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Search for Spatial and Temporal Coincidence Between *Fermi*-LAT Exposure Maps and GW Sky Localizations

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Abstract.

The poster describes a practical method to search for spatial and temporal coincidence of the *Fermi*-LAT exposure maps over a gravitational-wave sky localization. The method returns the overlap region between multi-frequency sky areas within a proper time window selected by the user. This approach offers a prompt setting of the observational strategies for searching potential electromagnetic candidates as well as a fast cross-matching between the LAT and the LIGO, Virgo and KAGRA databases for dedicated post-processing analysis. The tasks are performed using the encoded standard method named Multi Order Coverage Map and visualized in the Aladin Desktop.

1. Introduction

On August the 17th of 2017, for the first time, we were able to observe a Gravitational Wave (GW) event, produced after the merging of two Neutron Stars (NSs), and its electromagnetic counterpart, in the form of a short Gamma-Ray Burst (sGRB) and a following kilonova (Abbott et al. 2017). This event led the foundations of the Multi-Messenger astronomy.

The typical localization area of a GW is of the order of hundreds of square degrees, so localizing an electromagnetic counterpart by gamma-rays telescope such as *Fermi*, is very challenging. For this reason, more and more advanced tools are continuously developed, in order to support GW's follow-up. The Multi Order Coverage (MOC) method is particularly suitable for this purposes because allows the user to reconstruct and make logical operations between different sky regions, obtained from various experiments, in an intuitive way (Fernique et al.).

2. Multi Order Coverage map method

The Multi Order Coverage (MOC) method is one of the standard algorithms developed within the International Virtual Observatory Alliance context. The MOC procedure can reconstruct a sky region and compute logical operations such as the intersection, the union and the equality between different maps. It is based on HEALPix tessellation (Górski et al. 2005): once you get a spherical description of your region, HEALPix divides the sphere into 12 diamonds, each of them divided into 4 diamonds recursively. So, at each step, an increasing number of indexes (diamonds) characterizes a specific level that, at the end, defines the resolution of the MOC.

In this work we used a particular extension of the MOC method called Space Time MOC (STMOC), in which the space and time coverage are connected in order to easily understand where and when the observations took place (Daniel Durand 2019).

3. LAT exposure map and LIGO/Virgo GW170104

The LAT exposure map can be seen as an Aitoff projection of the sky observed by the telescope in a certain time window after a chosen trigger, in which the total exposure - area multiplied by time - for a given position on the sky can be found. Since the expected number of events is a function of the photons energy, also the exposure map has a dependency on the energy (*Fermi* LAT Collaboration 2008).

We decided to use the event of GW170104, downloaded from the public LIGO/Virgo database (GWO). Then we obtained the LAT exposure map in 10000 s after the trigger time of GW1701004.

4. STMOC intersection map of LAT exposure map and LIGO/Virgo skymap

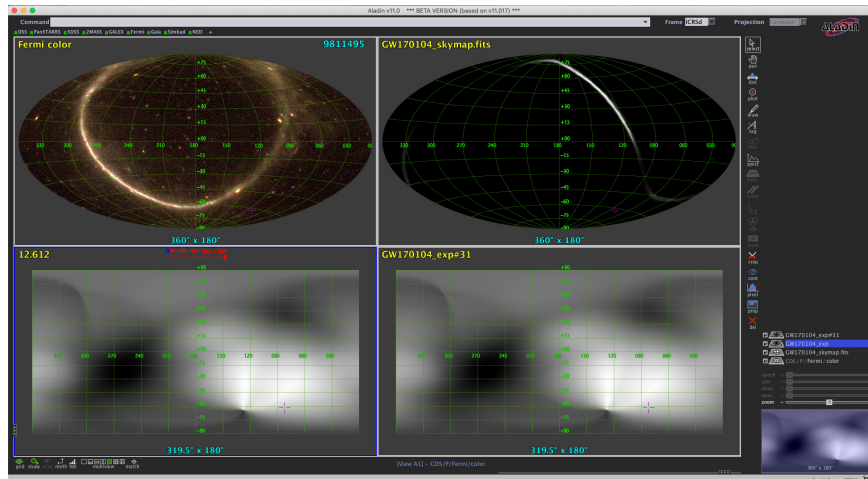


Figure 1. The visualization on Aladin of, turning clockwise, the sky seen by *Fermi*, the GW170104 skymap, the LAT total exposure map and the 31st energy bin of the exposure map.

We used the Aladin interface to visualize and make logical operations between the MOC map 1.

The first step consisted on the selection of all the most exposed pixels in the LAT exposure map, in order to compute the Spatial MOC map. We decided to consider only the pixels that have values greater than $10^7 \text{ cm}^2 \text{ s}$. After that, we read, from the fits header of the LAT file, the starting and the ending time of the observation, to provide a range over which a discretization of the temporal extension of the map can be performed. We then obtained the STMOC map.

Since we want to estimate the spatial and temporal intersection between the LAT map and the LIGO/Virgo event, we computed the STMOC map related to GW 170104. We firstly selected a probability threshold of 0.9 to obtain the spatial MOC map. Then, after reading the trigger time from the fits header of the file and copying it in the appropriate Aladin window, we were able to obtain the STMOC for the GW event, as can be seen in the figure 2.

The final step consisted on the production of the intersection map. We selected the STMOC maps obtained for the LAT map and the one obtained for the GW's skymap and then computed the intersection map displayed in 3. As can be seen from the time plot, the intersection is not only from the spatial point of view, but also from the temporal one.

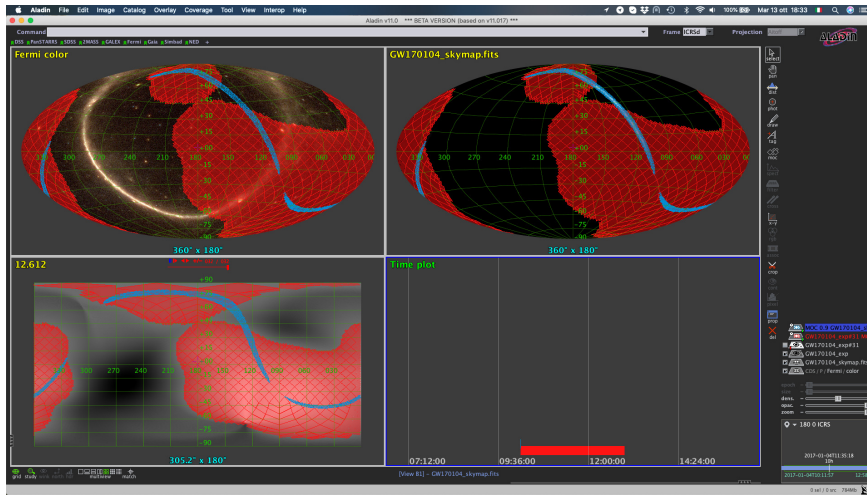


Figure 2. STMOC of the LAT exposure map.

5. Summary

In this work we showed a practical way to search for spatial and temporal coincidence between the LIGO/Virgo event GW170104 and the related *Fermi*-LAT exposure map, obtaining the intersection map with a technique called Multi Order Coverage method. Using real astrophysical data, this procedure gives a preliminary demonstration on how interesting the MOC method's could be. The capability to construct sky region in a

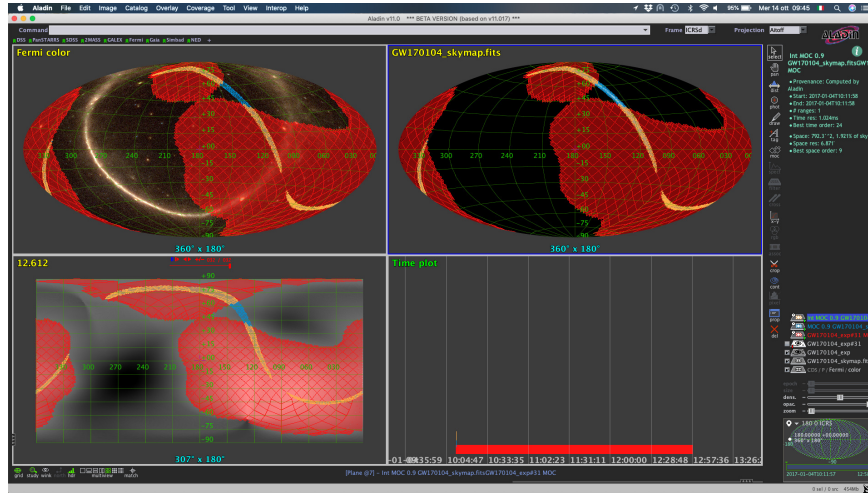


Figure 3. Intersection map between LAT map and LIGO/Virgo skymap.

user-friendly way and in small times will certainly represent a strong support for future the electromagnetic follow-up of GWs.

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