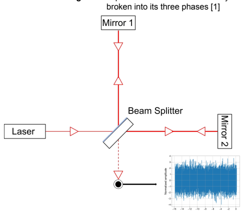


Figure 3: Basic LIGO schematic and its signal

GstLAL & Event Detection

- To discern gravitational waves from noise in the data, **matched-filtering pipelines** are used
- Matched-filtering is performed in time by cross-correlating data against a bank of templates that are generated by general relativity

$$\int_{-\infty}^{\infty} \hat{h}_i(\tau)\hat{d}(t+\tau)d\tau$$

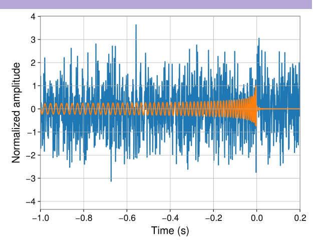


Figure 4: Gravitational wave signal hidden in LIGO data

- There are 1.8 million templates being used in O4 [2]
- Singular Value Decomposition (SVD) greatly reduces the number needed to perform matched filtering
- The output of these pipelines is called the signal-to-noise ratio (SNR).
- High spikes in SNR (where the pipeline thinks it has found a gravitational wave) result in **triggers**

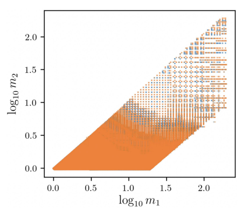


Figure 5: The vast number of templates being used by GstLAL in O4 [2]

Non-Gaussian Noise & Retractions

- LIGO data is plagued by transient noise sources, called **glitches**, that are typically the result of some instrumental effect
- Glitches are categorized by a machine-learning algorithm called **GravitySpy**

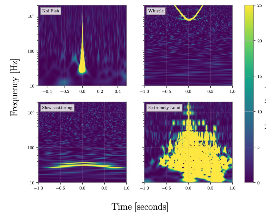


Figure 6: Multiple categories of glitches (S. Soni, 2021)

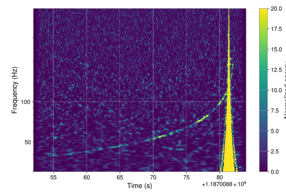


Figure 7: Spectrogram showing a glitch occuring during the time of a real gravitational wave event

- Pipelines regularly mistake these glitches for real gravitational wave signals

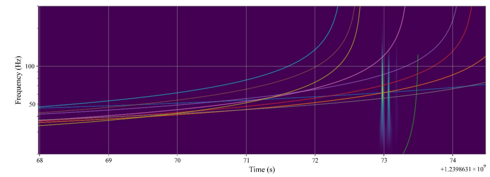
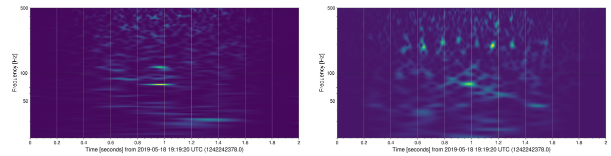


Figure 8: 10 randomly-selected triggers generated by a single glitch

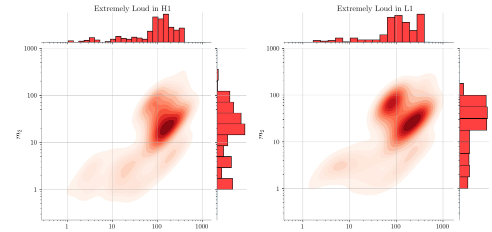
- Gravitational waves should pass through both detectors so these mistakes are often corrected when a glitch only occurs in a single detector
- When similar glitches are coincident across detectors, pipelines often attribute a very high probability that a gravitational wave has occurred
- These triggers that must later be retracted are called **false alarms**



Figures 9 & 10: An example of a retraction. Left is data from H1 and right is data from L1

Methods

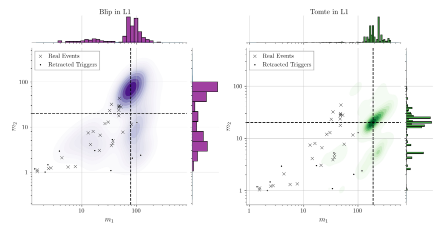
- **Goal**: Develop a method for classifying how likely a given trigger is to have been caused by a specific glitch type
- We analyze data from: various glitch types, retractions generated during O3, and real gravitational wave event data. We do this by creating **noise background** kernel density estimation (KDE) plots
- This is performed for mass and likelihood distributions



Figures 11 & 12: Mass distribution KDEs for triggers generated by extremely loud glitches in both detectors

Results

- We then overlay real event and retracted trigger data on these KDE plots
- We evaluate each retracted trigger on every KDE to determine a **causal probability** for each glitch type
- On average, we expect retracted triggers to be more aligned with each KDE than real events



Figures 13 & 14: Example of our method on two pervasive glitch types in L1. The black dashed lines indicate the median of each distribution

Trigger	m_1/m_2 Pred.	$\frac{\chi^2}{\rho^2}/\rho$ Pred.
0	SL	SL
1	KF	EL
2	KF	KF
3	SL	T
4	KF	KF
5	KF	EL
6	KF	None
7	KF	SL
8	KF	T
9	KF	T
10	KF	SL
11	KF	KF
12	KF	T
13	KF	T

Table 1: The glitch type predictions made by both of our methods in L1, denoted by acronyms. Highlighted rows indicate a match between the methods.

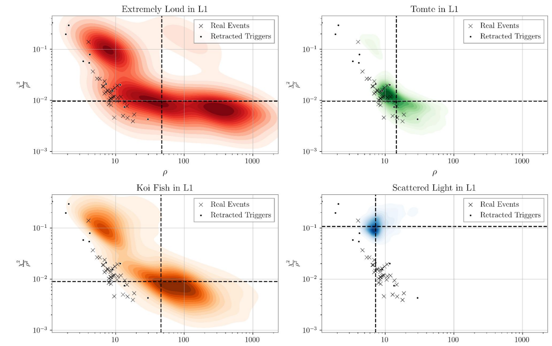


Figure 15-18: Likelihood distribution KDEs for the set of loud glitches that were primarily considered in this study

Conclusions & Future Work

- We have provided the framework of a method for determining the probability that a given trigger has been caused by a specific glitch type which could lead to improvements in GstLAL's event detection confidence
- The incorporation of additional parameters in this analysis would provide a more rigorous test of how likely a candidate was to be caused by a specific glitch type
- Future work will use KDE data that only considers regions in the given parameter space that are unique to specific glitch types

Google folder containing a more detailed project report, pdf of this poster, and contact information

References & Acknowledgments

References:

[1] Ota, Iara. "Black hole spectroscopy: prospects for testing the nature of black holes with gravitational wave observations." *arXiv:2208.07980* (2022)

[2] Shio Sakon et al. "Template bank for compact binary mergers in the fourth observing run of Advanced LIGO, Advanced Virgo, and KAGRA". arXiv: 2211.16674 (2023)

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