Searching for Neutrinos Coincident with Gravitational Wave Signals Using IceCube Cascade Events

Abstract

This study will perform a maximum likelihood method to look for neutrino signals coincident with the known gravitational wave sources reported by LIGO/Virgo. While some searches have been done previously, no significant signal has been found so far. One possible reason is that current analyses only include the track-like neutrino events detected by IceCube but ignore cascade events, which could also contain neutrinos from GW sources. As a result, exploring cascade events might result in the discovery of neutrino signals from the GW sources. Such a result could bring useful data for astrophysicists to develop a more thorough understanding of events like the mergers of black holes or neutron stars.

Introduction

Multi-messenger astronomy is the joint analysis of astronomical signals with different messenger particles such as photons and neutrinos, which provides people a more comprehensive understanding of an astronomical event. Since detecting the first gravitational wave (GW) signal in 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has provided new opportunities for multi-messenger astronomy. Astrophysicists believe that the discovery of other messengers, such as gamma rays or neutrinos, from blackhole mergers or blackhole-neutron star mergers could help us understand the dynamics of these processes. As such the IceCube Neutrino Observatory is actively looking for high energy neutrino counterparts from GW events, with data reported by LIGO/Virgo.

IceCube is a neutrino observatory located at the South Pole. The detector consists of strings of digital optical models (DOMs) arranged in a hexagonal pattern in the Antarctic ice. Each DOM contains a 10-inch photomultiplier tube [1]. When a high energy neutrino travels inside the earth, it can undergo a charged current interaction or a neutral current interaction, which generate high-energy charged particles that produce Cherenkov radiation. This light can be detected by the DOMs, and then the energy and direction of this neutrino can be reconstructed. With these reconstructed neutrino data, IceCube searches for neutrino signals coincident with the sky localization of each gravitational-wave event, using all neutrino signals from charged current interactions of muon neutrinos detected in a 1000 second time window centered around the time of GW event reported by LIGO. However, they found no neutrino signal coincident with any of detected GW events in LIGO’s O1, O2 and partially completed O3 runs [2].

One possible reason for this result is that only a subset of the neutrino signals has been taken into account in this search. There are two principle classes of Cherenkov events that can be easily identified by the IceCube detector: "tracks" and "cascades" [1]. A "track" comes from a muon neutrino that undergoes charged current interaction and generates a high-energy muon, which can travel extended distances (up to tens of kilometers) before losing its energy or decaying, leaving a track of Cherenkov light. Because of the long lever arm, such events have higher angular resolutions which is why they have been used in previous joint analysis. However, other neutrinos, those detected as "cascade" events, are not taken into account. A cascade occurs when any neutrino flavor that undergoes a neutral current interaction transfers its energy to a target nuclei, or when an electron or tau neutrino undergoes a charged current interaction. The result in both cases is a shower of charged particles which forms a spherical Cherenkov light front, as shown in Fig 1 [1]. Such events have lower angular resolution, but they could also originate from the source of GWs.

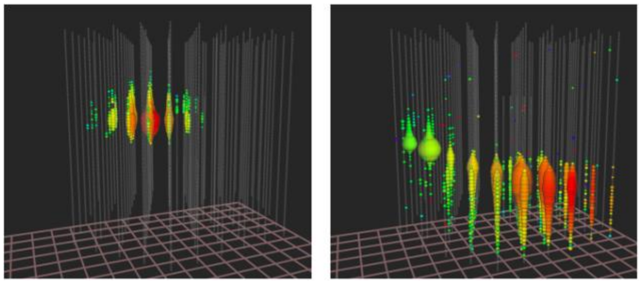

Figure 1 Cascade (left) vs Track (right)

Throughout this project, I will extend the search of neutrino counterparts to GW events to include cascade events. An unbinned maximum likelihood analysis will be performed for each GW event to calculate the consistency of our observed neutrino signals with hypotheses of multi-messenger emission. If our data are consistent with signal-like interpretations, we will be able to identify which GW events emit neutrinos. These results could be valuable for the further research on neutrino emission in GW events, which can help confirm current astrophysical models and reveal fundamental properties of events like blackhole-neutron star mergers, and mergers of two neutron stars.

Methods

The raw data we have include 10 years of IceCube cascade events. For each neutrino candidate event, we have a reconstructed direction, $\vec{x}_i$, and reconstructed energy, E_i [3]. Using the GW event time reported by LIGO, all reconstructed cascade signals within a 1000 second time window are collected as candidates that could come from the source of this GW event. However, since these neutrino signals contain not only signals from GW events but also atmospheric neutrinos and potentially other backgrounds, a maximum likelihood analysis will then be performed as follows to determine if there exist any signals that actually came from the same source as the GW event [4].

First, the sky is divided into equal-area bins using HEALPix [5], with pixel area roughly 0.01 deg^2. For a pixel at $\vec{x}_s$, supposing a GW source here emits neutrinos with an $E^{-\gamma}$ power law energy spectrum, the source probability density, which is the probability that one observed neutrino event with direction $\vec{\mathrm{x}}_\mathrm{i}$ and energy $\mathrm{E_i}$ comes from this source, is calculated:

$$S_i(\vec{\mathrm{x}}_\mathrm{i}, \vec{x}_s, \mathrm{E_i}, \gamma) = \mathrm{N}(\vec{\mathrm{x}}_\mathrm{i}|\vec{x}_s) * P(\mathrm{E_i}|\gamma), \text{ where}$$

$$\mathrm{N}(\vec{\mathrm{x}}_\mathrm{i}|\vec{x}_s) = \frac{1}{2\pi\sigma^2}\, e^{-\frac{|\vec{\mathrm{x}}_\mathrm{i} - \vec{x}_s|^2}{2\sigma^2}}.$$

The $\mathrm{N}(\vec{\mathrm{x}}_\mathrm{i}|\vec{x}_s)$ represents the spatial probability density based on how $\vec{\mathrm{x}}_\mathrm{i}$ deviates from $\vec{x}_s$, the $P(\mathrm{E_i}|\gamma)$ is the energy probability density, representing the probability of having an event with energy $\mathrm{E_i}$ given an $E^{-\gamma}$ power law energy spectrum of the source. This probability is precalculated using a sample of Monte Carlo simulated events. An example of this is shown in Fig 2 [4].

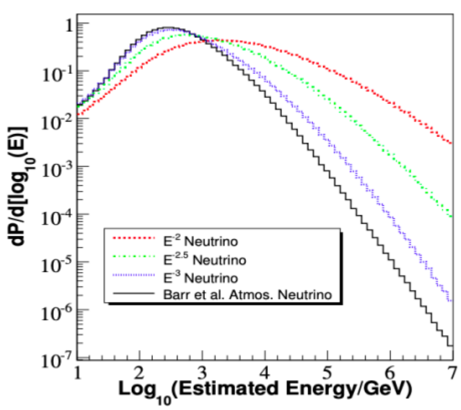

Figure 2 Energy spectrums with different power law

Then the background probability $\mathrm{B_i}$, which represents the probability that an observed event is actually due to background, is calculated. Assuming the atmospheric neutrino is the main source of background neutrino signals, the probability that an event with energy $\mathrm{E_i}$ originates from background is

$$B_i(\mathrm{E_i}) = \frac{P(E_i|\phi_{atm})}{\Omega_{pixel}}.$$

Here, Ω_{pixel} represents the solid angle of a pixel. $P(E_i|\phi_{atm})$ is the probability of having the event with energy E_i under the assumption of a fixed atmospheric neutrino energy spectrum ϕ_{atm}. In this step, the $P(E_i|\phi_{atm})$ will be determined individually according to the position of each pixel.

After we calculate for each neutrino event how signal like it is (S_i) and how background like it is (B_i) with respect to a source at pixel $\vec{x}_s$, for all N cascade type of neutrino signals detected during the 1000 second time window, the likelihood L at this pixel $\vec{x}_s$ is defined as

$$L(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^{N} [\frac{n_s}{N} * S_i + (1 - \frac{n_s}{N}) * B_i].$$

Here, n_s here is the number of neutrinos that come from the source at $\vec{x}_s$, out of the total events detected, N, and γ is the power law energy spectrum of the source. In other words, L represents the likelihood that a source with power law energy spectrum γ and direction $\vec{x}_s$ will generate n_s number of neutrinos in the total N neutrino signals detected by IceCube. Larger values of the likelihood, L, represent regions of parameter space where the data are most compatible with the given hypothesis. As the result, the n_s and γ should be set to maximize the likelihood L. This operation will be done by minimizing the quantity $-\ln(L)$ using the MIGRAD minimizer in MINUIT [6].

As a result, now for each pixel $\vec{x}_s$ in sky we have a maximized L_{max}, and by setting $n_s = 0$ we also get a L_0 representing the probability of having a purely background case, so we calculate $\ln(\frac{L_{max}}{L_0})$ to represent how signal like events in this pixel are. According to data from LIGO, the probability for GW events to occur at pixel $\vec{x}_s$ can be defined as $\omega = \frac{P_{GW}(\vec{x}_s)}{\Omega_{pixel}}$, so for each pixel we define a test statistic[2]:

$$\Lambda = ln(\frac{L_{max}}{L_0}) + ln(\omega).$$

Large, positive values of Λ, especially those inconsistent with our expectation from atmospheric backgrounds, could be an indication that progenitors of GWs are also sources of high energy neutrinos.

Project Timeline

Starting on May 20th, I will begin working on this project for at least 40 hours per week with the hope of finishing it before the beginning of the 2020 Fall semester. In the first few weeks I will get familiar with data used in this research as well as the software tools used in IceCube. Then during the next month, I will work on writing the program that performs the unbinned maximum likelihood analysis on these data. I will spend the next few weeks testing and debugging this program, and then I will use it to analyze the data and collect the output. In the end a skymap showing the neutrino events found to be coincident with GWs will be made, and a final report will be written to summarize the works I have done and to help future analyzers. My research mentor, professor Justin Vandenbroucke, and two Ph.D. students in IceCube, Alex Pizzuto and Raamis Hussian, will be guiding me during the research, and I plan to meet them once or twice every week to discuss my code and analysis methods I will use. Additionally, I will develop skills working with an international research collaboration, and occasionally present my progress and results to a group of researchers within the IceCube collaboration who are focused on pinpointing the sources of astrophysical neutrinos.

Conclusion

After the detection of gravitational waves in 2015, many are actively looking for neutrino counterparts to GW events. Previous analyses have used only track events to perform such a search but to date no significant signals has been found. In this project, I will extend this analysis to cascade events, and perform an unbinned maximum likelihood method to search for neutrinos coincident with GW sources. By including this additional interaction channel, it is possible that some neutrino coincidences will be found. The discovery of such neutrino coincidences will provide important constraints for understanding the nature of GW progenitors.

References

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