Initial Team Report: Correlation Analysis between Gravitational Wave Events and Gamma-ray Bursts

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Introduction

Gamma-ray bursts, since ever being observed, had been fascinating people with its abnormally high photon energy range and its highly unpredictable time-domain pattern in the light curves. People have been developing models for explaining why this phenomenon can ever happen in the nature, potentially generated by some extreme astronomical events. On the other hand, gravitational wave, another completely different physical mechanism other than electromagnetic wave, is now becoming clearer to us thanks to the appearance of highly accurate laser interferometers such as LIGO and VIRGO. Gravitational wave as a newly discovered tool other than electromagnetic waves, is now providing us with more insight into some extreme astronomical phenomena such as the merger of blackholes or neutron stars. Now the intriguing question is that: can these two kinds of seemingly totally different waves come from the same sources?

There is observational evidence to support that when two Neutron Stars coalesce, gamma ray bursts are produced [1, 11]. It is also theorized that when a binary black hole system coalesces, it also produces gamma ray bursts [14]. When a binary system of Neutron Stars or Black Holes coalesce, they produce gravitational waves. Gamma ray bursts are detectable from Earth using space telescopes. Gravitational waves are detectable from Earth using laser interferometers. Since there the mechanism that produces Gamma Ray Bursts and Gravitational Waves are the same, there could be a potential correlation between the time and location of these events. In this project, we will calculate the correlation between the time and the angular correlation between Gamma Ray Bursts and Gravitational Waves.

Background

Gamma-Ray Bursts (GRBs)

Gamma-ray bursts (GRBs) are an intensive radiation of gamma-ray photons in the universe. The occurring time and positions of GRBs are highly random and uniformly distributed in the angular positions on the sky [4]. There are more than one hundred models models discussing the generation of GRBs [15], but with growing analysis on the light-curves of various GRBs [3] and on its afterglow [21][10] (in X-ray or Ultraviolate ranges), people start knowing more about the mechanism generating the GRBs, and the inner engine containing the enough energy to generate them.

The current most widely accepted model for the generation of a GRB is the fireball model [17][5][9]. Provided that there is any "inner engine" that is able to release a large amount of energy, the released energy will expand outward in the form of a "fireball" of plasma of photons, electrons, and baryons. Then part of the kinetic energy of the outgoing flow will be transformed into radiation through inner shock mechanisms. The magnetic field within the shock will then induce synchrotron radiation from the flow and thus generate a GRB.

Previous observation on GRBs revealed that the T90 duration of GRBs, i.e. the duration during which 90% of the photons have been counted, exhibit a bimodal distribution with roughly a threshold at 2 seconds [12](see Figure). Based on this bimodal distribution, we can classify the GRBs into roughly two classes: long-GRB (T90>2sec) and short-GRB (T90<2sec). long-GRB mostly comes from the death of massive stars, which could create hypernovae and become the inner engine of a long-GRB [18]. Short-GRB, on the other hand, comes from the collision of two extremely massive and compact objects, such as neutron stars or blackholes. Binary neutron star collision, for example, will create kilonova and thus generate short-GRB [20]. Such mechanism was originally doubted but finally confirmed by the observation of the simultaneous occurrence of GRB event GRB170817 and the GW event GW170817 [1][11] [7], by which people verified that the short-GRB was generated by the merger of binary neutron stars by analyzing the correlation of both the GRB and the GW features as well as the analysis on its afterglow patterns [19].

In this project, we mainly focus on the short-GRB, since it is closely correlated with the collision of massive and compact objects, which in the meantime will also generate intensive gravitational waves, allowing us to determine the correlation analysis on a basis of data survey.

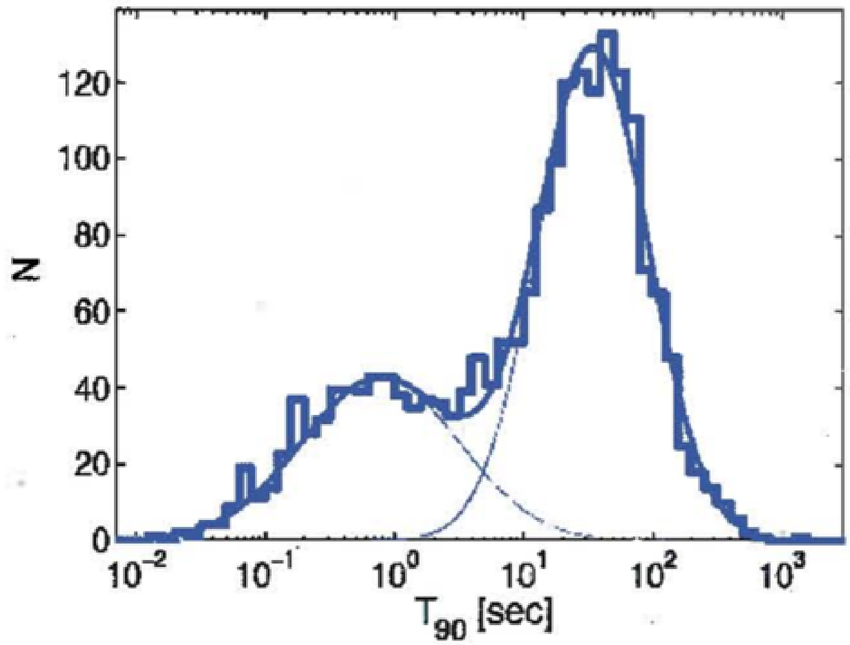

Figure 1

Bimodal distribution of T90 duration on GRB events in previous work [12].

Gravitational Waves (GWs)

Gravitational Waves (GWs) are waves that propagate through space-time [16]. GWs are created by many different sources. However, only the largest sources that create the largest GWs are able to be detected on Earth. These are the coalescence of binary systems of compact objects. Compact objects include Black Holes and Neutron Stars. Binaries consisting of these compact object will lose energy in the form of gravitational waves which causes the binary system to shrink until the objects collide. When these compact objects coalesce, massive gravitational waves are produced. These large waves produced are what is able to be detected.

These GWs are able to be detected with LIGO-Virgo [13, 2], which are laser interferometers. When a GW passes through an area, the distances between objects will increase in a direction and decrease in the direction perpendicular to the direction that increases. When a GW passes through a laser interferometer, the arms of the system will increase or decrease in length, causing an interference pattern to be made. LIGO-Virgo is constructed such that the signal from the two arms destructively interfere if no GW is passing through. When a GW passes through the arms, the signals from the arms constructively interfere.

With a single laser interferometer, information about the binary compact object system can be found from properties of the interference pattern [8, 6]. Having multiple detectors allows for a greater amount of information about the system. Numerical General Relativistic simulations of compact objects merging with different parameters for properties of the compact objects, their orbit, and their location. These are then compared with the signal detected by LIGO-Virgo to find possible candidates of binary compact objects that produced the detected gravitational wave. If multiple detectors detect a gravitational wave, spatial localization of the gravitational wave is possible.

Objectives

Our objective is to create probability densities of time and angular position on the sky for the population of both gamma ray bursts and gravitational waves. From this, correlation studies for timing and position will be carried out between the gamma ray burst and gravitational wave populations. This will explain if there has been an observed correlation between gamma ray bursts and gravitational waves due to the singular mechanism that produces both.

Data Description

Fermi Gamma-Ray Telescope Data

Gamma-ray is the shortest wavelength of electromagnetic wave in the nature, and its high absorption in the atmosphere makes the cosmic gamma-ray almost impossible to detect by detectors on the Earth. Fortunately, in 2008, NASA launched Fermi Gamma-ray Telescope, named after the great physicist Enrico Fermi, to low orbit around the Earth, serving as a stable detector to observe the gamma-ray radiation from the universe.

Fermi (originally named as GLAST) consists of two components, the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). LAT observes the high energy gamma-ray photons (10MeV-1GeV) while GBM is constantly monitoring GRBs in the universe and is detecting lower energy gamma-ray photons (1keV-30MeV).

Compared to steady emission sources of gamma-ray, GRBs consist of more intensive and shorter (1ms-100s) radiation of gamma-ray photons. Also GRBs are highly random and uniformly distributed on the sky, and therefore is almost impossible to predict the next occurring time and positions. Therefore, GBM is equipped with scintillator detectors that are highly sensitive to the gamma-ray photons as triggering detectors for GRBs. Once triggered, the satellite will be reoriented to the direction of the GRBs and will collect the data of the incoming GRBs. On GBM, there are twelve NaI (Sodium Iodide) detectors, with energy range of 1keV-1MeV, and two BGO (bismuth germanate) detectors, with energy range of 150keV-30MeV. Each detector is oriented different directions to provide a better angular resolution to localize where the GRBs come from.

In our project, we will mainly focus on the data of GBM, as we want to correlate the GRB events with the gravitational wave events. We are able to access the GBM data from the free online database from NASA. For each GRB event, we may access its catalog (containing the general information such as time and duration), light-curves of different detectors extracted from TTE (Time-Tagged Event) data, as well as the probability distribution of the location where the GRB may have come from.

We mainly focus on the data within the GRB catalog files (glg_bcat_all_bnxxx.fit) and the location probability distribution files (glg_locprob_all_bnxxx.fit) to extract the time and position information of the GRB events, where bnxxx is the number label of each GRB. Both kinds of files can be downloaded via free online database of Fermi Telescope.

GRB catalog files contain the general information of a certain GRB event, such as the date, the energy flux, the peak flux intensity, and the T90 duration (see Fig 2). From which we can firstly extract the T90 duration to filter out the long-GRBs and focus on data of short-GRBs only. Later, we can also know the date of each GRB event, so that we can compare later with the date of each GW event to implement time-correlation analysis.

Location probability distribution files contain a sky map of the posterior probability distribution of the position where the GRB had occurred (see Fig 3). Since we had only 14 scintillator detectors in total (twelve NaI and two BGO detectors), all the information we have is

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2. FIT PARAMS - Type: BinTableHDU, Dimensions: (1783, 15)

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- TELESCOP              = GLAST
- INSTRUME              = GBM
- OBSERVER              = Meegan
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- TSTOP                 = 754536789.1126
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- FLU_ERR               = 2.73946e-08
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- T90                   = 51.968
- T50                   = 24.064
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Figure 2

GRB catalog data file content. Each catalog file contains three HDUs (header-data unit): primary hdu (containing general information), detector data hdu(containing some data from the detectors), and fitting parameter hdu (containing some posterior fitting parameters from the detector data). We mainly extract the dates and T90 duration times of GRBs from the primary hdu. Below is just some example data within the header of primary hdu.

actually the light-curve data from all these 14 detectors and NASA provided the posterior probability of the location of the GRB based on the orientation of each detector when GRB happened and the intensity of the detected GRB they detected (see Fig 5). Based on this probability skymap, we can roughly know the position of each GRB and implement two-point angular correlation analysis with the GW events.

We explored what the data of GRB events may look like by plotting the histogram of the T90 duration, the date, and the angular position of all the GRB events Fermi detected from 2015 (the year when LIGO was launched) to present. Basically, the preliminary data exploration revealed to us the features of GRBs that we expected.

T90 duration histogram (see Fig 6) shows a clear bimodal distribution of both long and short-GRBs, consistent with the observation from previous works [12].

Histogram of dates (see Fig 7) shows a totally random and uniform distribution of the occurrences of the detected GRB events by Fermi. It also shows us that Fermi did not have any downtime due to malfunctioning or maintenance; rather, it seems to stably detects and transmits observed GRB data.

Histogram of angular positions (see Fig 8) on the skymap reveals that the GRB events are indeed randomly happening on the sky with a uniform distribution in all directions on the sky, consistent with previous observation of GRBs [4]. Compared to the stable emission sources in the Milky way that constitute the famous astronomical structure of Fermi Bubble, GRBs seems to happen mostly from galaxies outside the Milky Way.

LIGO-Virgo Data

LIGO-Virgo has three different laser interferometers located in different orientations and has had three detection runs where LIGO-Virgo is actively running and searching for gravitational waves [13]. LIGO-Virgo detects strain from the change in length of the arms of the laser interferometers. Once a detection is found, parameters of binary compact systems are fit to the detection. Detection signatures from the three different detectors are then compared to fit more parameters of the binary system. The posteriors can be downloaded from zenodo.

For a single detection, combinations of different parameters can lead to the detected gravitational wave within error. The posteriors provided by LIGO-Virgo are the parameters of different binaries that could lead to signal detected. An example of the posterior distribution for right ascension is shown in Fig 9. When LIGO-Virgo reports the parameters of a binary system, they report the median of the posteriors they obtain.

There are two data files for a single gravitational wave detection. There is a ‘nocosmos’ and a ‘mixedcosmos’ file. These two files correspond to for parameters that are not adjusted for comoving distance and are adjusted for comoving distance. In this project, we will use the 'mixedcosmos' files. In each file, there are multiple different reductions. These give slightly different posteriors since they use different analyses to calculate the posteriors. An example of how the posteriors change based on the analysis method used is shown in Fig 10. We will use the C01:Mixed analysis for this project. For certain gravitational wave detections, there are additional analysis based on if the system has high spin or low spin. In this project we will use high spin.

Parameters that are fit to every gravitational wave posterior that will be used in this project are Right Ascension, Declination, and Geocentric Time. This gives a probability distribution for each parameter. The width of these distributions depend on how many laser interferometers were able to detect the event. With more laser interferometers, better constraints are able to be put on the source of the wave. These probability distributions can then be combined into a probability distribution for all gravitational wave events. However, the size of posteriors for each of these parameters varies for each GW. To account for the different sample sizes, we will weight the posteriors such that the weight of all samples for a single GW added together will be 1. The weight applied to all the samples for a single GW is $W = 1/n$ where n is the total number of samples for the GW.

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- CUNIT2               = deg
- CTYPE1               = RA---TAN
- CTYPE2               = DEC--TAN
- CRVAL1               = 245.5
- CRVAL2               = 1.1
- RADESYS              = ICRS
- BUNIT                = significance
- EXTNAME              = PMAP
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Figure 3

GRB location probability data file content. Each location probability data file contains two HDUs (header-data unit): primary hdu (containing general information) and image hdu (containing probability distribution image on the skymap coordinated with ICRS system). We mainly extract the probability distribution data from the image hdu. Below is just some example data within the header of image hdu.

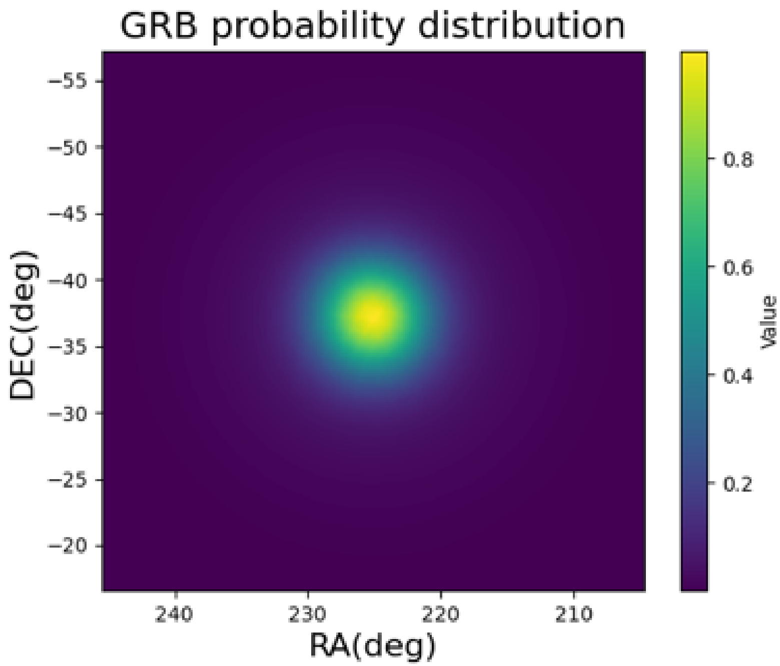

Figure 4

Posterior probability distribution of the location of GRB250121983 on the skymap. We are labeling its location with international celestial reference system (ICRS). Right ascensions (RA) and declinations (DEC) are used to localize the angular position. In this plot, we are using tangent plane projection method to plot this angular position probability distribution.

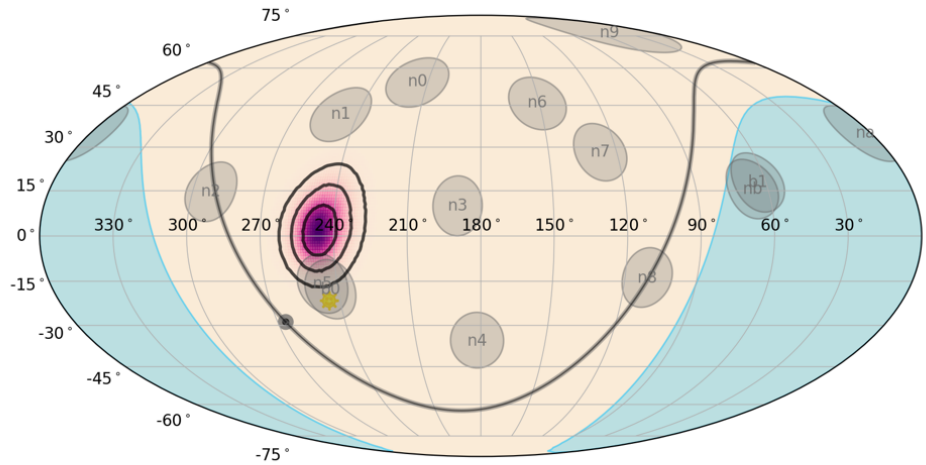

Figure 5

The skymap of GRB241129064. Grey shades representing the orientation of all the scintillator detectors are labeled on it. For example, N1 stands for the number one NaI detector, and B1 stands for the number one BGO detector. The purple area is the posterior probability distribution of the location of GRB241129064 calculated by the data from the scintillator detectors. Bright orange areas are the visible area for Fermi while blue area is the invisible area shaded by the Earth.

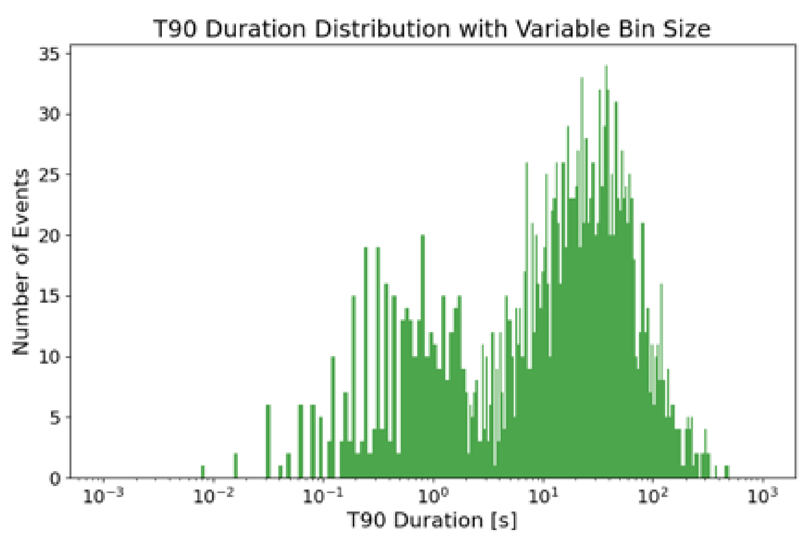

Figure 6

Histogram of T90 data of all detected GRB events by Fermi since 2015. We can clearly see a bimodal distribution with a threshold at around 2 seconds.

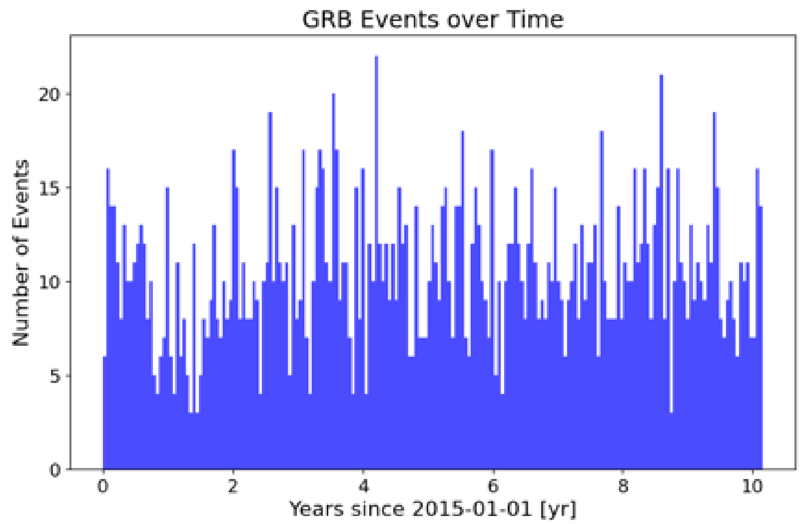

Figure 7

Histogram of dates of all detected GRB events by Fermi since 2015. We can see that the distribution is quite random and uniform, and there is no downtime for Fermi.

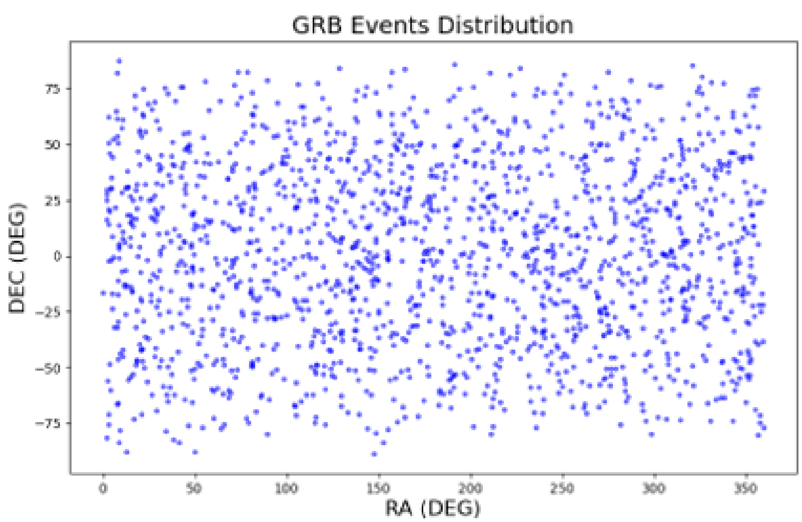

Figure 8

Histogram of angular postions of all detected GRB events by Fermi since 2015. We can see that the distribution is quite random and uniform in all directions on the sky.

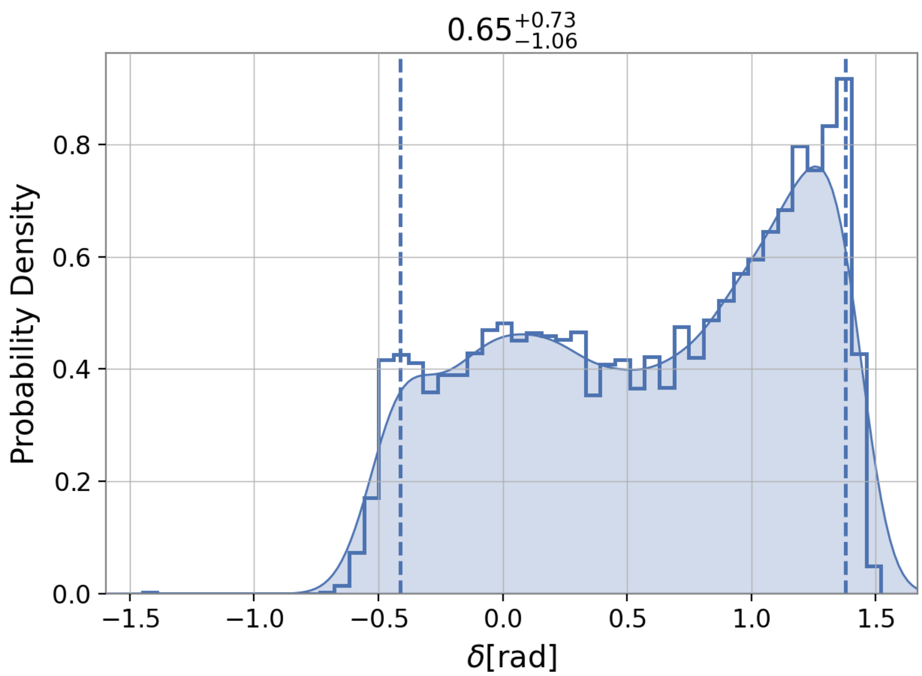

Figure 9

An example of a posterior distribution for a parameter of a gravitational wave detection. Shown is the right ascension distribution for the gravitational wave event GW191103-012549.

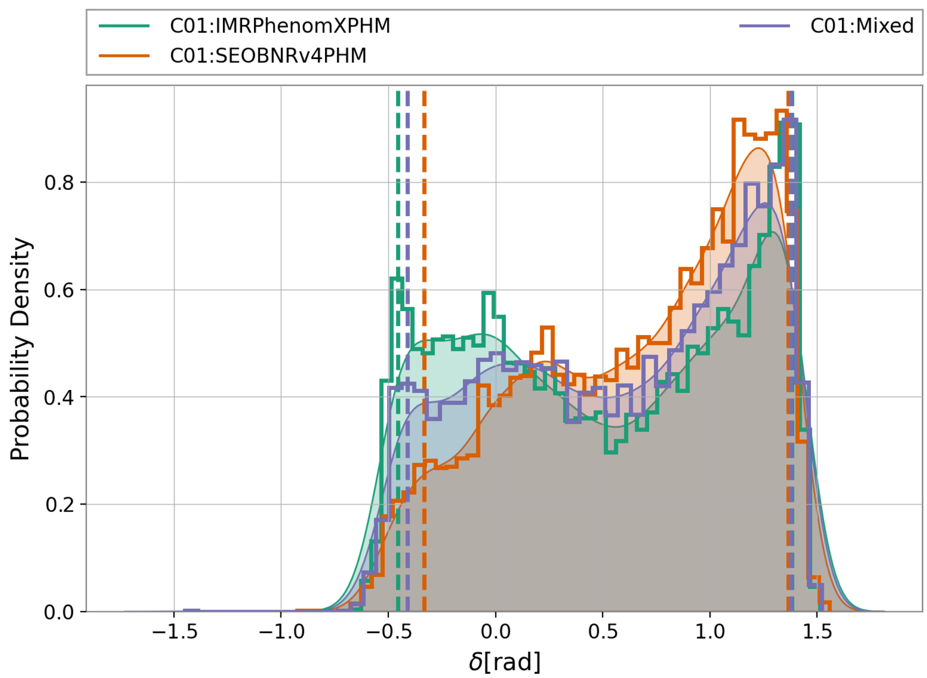

Figure 10

The posterior distribution of declination for GW191103-012549 utilizing three different analysis methods.

Pipeline Design Plan

In this section, we discuss the pipeline plan for this project. A flowchart of the pipeline plan can be seen in Fig 11. Datasets for GRBs and GWs will be collected. GW data will then be reduced to have geocentric time and angular position on the sky. The GW detectors started running in 2015 and have not run 24/7 since they first started collecting data. The GRB detector starting running before 2015 and runs 24/7. The GRB data will then be reduced to match the geocentric time of GW data due to the runtime of detectors. The reduced number of GRBs will then have their respective angular positions on the sky collected. Correlation between the two reduced datasets will then be conducted.

In the time-correlation analysis, we will be investigating the possibly correlated GRB-GW pairs during all time. To do so, we can calculate the no-correlation time-scale T_{no} by the following formula:

$$T_{no} = \sqrt{\frac{0.1}{R_{GW}R_{GRB}}} \tag{1}$$

Where R_{GW} and R_{GRB} are the average rates for the occurrences of GW or GRB events separately. This formula comes from the estimation that on average, the expected occurrence number of uncorrelated GW and GRB event pair within a time-scale T will be:

$$N_{GW-GRB} = R_{GW}R_{GRB}T^2 < 0.1 \tag{2}$$

If we wish this expected number of uncorrelated GW-GRB pair to be less than 0.1, then this no-correlation time-scale T_{no} will be just like what Eq. 1 describes, which means that within this time-scale, there should be no uncorrelated GW-GRB pair occurs. We can examine in the GW and GRB data that if there are any GW-GRB pair happens within this T_{no} time-scale. Once we find any pair, we can proceed to do correlation analysis on the angular position of the GW-GRB pairs.

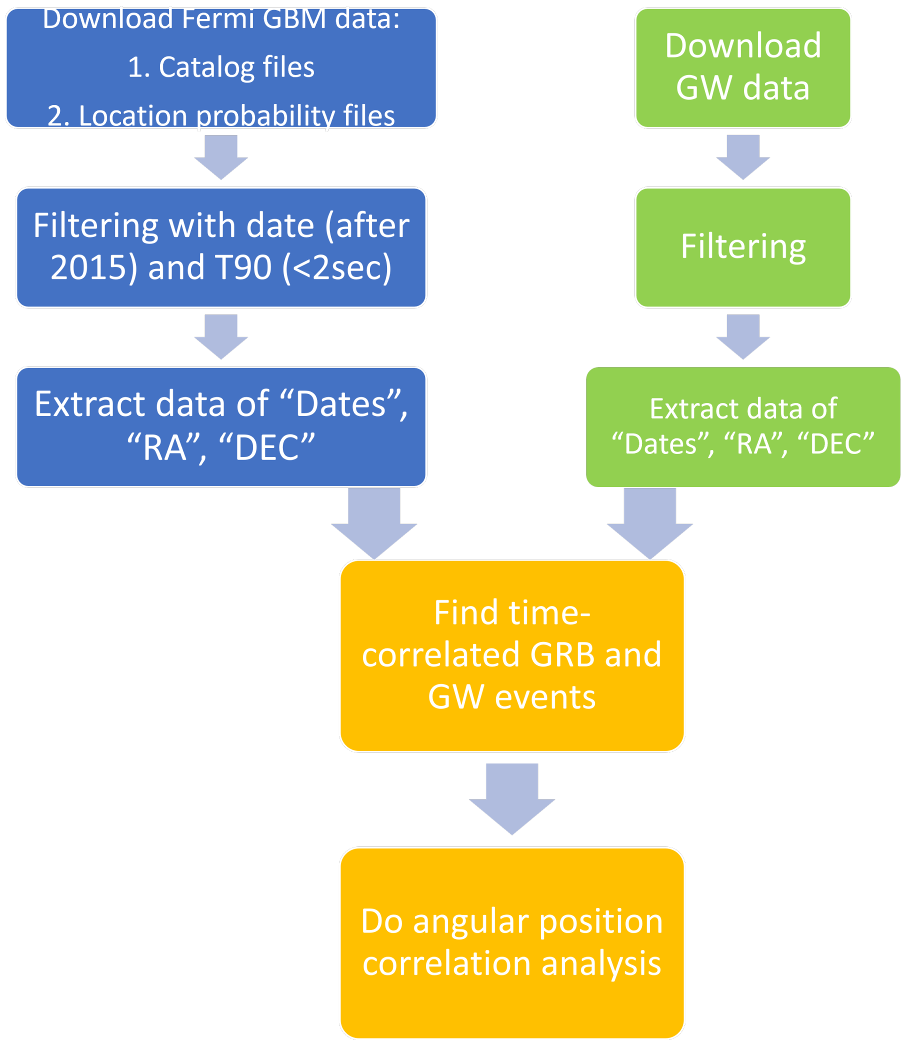

Figure 11

This is the pipeline plan of our project. For both GRB data and GW data, downloading the appropriate data sets is the first step. Then filtering both data sets. GRB will be more filtered due to the GRB detector running for longer periods of time than the GW detectors. Then correlations in time domain and in angular probability will be carried out between the two data sets.

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