Archival Search for Binary Neutron-Star Mergers in Gravitational-waves and Very High Energy Gamma-Rays

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Abstract

The discovery of electromagnetic signals spatially and temporally coincident of gravitational waves from the binary neutron star merger GW170817/GRB170817A has revolutionized our understanding of transient events and underscored the importance of multi-messenger campaigns to understand highest energy astrophysical events in our universe. This report presents the search through VERITAS archival data for spatial and temporal coincidences with LIGO run O3 sub-threshold candidate data. It also shows the search for signals within those observations for very high energy counterparts to gravitational wave signals. This report focuses specifically on binary neutron star mergers and the new physics that can be extracted from the studies of these systems and provides an overview of gravitational-wave physics and gamma-ray physics. By applying this multi-messenger approach, we seek to gain deeper insights into the nature of these extraordinary astrophysical events.

Contents

1 Introduction

Binary neutron star mergers sit at the forefront of many of the interesting physics we seek to probe. Neutron stars are believed to form from the collapsed cores of massive stars and stand as the densest celestial bodies, second only to black holes. The mergers of these systems are of significant interest because they have been long theorized to be sources of gravitational radiation. Additionally, these mergers are theorized to be sources of electromagnetic and neutrino emission. Furthermore, the immense energy released during these mergers has the potential to play a vital role in the formation of the most massive elements known to exist. They have also been long theorized to be a source of short gamma-ray bursts. This makes binary neutron star mergers excellent targets for multi-messenger studies. This project will focus specifically on a study between a gravitational-wave observatory, LIGO, and a gamma-ray observatory, VERITAS.

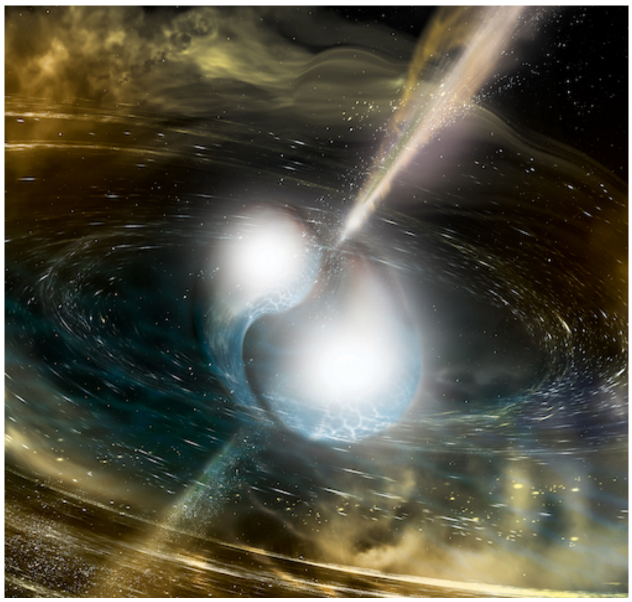

Figure 1: Artist rendition of a binary neutron star merger

In this report, we hope to develop a better understanding of transient events in gravitational waves and very high energy astrophysics by searching through LIGO run O3 data gravitational-wave sub-threshold data to find very high energy electromagnetic counterparts.

1.1 Stages of a binary neutron star merger

There are 3 stages of these mergers. The merger and inspiral phases will be of upmost importance to us.

- Inspiral phase: The two binary objects are moving closer and closer to one another, as this occurs the gravitational wave amplitude and frequencies decrease.
- Merger phase: This is where a remnant body is produced from the merger. When this body is produced, there is also a 'prompt emission' phase of the event, which is when the gamma-ray jet is ejected from the body. This is the phase we are most interested in, because this is when we are most likely to see very high energy output.
- Post-merger phase: This is when the remnant body settles into a new stable configuration. It is thought that sometimes there could be an "afterglow" remnant in this phase where there could be some high energy output.

1.2 Discovery of GW170817/GRB170817A

On 17 August, 2017 at 12:41:04 UTC the Advanced LIGO and Virgo Gravitational-wave detectors made their first detection of a binary neutron star merger. 1.7 seconds later, Fermi-GBM detected a short GRB corresponding to this same event. This triggered international follow-up of this event. For the very first time, electromagnetic signals were found in temporal and spatial coincidence with gravitational-wave signals from the same source[1]. Multi-messenger observations from LIGO/Virgo, Fermi-GBM, and INTEGRAL helped to localize the event, as shown in Figure 2.

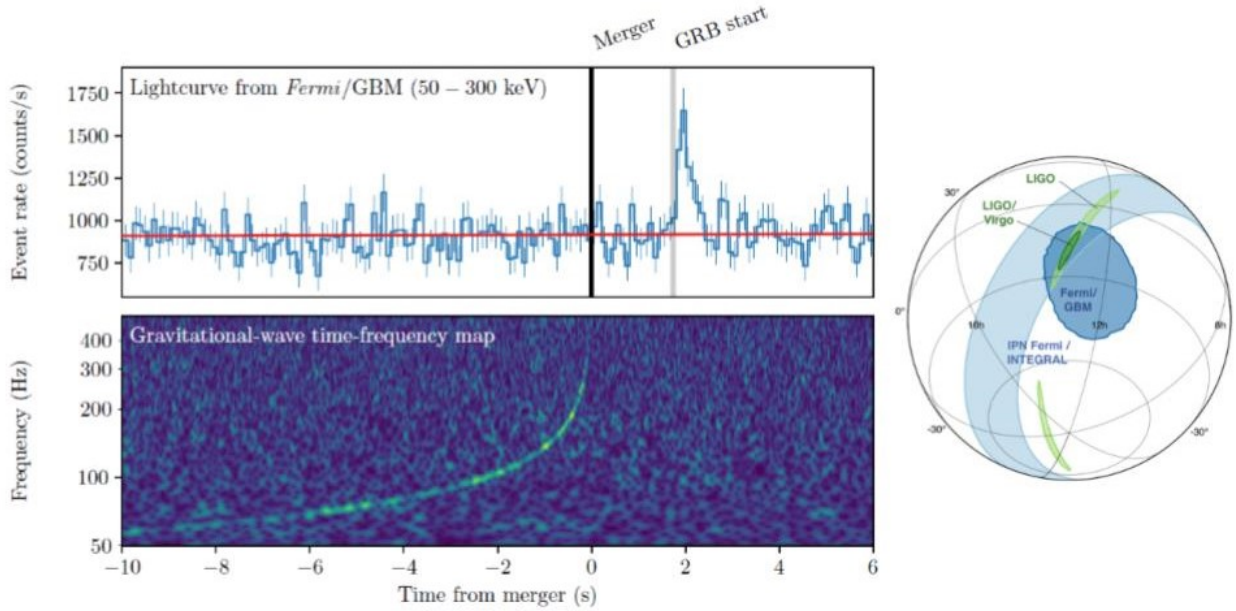

Figure 2: Multi-messenger detection of GW170817/GRB170817A [1]

This discovery gave evidence to a long standing theory that short gamma-ray bursts originate from binary collapsar models (like a binary neutron star merger). It also served as a catalyst for future multi-messenger searches for transient events in our universe. In particular, this discovery has motivated my search for very high energy counterparts to gravitational-wave sub-threshold candidates.

2 Messengers and Observatories

2.1 Gamma-ray Astronomy and VERITAS

Gamma rays are the highest energy window in the electromagnetic spectrum, letting us see and observe the brightest objects and events in the sky. They originate from non-thermal processes like strong electromagnetic fields and nuclear decay processes and interactions. They were first detected in 1967 by the Vela Satellites (which were operated to detect nuclear explosions during the height of the Cold War) and were unlike any known nuclear weapons signatures. After some questioning of the source of the high energy event, it was found that the burst phenomena was not due at all to nuclear testing from Earth. They were coming from space [8]. This discovery ushered in an era of gamma-ray astronomy, along with ground-based and space telescopes.

VERITAS (Very Energetic Radiation Imaging Telescope Array System), shown in 3, is a ground-based gamma-ray telescope located at the Fred Lawrence Whipple Observatory in southern Arizona and consists of

4 Imaging Atmospheric Cherekov Telescopes (IACTs) that detect direct flashes of Cherenkov light, exploring very high energy gamma rays from 100 GeV to 30 TeV.

Figure 3: VERITAS array at FLWO, Credit: VERITAS

2.1.1 Ground-based gamma-ray telescopes and IACTs

Ground-based gamma-ray telescopes like VERITAS, MAGIC, H.E.S.S., and HAWC operate by detecting flashes of Cherenkov light, shown in Figure 4. These are flashes of electromagnetic radiation from charged particles that propagate through a medium (in this case, the atmosphere) at a speed greater than the phase velocity of light in that medium. They use optical telescopes that detect the air shower and cascade of particles, as shown in Figure 4, functioning indirectly as ground-based γ-ray telescopes.

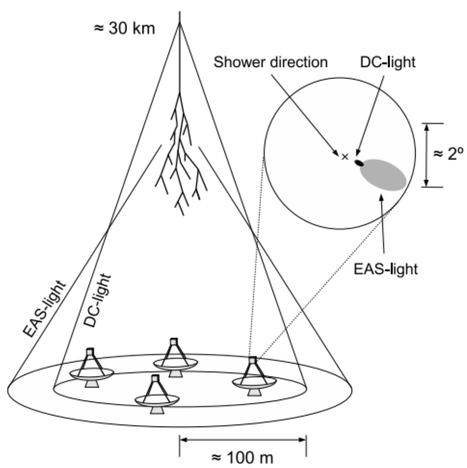

Figure 4: Schematic diagram of a Cherenkov radiation air-shower, Credit: VERITAS Collaboration

2.1.2 Gamma-ray Bursts

Gamma-ray bursts (GRBs) are some of the brightest transient events observed in our skies. These can be difficult for telescopes like VERITAS to observe because of their limited field of view. However, VERITAS conducts follow-up observations on detections by SWIFT and Fermi-LAT (which have a much wider field of view) to generate a better picture of these transient events. There are two different types of gamma-ray bursts we can categorize:

- Long GRBs: 2 seconds to several minutes, typically associated with the death of massive stars as a supernova.
- Short GRBs: Less than 2 seconds, typically associated with and thought to originate from binary system mergers.

A statistically significant detection in the very high energy range of a short or long GRB (greater than 5σ) has yet to be found in the very high energy range by VERITAS. However, MAGIC has detected a long GRB [7] and measured a 3σ hint of a signal from a short GRB in the above ∼0.5 TeV range.

2.1.3 VEGAS Software and Implementation

VEGAS, the VERITAS Gamma-ray Analysis Suite, is a data analysis software that takes in single or multi-telescope data from the VERITAS array and processes it and analyzes in five distinct stages [4].

- *Stage 1*: Raw Data → Calibration Data
  - For calibration calculation (ex. Pedestal Calculation, Relative Timing Calibration and Relative Gain Calibration).
- *Stage 2/3*: Raw + Calibration Data → Calibrated Events → Parameterized Events
  - Optimizes the integration window to maximize the signal to noise ratio.
  - Malfunctioning pixel exclusion.
  - Image cleaning where pixels with SNR > 5 and boundary pixels with SNR > 2.5 are identified and picture pixels without a boundary are removed.
- *Stage 4*: Parameterized Events → Reconstructed Showers
  - Shower origin in sky and shower location on the ground are determined.
  - Here, Monte-carlo simulations of gamma-ray showers help us calculate mean scaled width, mean scaled-length and an energy for each event.
  - Produces gamma-ray shower development simulation (CORSIKA).
  - Produces VERITAS detector response simulation (GrISUDet).
  - Produces an energy look up table for each telescope.
- *Stage 5*: Reconstructed Showers → Selected Events
  - Time-cuts are considered here.
  - Background rejection is performed using gamma/hadron cut (Machine Learning) and optimized cuts are performed based on source and the spectrum.
- *Stage 6*: Selected Events → Statistics and Figures
  - Plots and graphs are produced.
  - Background estimation is performed.
  - Probability of a detection is performed using Li&Ma.

2.2 Gravitational waves and LIGO

In 1916, Einstein's Theory of General Relativity predicted the existence of gravitational waves. The theory predicted an ever-changing curvature of space-time caused by the presence and acceleration of massive objects that would produce ripples in the fabric of space-time. These waves propagate at the speed of light and provide a new window into the astrophysical phenomena of our universe. They were theorized to come from a multitude of events, black hole mergers, binary neutron star mergers, supernovae, and more.

Nearly a century after Einstein first theorized gravitational waves, LIGO detected gravitational waves from a Binary Black Hole Merger in 2015 [2]. LIGO, the Laser Interferometer Gravitational-wave Observatory, is a ground-based gravitational wave detector located in Livingston and Hartford. There are 3 different gravitational wave detectors currently in operation, LIGO, KAGRA, and Virgo.

Figure 5: LIGO detector in Livingston, Credit: Caltech/MIT/LIGO Lab

2.2.1 Interferometer

LIGO is an interferometer, the schematic shown in Figure 6, which means it superimposes two sources of light to create an interference pattern. When a gravitational-wave passes through, that wave will stretch space in one direction and compress it in the perpendicular direction. Thus, one arm of the interferometer will be slightly longer than the other. This small change in distance means that when we shine a light through the arms, one will come back slightly later than the other. They are then, out of phase and create an interference pattern, as shown in Figure 6. This signal is then detected by LIGO.

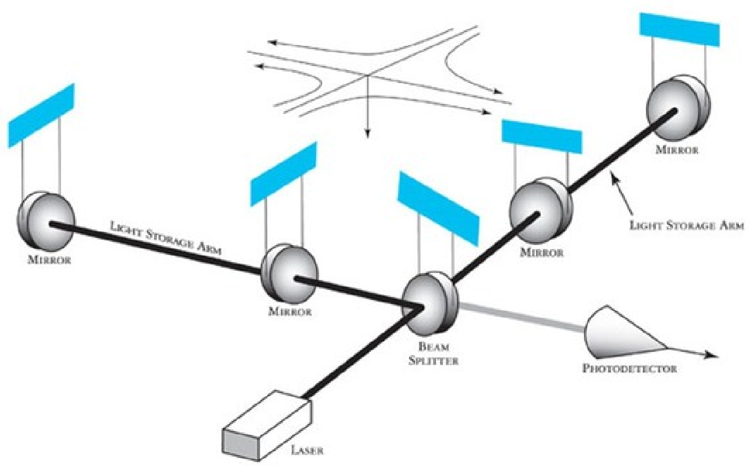

Figure 6: Basic schematic of a interferometer, Credit: Caltech/MIT/LIGO Lab

2.2.2 Detector noise and FAR

A typical gravitational-wave signal is buried in noise, as shown in Figure 7. This can be compared to being in a loud, large room filled with many people talking at once. Imagine in this scenario, a song starts playing or a new sound of some sort is introduced into this background. The sought-after sound would be buried within the noise of the room and unless you are looking for it carefully and cleverly, it will be difficult to

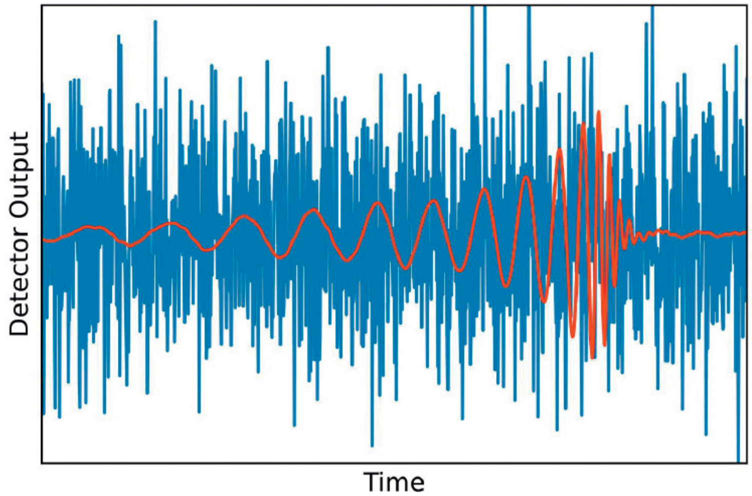

Figure 7: Typical gravitational-wave signal buried in detector noise [9]

detect. One of the ways LIGO sifts through the available data to find the most interesting events to look at is by looking at the "False Alarm Rate" (FAR). This is calculated in Equation (1).

$$FAR = \frac{N}{T_{BKG}} \tag{1}$$

"False Alarm Rate" is calculated by diving the total number of detector background noise events with a ranking statistic equal to or greater than that of the candidate (N) by the total duration of the background data (T_{BKG}). The smaller the FAR of an event, the less likely it is that this event is due to detector background and the more likely it is to be of an astrophysical source [9].

LIGO defines a certain FAR standard to be used as a filter for events. For example, for O3 candidates, the FAR for events that passed this test were ones that were likely to occur less than 2 times per day.

2.2.3 Analysis pipelines

The sub-threshold candidates consisted of 5 different analysis pipelines. These pipelines help characterize a gravitational-wave signal by taking in raw data, cleaning and processing it, and transforming it to extract certain interesting features. There are two types of analysis pipelines and searches. One is the unmodeled search consisting of the cWB (coherent WaveBurst) pipeline which is an unmodeled gravitational-wave data analysis pipeline. It only provides us with an astrophysical probability and a terrestrial probability. Then we have modeled searches that impose models and assumptions on the data to give information about the masses, spins, distances, and other parameters of mergers, allowing us to do more detailed astrophysical studies. The modeled searches consist of GstLAL (Gstreamer LAL), MBTA (Multi-Band Template Analysis), PyCBC (Python Compact Binary Coalescence), and PyCBC Highmass pipelines. They can provide us with the chirp masses of the binary system we are interested in, the mass ratios, the individual masses, the distances and probabilities of it being a certain type of merger event (BNS, BBH, NSBH) along with an astrophysical and terrestrial probability. These modeled searches are also low-latency, which means they process and analyze the LIGO data very quickly and if it is confirmed to be a gravitational-wave event then it is announced to telescopes all around the world to conduct follow-ups.

3 Analysis

3.1 Previous search through O1 sub-threshold data

The previous search through run O1 sub-threshold data searched for VERITAS archival observations that were spatially and temporally coincident with the sub-threshold candidates from LIGO's first run. The first run consisted of 103 sub-threshold candidates. 7 of these candidates were found to be spatially and temporally coincident with 11 VERITAS Observations from a time window of $-10 \leq t_o \leq 10^4$, where t_0 is the time of the LIGO event. The probability that VERITAS observed at least one astrophysical merger with the exact spatial coincidence in the time windows was estimated to be 0.04% [3]. Figure 8 shows one of the LIGO BNS Merger candidates with two overlapping VERITAS observations in LIGO's 90% localization probability map, which demonstrates how candidates were found to be temporally coincident.

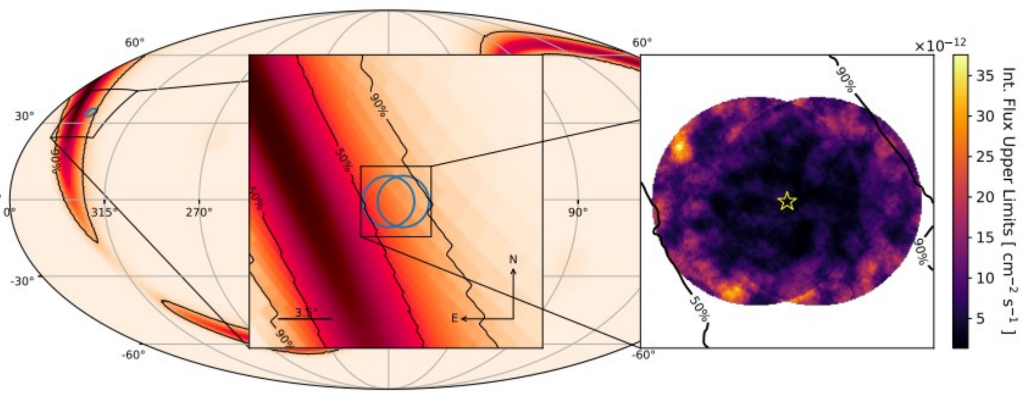

Figure 8: 90% Localization Probability Map of LIGO BNS merger candidate with the two overlapping VTS Observations [3]

The first run of LIGO did find the first binary black hole merger [2] but failed to find a binary neutron star merger (the 2017 detection discussed above being from the second run). To date, there have only been 2 confirmed binary neutron star mergers detected and of the two, only one has been found to have an electromagnetic counterpart. However, with the new upgrades between LIGO run O2 and O3, increased sensitivity of the instruments and new data warrant and encourage another archival search for serendipitous observations.

3.2 Finding spatially and temporally coincident candidates

Using the same archival search algorithm from the previous search, we searched through the list of over a thousand sub-threshold candidates from LIGO's run O3 that passed the FAR (False Alarm Rate) test [5]. From those candidates, 37 candidates were found to overlap between -10 to 1,000 seconds of the LIGO event time (a change from the previous time range of -10 to 10,000).

The O3 sub-threshold data separated the astrophysical probability into the sum of the following probabilities, which are produced from imposing different analysis pipelines on the data: binary black hole (BBH), binary neutron star (BNS), neutron star black hole (NSBH).

3.3 VERITAS Observing Capability Filtering Criteria

The previous search analyzed all of the spatially and coincident observations. In this search, we will consider VERITAS a factor we called 'VERITAS Observing Capability'. These are the factors that are most important for a possible VERITAS detection of an event:

1. *An observation that overlaps specifically with LIGO event time*: This is because VERITAS is most sensitive in the very high energy range and thus, the prompt emission phase is of upmost importance

in this search. This phase occurs in the first couple of seconds (-1 to 5 seconds) so it is best to look for observations that were overlapping with the gravitational-wave event time.

2. *An observation corresponding to a LIGO event that has any probability (>0) of being a binary neutron star merger event.* This is to prioritize events VERITAS is likely to see any electromagnetic counterpart to. Binary neutron star mergers are most likely to have some sort of gamma-ray burst output so focusing on these mergers is very important for our search.
   - There is a chance that accretion disk matter and tidal forces in binary black hole mergers or neutron star-black hole mergers could lead to some sort of gamma-ray detection but we chose to focus specifically on binary neutron star mergers for the purpose of this project.
3. *An observation's integrated VERITAS field of view probability on the LIGO skymap.* This integrates the LIGO event probability values for each pixel within the VERITAS field of view. From the LIGO skymap, the ones that have the highest probability overlap will be prioritized as those will be most likely to contain the LIGO event.

From the list of 37 coincident events, 4 events overlapped with the LIGO event time and also had any probability of being a binary neutron star merger. These events were then ordered by the integrated probability in order to create a priority list of candidates.

3.4 Finding ideal time window

Having selected the sub-threshold candidates and corresponding VERITAS runs, the next step was to run an analysis with VEGAS. The primary concern with moving forward was determining the time window of analysis. For a time window that is too long, the short signal that is being sought after might be entirely washed out. On the other hand, a time window that is too short may fail to yield a statistically valid result. VERITAS calculates a source's significance using the Li and Ma significance method. For a source's significance to be valid, the background must have a Gaussian distribution around a mean of 0.

In order to find the ideal time window for analysis, we decided to conduct a VEGAS analysis on a patch of sky where we don't expect to see anything. This means this run should be all background. We looked at the source Draco, which was nominally for dark matter annihilation searches but also works well as a 'blank' sky patch. This run was analyzed for a multitude of different time windows and then the histograms of the significant distributions were looked at to see at which time window does it converge to a Gaussian distribution, as shown in Figure 9.

A time window of 20 minutes for the analysis was chosen even though the full 30 minute run converges to a Gaussian. In the images in Figure 9, the time windows are consistently facing challenges when attempting to reach a Gaussian distribution on the lower end of the significance curve. Even when it does converge to a full Gaussian in the 30 minute run, the left side is not as smooth as the right side. Some of the lack of convergence at the 20 minute window can be attributed to low statistics at the edge of the camera. Thus, our candidates will be analyzed for a time window of 20 minutes, with the caveat that any edge pixels may not be trustworthy.

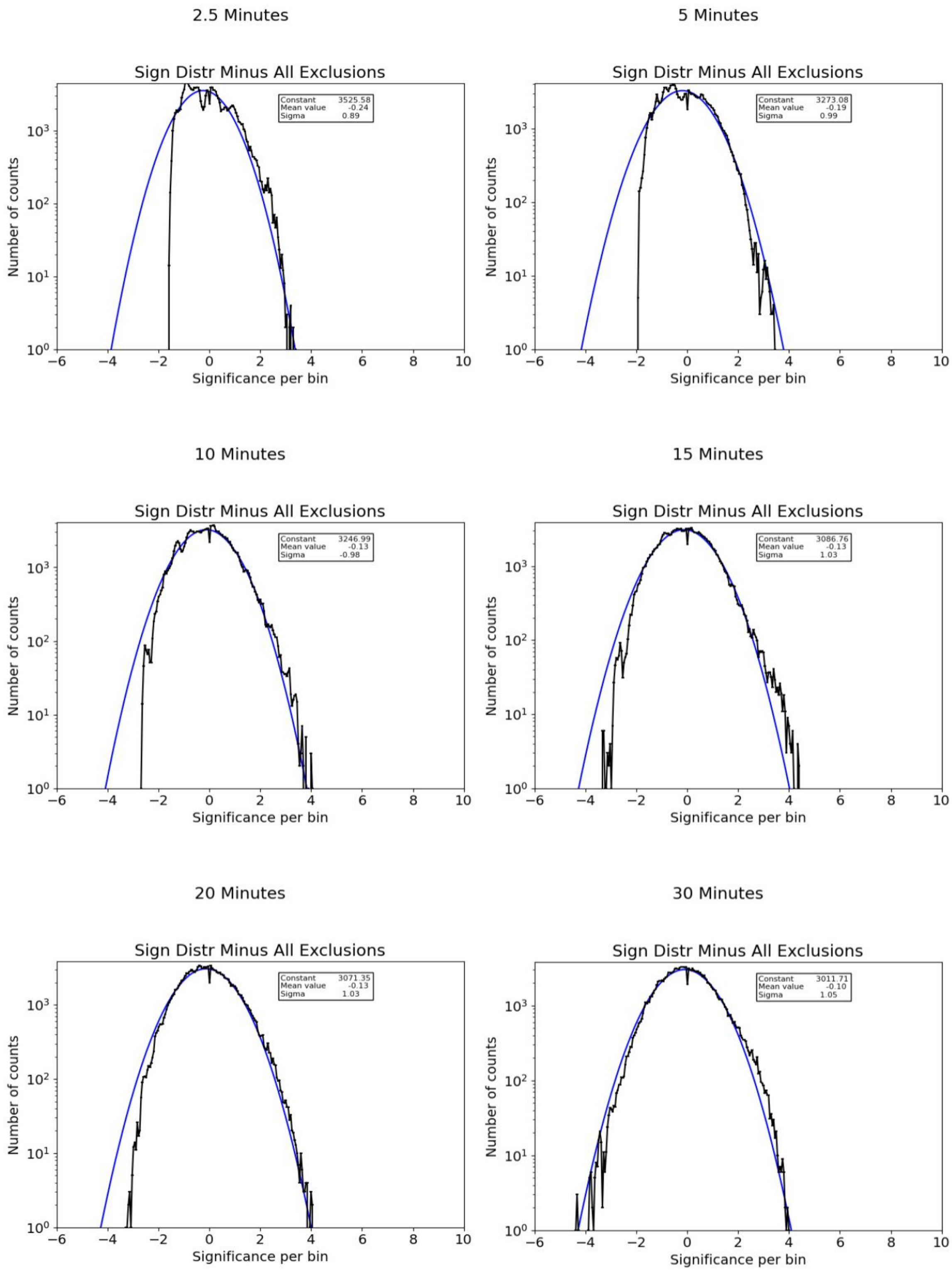

Figure 9: Draco blank sky analysis: 2.5, 5, 10, 15, 20, 30 minutes

3.5 Analysis of the candidate

This analysis will be a preliminary analysis of a single source. The analysis time window of 20 minutes made it difficult to analyze any of our candidates, since all of them overlap temporally very close to the end of the VERITAS run duration. Thus, the only source that was analyzed was one with a corresponding sequential run of the same source.

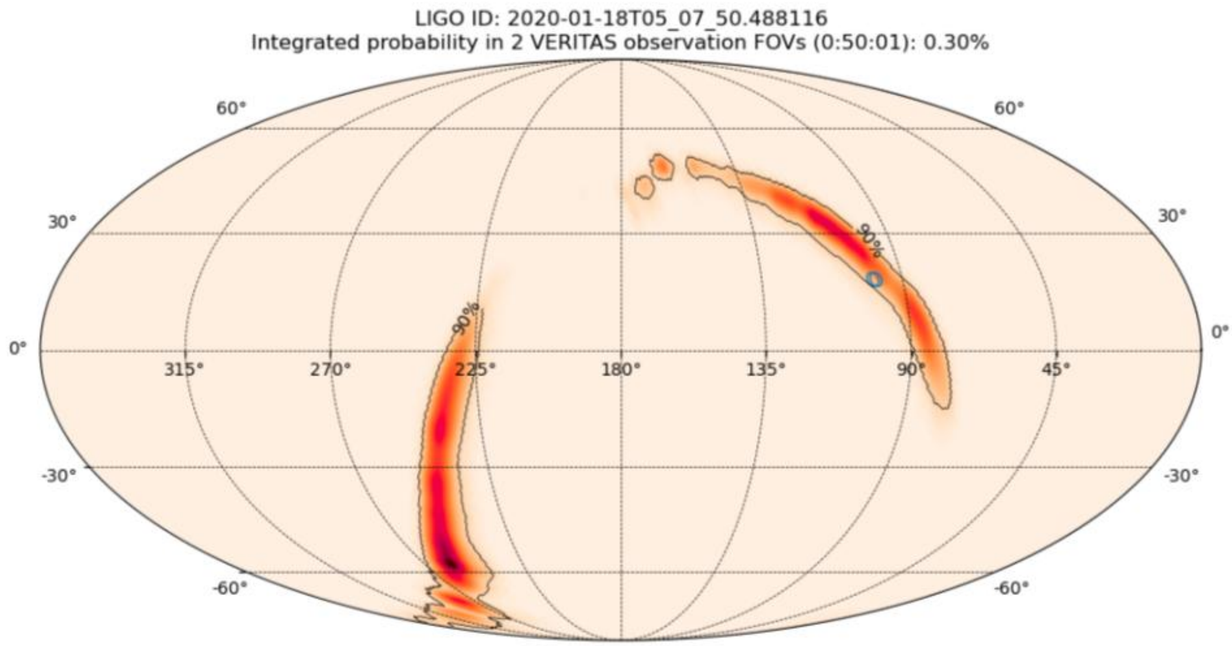

Figure 10: Candidate FOV in LIGO Probability Map

The VERITAS runs we looked at were 95279 and 95280 corresponding to LIGO Event that occurred at 1/18/2020 5:07 UTC. These runs were nominally for the supernova remnant Geminga and Geminga-E (a wobbled observation of the same target). A significance map plot was produced in in Figure 12, which is a 2D histogram of the significance at each RA/DEC value. Also, a significance distributions plot was produced in Figure 11, subtracting all the exclusions from the source it was looking at. If we were to see a source, there would perhaps be a signal in a high significance bin.

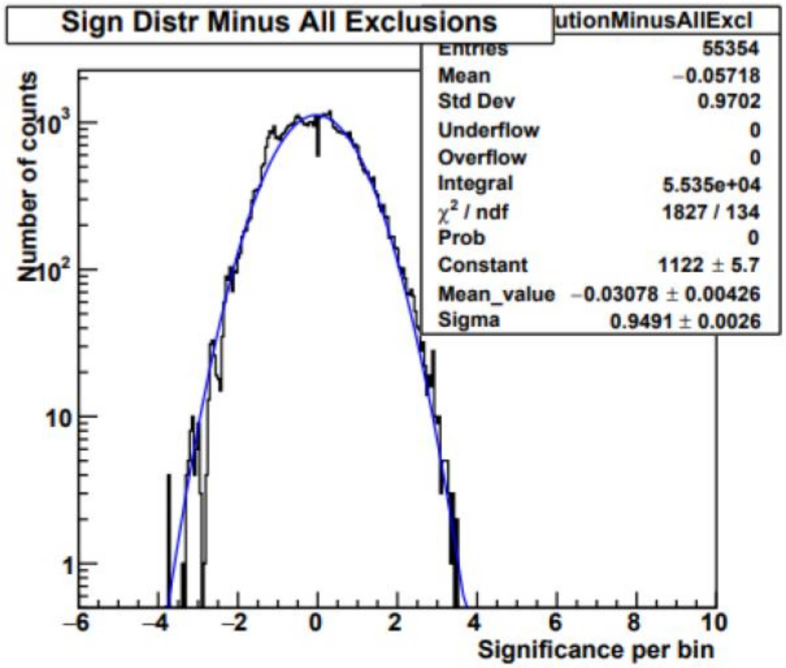

Figure 11: Candidate Significance Distribution

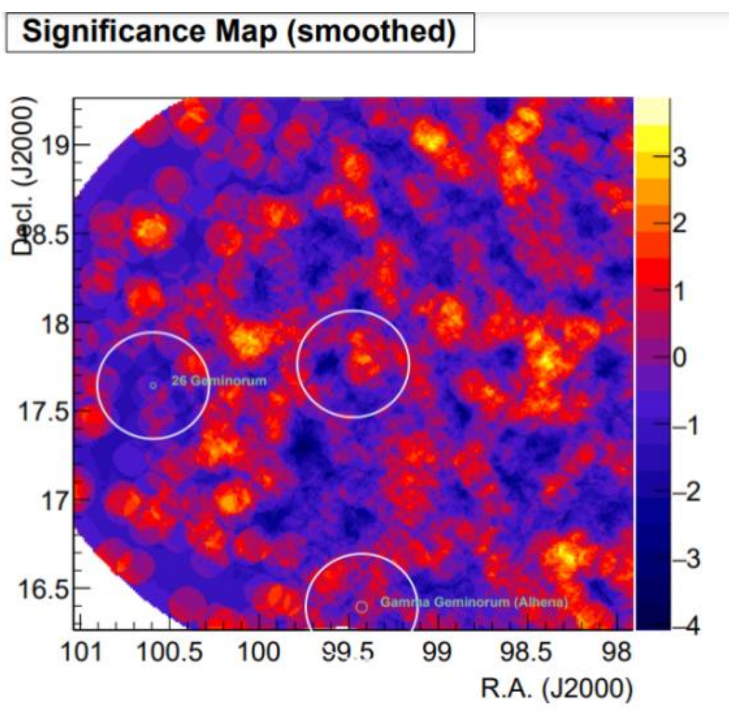

Figure 12: Candidate Significance Map

4 Results and Discussion

The analysis did not find any significant signal from the candidate. If there was to be a significant signal, we would see a bright spot on the map and a peak in counts in the higher significance bins in the distributions histogram. Since the significance histogram we are looking at subtracts any number of counts coming from the source, it is only showing us the background counts. Thus, if we had seen a peak somewhere in the background, that give a signal we would be interested in.

It is important to consider that the probability that the VERITAS field of view was looking at a gravitational wave event (VERITAS integrated probability) and the probability of this event being a binary neutron star merger of this candidate was 1.04×10^{-6}.

It is not very surprising we did not find a signal. The signal we are looking for would be short and concentrated to the very beginning of the time window of analysis. Analyzing for a time window of 20 minutes (1200 seconds, when the most relevant signal is in the first 5 seconds), will have entirely washed out any signal that could have existed in those first few initial seconds. This demonstrates the extreme importance we should be placing on the analysis time window for future searches for transient events such as a binary neutron star merger.

Although no signal was found, archival searches such as these can be very useful tools in the detection of transient events. While VERITAS does conduct follow-up observations to gravitational-wave and gamma-ray burst alerts, usually, these occur many seconds or minutes after the alert is sent. VERITAS stands out due to its exceptional angular resolution, enabling it to capture a detailed 'picture' of a source, unlike other all-sky telescopes; however, it is crucial to understand that VERITAS is not designed as an all-sky survey aimed at detecting gamma-ray events indiscriminately. Instead, it operates by targeting specific sources with pre-identified exact locations and conducts follow-up observations in collaboration with other telescopes (SWIFT, Fermi, IceCube, LIGO, etc). With a fixed field of view of approximately 3.5 degrees, VERITAS cannot scan its surroundings for potential phenomena. Its performs optimally when it already possesses precise knowledge of the location of the targeted source. Thus, we must prioritize the benefits that come with archival search methods to search for transient events. This demonstrates the need for a analysis framework that doesn't miss the 'needle in the haystack'-like signal we are searching for.

5 Future Directions

5.1 Time-dependent Analysis

The next direction for this project lies in conducting a time-dependent analysis. A time-dependent analysis will prioritize and weight the signals that come in earlier to some chosen time t_0. In the future, running a time-dependent analysis would be beneficial to the search. In a time-dependent analysis, the time duration of the analysis would be inconsequential as events occurring much after t_0 would carry less weight. Figure 13 shows how the Li and Ma significance method peaks at some observation time before falling off while the time-dependent model increases and flattens out at some later time.

The current model of Li and Ma significance weights all of the run equally, which is helpful for point sources and non-transient signals. However, in this search for transient, extremely short signals, we find ourselves needing an analysis model that reflects the physical system being studied.

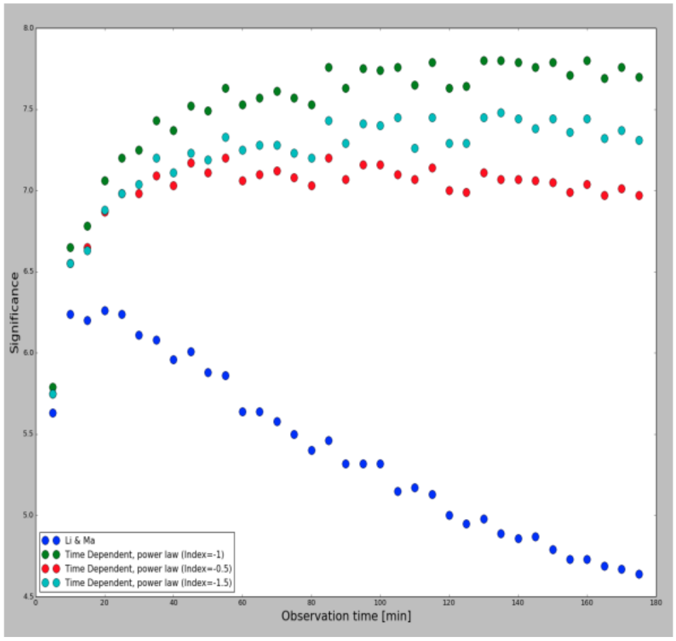

Figure 13: Li and Ma significance peaks and then falls off, Credit: Ori Weiner

5.2 Future Possibilities with pSCT

For LIGO's fourth run (O4), there are plans for pSCT (prototype Schwarzschild-Couder Telescope to follow-up on Gravitational-wave alerts with VERITAS, an example of this tiling shown in Figure 14. The superior angular resolution of SCT could increase the likelihood of detecting a transient event from a Gravitational-wave event signal [6].

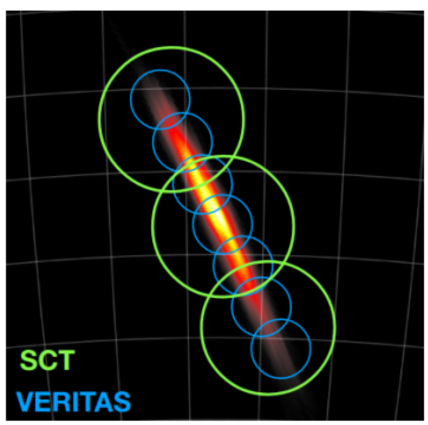

Figure 14: How SCT and VERITAS could be used to follow-up on a Gravitational-wave event [6]

6 Conclusion

The discovery of GW170817/GRB170817A has motivated multi-messenger efforts to study the most energetic astrophysical events. Because of delays in follow-up programs, conducting archival searches through data can help identify any signals that may have been missed. In this report, we have filtered through a list of 1000+ candidates to find 4 candidates that were serendipitously in the VERITAS field of view and passed our 'VERITAS observing capability'. Then, an analysis time window of 20 minutes was found by analyzing a 'blank' patch of sky. From the candidates, 1 binary neutron star merger candidate was analyzed for a time window of 20 minutes. This analysis did not find any significant signal coming from this event with the time window used. However, in the future, a time-dependent analysis on the candidates will be performed to amplify the signals that come closest to the LIGO event time.

7 Acknowledgements

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8 Appendix: Other Filtered Candidates

The figures below consist of other candidates that passed the filtered candidates test.

1. VERITAS Run #s: 95396, LIGO Event ID: 1263888184
    - VERITAS Observing Time: 1/24/2020 7:22 to 1/24/2020 8:02
    - LIGO Event Time: 1/24/2020 8:02

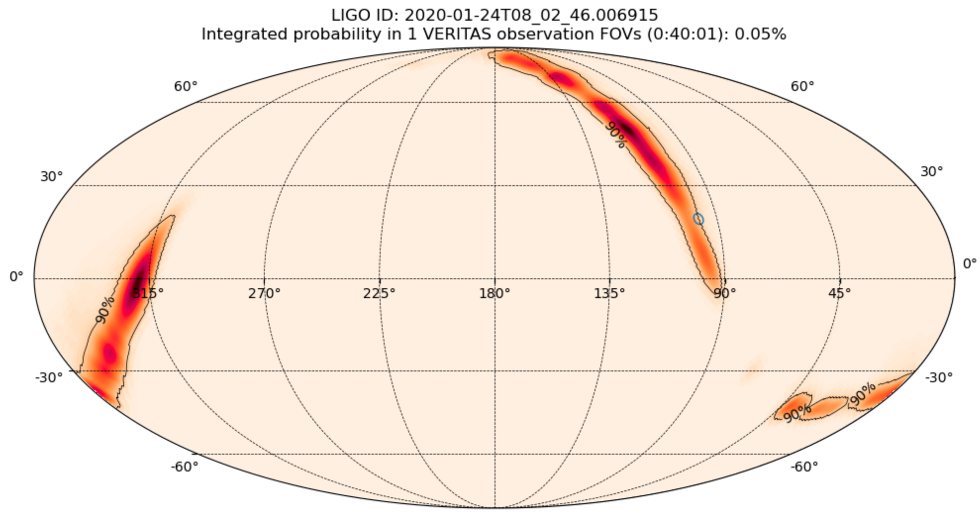

Figure 15: Candidate FOV in LIGO Probability Map

2. VERITAS Run #s: 95528, LIGO Event ID: 1264327620
    - VERITAS Observing Time: 1/29/2020 9:32 to 1/29/2020 10:07
    - LIGO Event Time: 1/24/2020 8:02

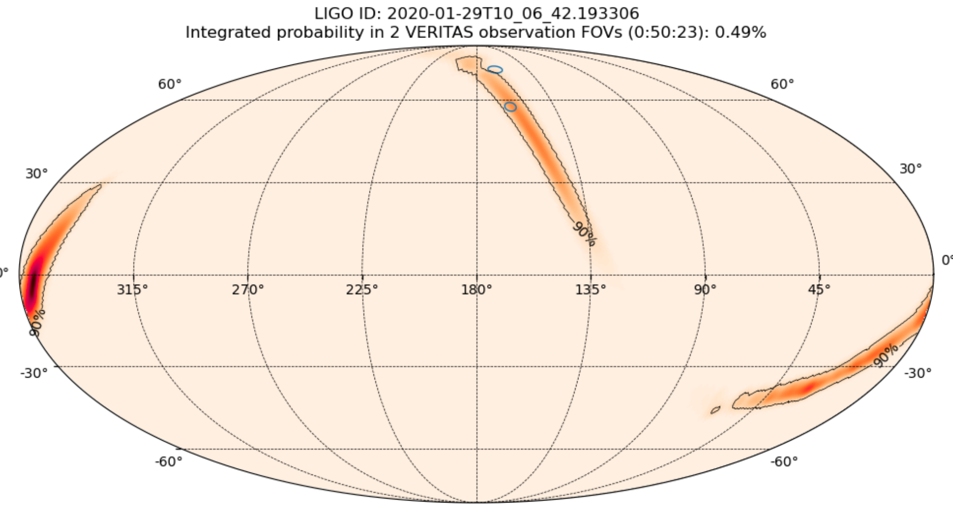

Figure 16: Candidate FOV in LIGO Probability Map

3. VERITAS Run #s: 95667, LIGO Event ID: 1264747176

   - VERITAS Observing Time: 2/3/2020 6:14 to 2/3/2020 6:44
   - LIGO Event Time: 2/3/2020 6:39

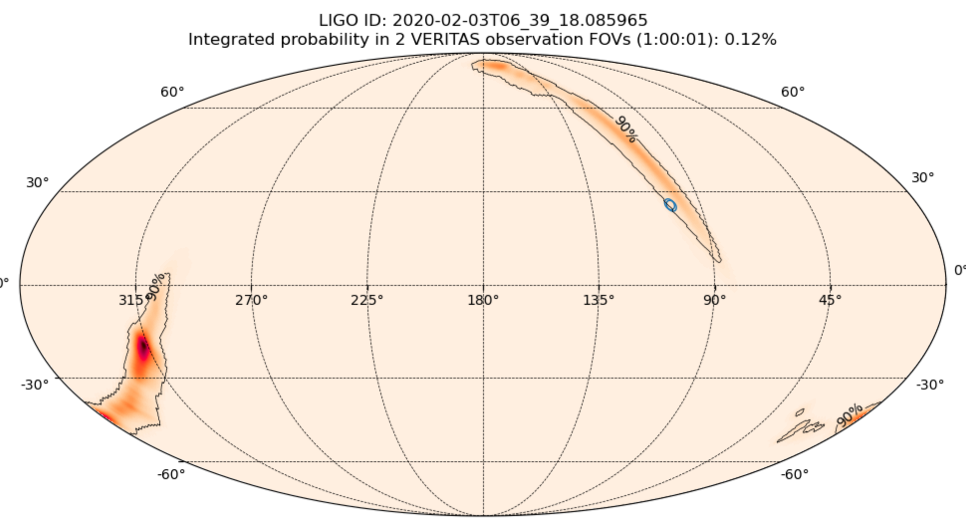

Figure 17: Candidate FOV in LIGO Probability Map