Using LIGO data to plot a map for multiple events

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Introduction

The general topic of this paper is about the distribution of detected Gravitational Waves. The python scripts presented in this paper are used to show the distribution of all events detected by LIGO and Virgo. The first one is used to plot Mollweide projection and "astro globe" projection of the events, while the second part is used to make animated GIF images using the "astro globe" maps produced in the first part of the script. All data used in the script are available online, including those from observation run one, two and three.

Background

Gravitational waves are time-varying oscillations of the gravitational field. They are ripples produced by some of the most violent processes in the universe[1]. There are four potential sources that would generate gravitational waves—— Stochastic background from the early universe, like the Big Bang; Continuous Wave sources, for example oscillating neutron stars; Coalescence of binary systems (the one that was first detected in 2015); Bursts that can be produced by events like supernovae[2]. Unlike electromagnetic waves that can be generated by a changing dipole charge distribution, gravitational waves require changing quadrupole mass distribution[3].

Gravitational waves were first predicted by Einstein in 1916 based on his theory of general relativity. Since 1995, scientists have been trying to find direct evidence to support Einstein's prediction. In 2015, almost 100 years after Einstein's prediction, scientists observed gravitational waves generated by two merging black holes using the LIGO observatory. After that, scientists improved the sensitivity and the range of observing gravitational waves by redesigning LIGO's instruments and increasing the length of the arms[4].

LIGO is the world's largest observatory for gravitational waves, which comprises two laser interferometers located in Livingston Louisiana and Hanford Washington to measure the change in length of the arms cause by the gravitational waves. This is done by splitting a single laser beam into two and each is transmitted into one arm. Laser light in each arm bounces back and forth between the mirror placed at the end of the each the arm and the mirror placed near the beam splitter, and returns to the intersection where it interferes with light from the other arm. If there is light pattern observed at the out put of the detector, it means that one arm is stretched and the other is compressed[5]. Another observatory Virgo is based in European Gravitational Observatory, located at Cascina(Pisa), Italy[6].

However, not just the passing gravitational waves would cause changes in the length of the LIGO arms, including seismic noise, atomic vibrations and shot noise can all change the length of the arms. These are competing noises that need to be removed from the data. The sensitivity of the detector is measured by the lowest frequency which can be distinguished from the noise. Observation run 1 and observation run 2 released 11 sets of data in total, including 10 binary black hole systems and one binary neutron star system[7]. Until July 31 2019, there are 22 additional gravitational waves candidate events released in observation run 3[8].

Purpose

Although there are scripts released by LIGO that can plot each event on a single map of the sky, the pattern within the distribution of events is not explicitly shown in separated maps. The script that plots all events on one map, which was also released by LIGO, is not convenient for scholars or anyone interested in it to use. As a result, the objective of my script is to plot multiple events, including events from O1, O2 and candidates from O3, on one map using a more flexible code. More specifically, to plot all binary black hole mergers, binary neutron star systems and the retracted events released during O3 in different maps using a script that can be easily used by students and scientists to plot any number of events they need without changing or understanding

the code. After plotting all events on one map, one can make an animated GIF image using the previously plot maps to better see the pattern of distribution.

Method

Because LIGO released all the sample codes in python[8], I used Python to plot the map. In order to run the code successfully, one has to first download all the available data from GraceDB[7]. Since all data are released either in the file that end with `bayestar.fit.gz` or `bayestar.fits`, the code will only read in files that include "fits". The first thing the code does is to import all the modules needed, like `matplotlib.pyplot` is used to plot the map, `ligo.skymap.plot` that is used to read LIGO data. The code given below is an example of importing one of the modules.

```
import matplotlib.pyplot as plt
```

The next step of the code is to start the outer loop that helps change the center of each map from 0h to 23h. This serves for the purpose of making a GIF image with the "astro globe" projection later, or to see the detail of "astro globe" projection by changing its center. The next part of the code is used to set the contours of each event plotted on the graph since the location of every event is not a certain point but a range of possibility. When contour levels are set to (25,50), meaning the possibilities of the events took place in the contour are 25 percent and 50 percent, the map is relatively readable. The code that sets the contour is shown below.

```
contour_lvl=(25,50)

fmt =  '%g%%'  # or try
```

The following step is served to pick colors for the events. Because there have been over thirty events already, it is convenient to use different colors to distinguish them. The list contains seven colors, including black, blue, green and yellow. Although they are much less than the number of detected events, the map is already clear enough to read. The code that chooses the color for events is shown below.

```
Nfile=0
```

```
colors=['k','b','g','y','r','c','m']
```

The seventh and the most essential step of this code is to read files from the folder. After downloading the code and all the files online, one should put all files inside a folder called "fits", and then make sure that the code and the fits folder are inside the same directory. The `if` condition inside the `for` loop is to make sure that the code reads only the "fits" files. Next, is to add contour and colors to the map based on the contour level inserted before and the list of colors. The final step is to save the maps, when the user is changing the center from 0h to 23h, he will need multiple file names in order to save all images.

After plotting all the "astro globe" maps, one can choose to use the second part of the code "skymap animated" to make a GIF image. The first part of it is to import modules and create three lists for later use. The code below shows the only two modules that need to be imported.

```
from PIL import Image
```

```
import os
```

The following two for loops are used to read in the images and save them inside a list. The last step of the code is to make the GIF image and save it to the same folder as the script. In order to open the GIF image, one need to use a browser to open it instead of opening it directly. The complete code for both scripts can be downloaded from http://www.spy-hill.net/myers/astro/ligo/pioneer/summer2019/, "skymap_plot_multiple_maps.py" and "skymap_animated.py".
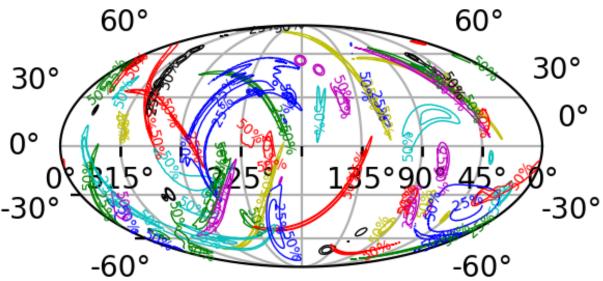
Fig.1 The mollweide projection that contains all detected events from observation run one, two and three until July 31 2019
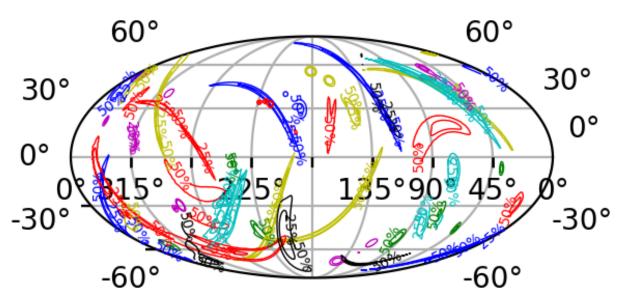
Fig.2 The mollweide projection that contains all detected binary black holes from observation run one, two and three until July 31 2019
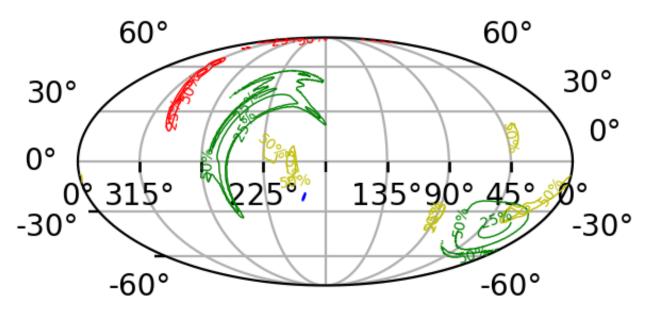
Fig.3 The mollweide projection that contains all detected binary neutron stars from observation run one, two and three until July 31 2019
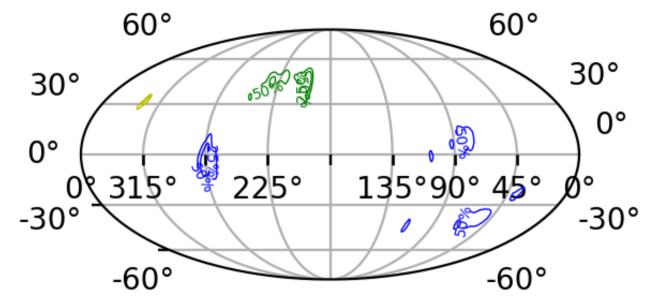
Fig.4 The mollweide projection that contains three retracted events from observation run three until July 31 2019
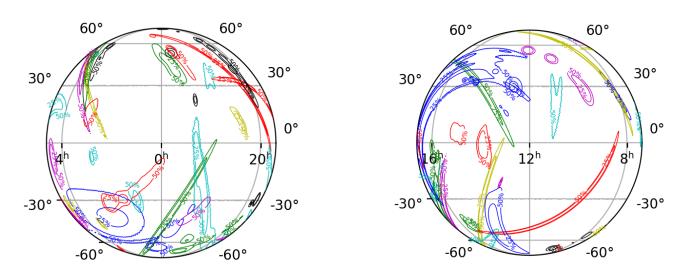

Fig.5 The "astro globe" projection, centered at 0h, 0h, contains all detected events from observation run one, two and three until July 31 2019
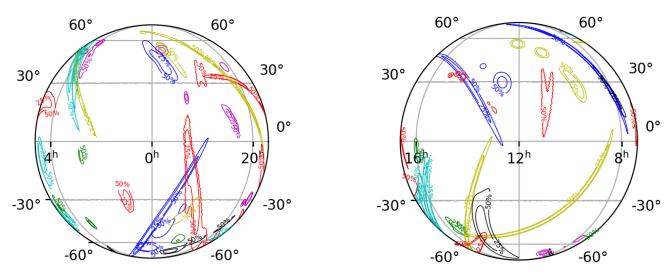

Fig.6 The "astro globe" projection, centered at 0h, 0d, and 12h, 0d, contains all detected binary black holes from observation run one, two and three until July 31 2019
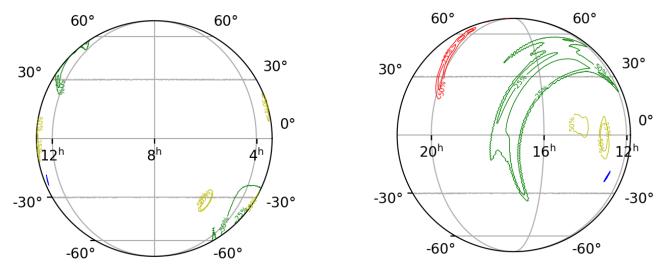
Fig.7 The "astro globe" projection, centered at 8h, 0d, and 17h, 0d, contains all detected binary neutron stars from observation run one, two and three until July 31 2019
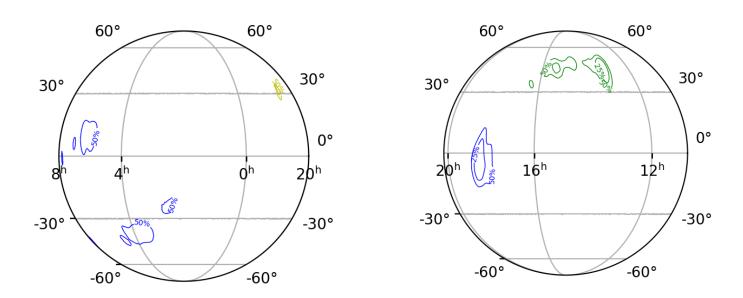

Fig.8 The "astro globe" projection, centered at 3h, 0d, and 15h, 0d, contains all retracted events from observation run one, two and three until July 31 2019

Result

The results of my code are Mollweide projections, "astro globe" projections and animated GIF images[8] that show the distribution of detected events. I plotted eight maps in total: the mollweide projection that includes all events detected[Fig.1]; the mollweide projection that includes only the binary black holes[Fig.2]; the mollweide projection that includes only the binary neutron stars[Fig.

3]; the mollweide projection that includes only the retracted events from observation run three[Fig. 4]; the "astro globe" projection that includes all events detected, centered at 0h, 0d and 12h, 0d[Fig. 5]; the "astro globe" projection that includes only the binary black holes, centered at 0h, 0d and 12h, 0d[Fig.6]; the "astro globe" projection that includes only the binary neutron stars, centered at 8h, 0d and 17h, 0d[Fig.7]; and the "astro globe" projection that includes only the retracted events from observation run three, centered at 3h, 0d and 15h, 0d[Fig.8]. Apart from these, I also created four animated GIF images using the second part of my code to better illustrate the all-sky distribution. All the animated GIF images can be downloaded from http://www.spy-hill.net/myers/astro/ligo/ pioneer/summer2019/, "all_BBH_map_movie.gif", "all_BNS_map_movie.map", "all_events_map_movie.gif", "retracted_events_map_movie.gif".

Conclusion

Looking at the four mollweide projection[Fig.1,2,3,4], three of the Binary Neutron Star events—— depicted in red, yellow and green in Fig.3—— are more widely spread on the map, indicating the detection of the binary neutron stars' location is not accurate, which might be caused by the great difference in mass compared with binary black holes systems. However, the binary neutron star event that is depicted in blue is almost a spot on the map, meaning its position is relatively precise compared to all other events. Fig.4 is the map for the three retracted events in observation run three. Although they are retracted events, they show great similarities with the confirmed binary neutron star events, especially the binary neutron star event depicted in yellow in Fig.3(S190510g). According to GraceDB, S190510g was classified three times; it was first classified as binary neutron star event, with only 2% possibility of being a terrestrial. However, on May 11, 2019, it was classified as having 58% possibility of being a terrestrial, but still a binary neutron star event instead of a retracted event[9].

For the four "astro globe" maps[Fig.5,6,7,8], there isn't much additional information shown in them, but looking at the right figure in Fig.7, centered at 8h, 0d, there is almost no binary neutron

star event located between 12h and 4h. We can also see in Fig.6 that some binary black hole events overlap each other. However, although there are similarities in the distribution of events, there is no obvious pattern in between.

Summary

Up until July 31 2019, LIGO and Virgo have detected 32 events in total, including 4 BNS events and 28 BBH events. The code that plots the map presents a more flexible and convenient method for plotting multiple events on one map, while the one that makes the GIF image can helps better illustrate the distribution of detections.

Cited resources

[1]https://www.space.com/25088-gravitational-waves.html, Gravitational Waves: Ripples in Spacetime, by Calla Cofield

[2]https://www.ligo.caltech.edu/page/gw-sources, Sources and Types of Gravitational Waves

[3]http://jila1.nickersonm.com/papers/An%20Introduction%20to%20Gravitational%20Waves.pdf An Introduction to Gravitational Waves, by Michael Nickerson

[4]https://www.ligo.caltech.edu/page/facts

[5]https://www.ligo.org/science/GW-IFO.php

[6]http://www.virgo-gw.eu, Visits

[7]https://gracedb.ligo.org/latest/, GraceDB — Gravitational-Wave Candidate Event Database

[8]https://lscsoft.docs.ligo.org/ligo.skymap/ligo/skymap/plot/allsky.html, Sky Map Plotting

[9]https://gracedb.ligo.org/superevents/S190510g/view/