Gravitational waves and the Virtual Observatory

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Introduction

On August 17, 2017 a gravitational wave (GW) event, known as GW170817, was observed by the Advanced LIGO and Advanced Virgo detectors (Figure 1, left). The event was the result of the merger of two neutron stars in the galaxy NGC 4993.

Less than two seconds after the GW170817 signal, NASA's Fermi satellite observed a gamma-ray burst (GRB 170817A, Figure 1, right). This was the first unambiguous coincident observation of gravitational waves and electromagnetic radiation from a single astrophysical source and marked the start of gravitational-wave, multi-messenger astronomy. More information on this event can be found here.

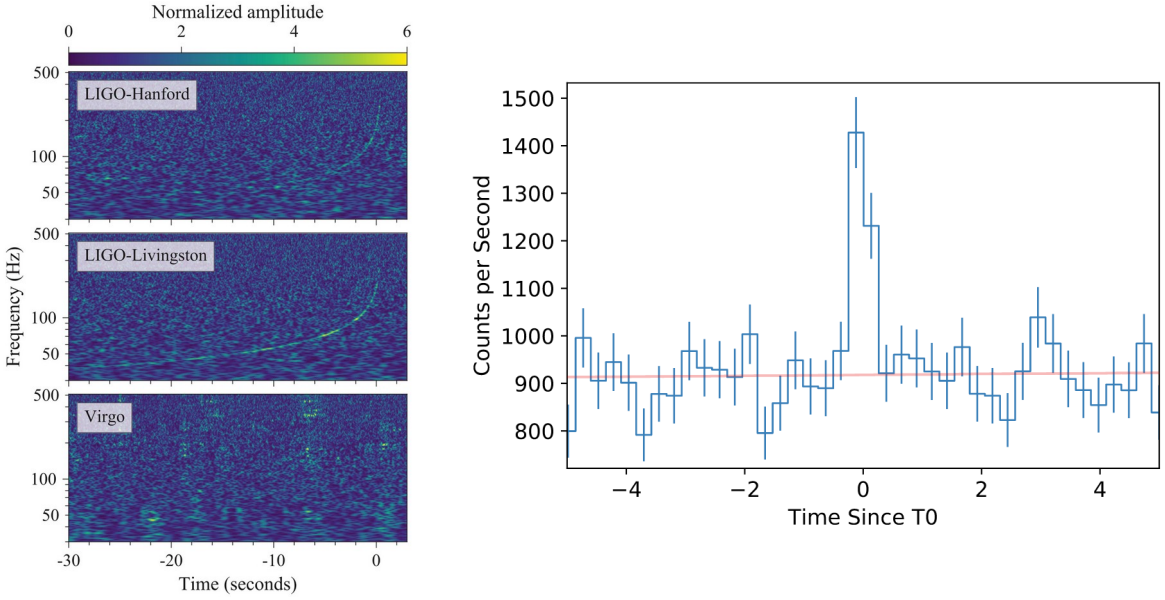


Figure 1. **Left:** The GW170817 signal as measured by the LIGO and Virgo gravitational wave detectors. Signal is invisible in the Virgo data. **Right:** The GRB170817A light curve in the 50–300 keV band observed by Fermi (Goldstein et al. 2017).

This tutorial aims to analyze the GW170817 event in the context of the Virtual Observatory using the Aladin sky atlas.

Workflow:

- **Gathering and visualising a gravitational wave sky location**. Unlike other type of transient objects whose position in the sky can be accurately determined (e.g. supernovae, Figure 3), the sky location of a gravitational wave event is not straightforward at all. This is done by complex algorithms like BAYESTAR which, in a few seconds, are able to generate a probability sky map of the event.

Figure 3. The SN2011fe supernova explodes in the Pinwheel galaxy. Photograph: Bj Fulton/PA

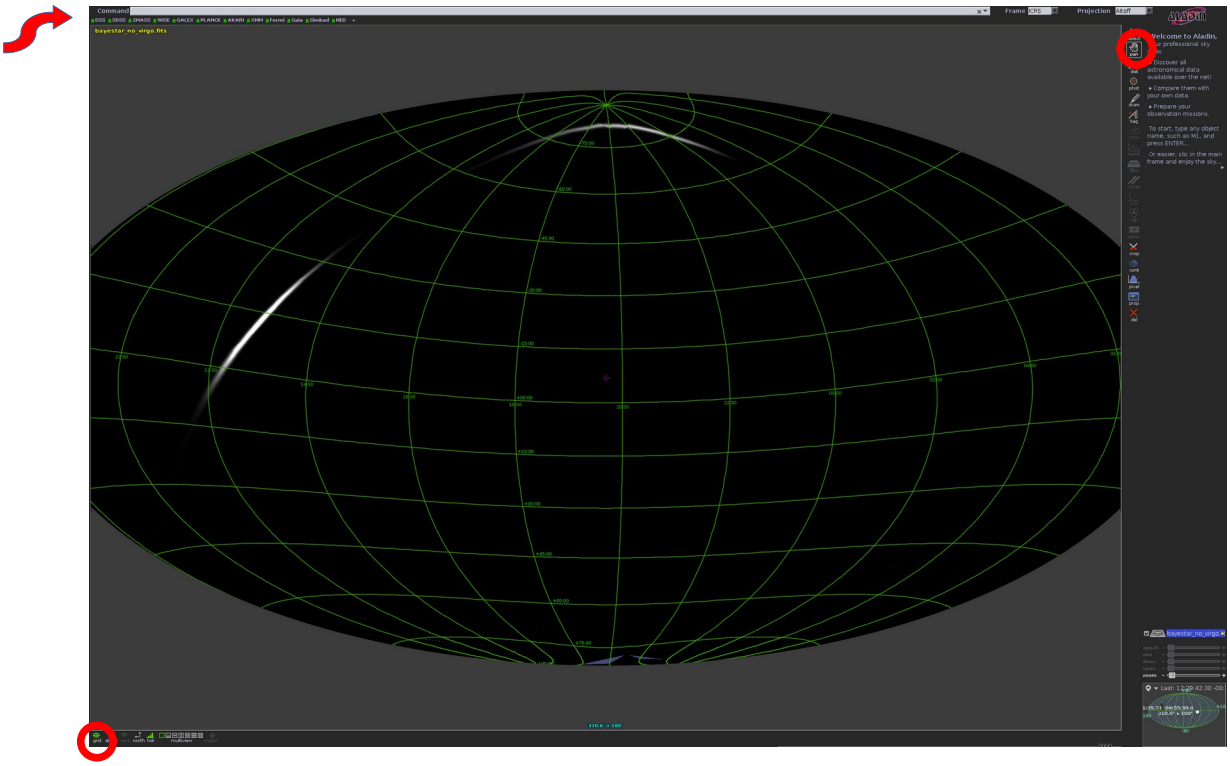
Let's use the **Aladin** sky atlas to gather and visualize the sky map of GW170817 generated using data from the two LIGO interferometers:

- Launch Aladin:
  - Download the Aladin.jar file from here
  - Open a terminal and type: java -jar Aladin.jar &

- Load in your computer the sky map generated using data from the two LIGO interferometers:
  https://dcc.ligo.org/public/0146/G1701985/001/bayestar_no_virgo.fits.gz
  - Alternatively, you can write this URL address in the "*Command"* box, at the top of the Aladin window.

- In the Aladin window: File --> Load local file (to upload the sky map in Aladin)

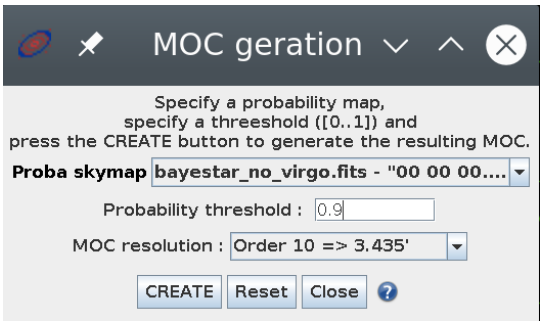
- Click on *Grid* (bottom left) to overplot a grid of coordinates and *pan* (top right) to drag the image.

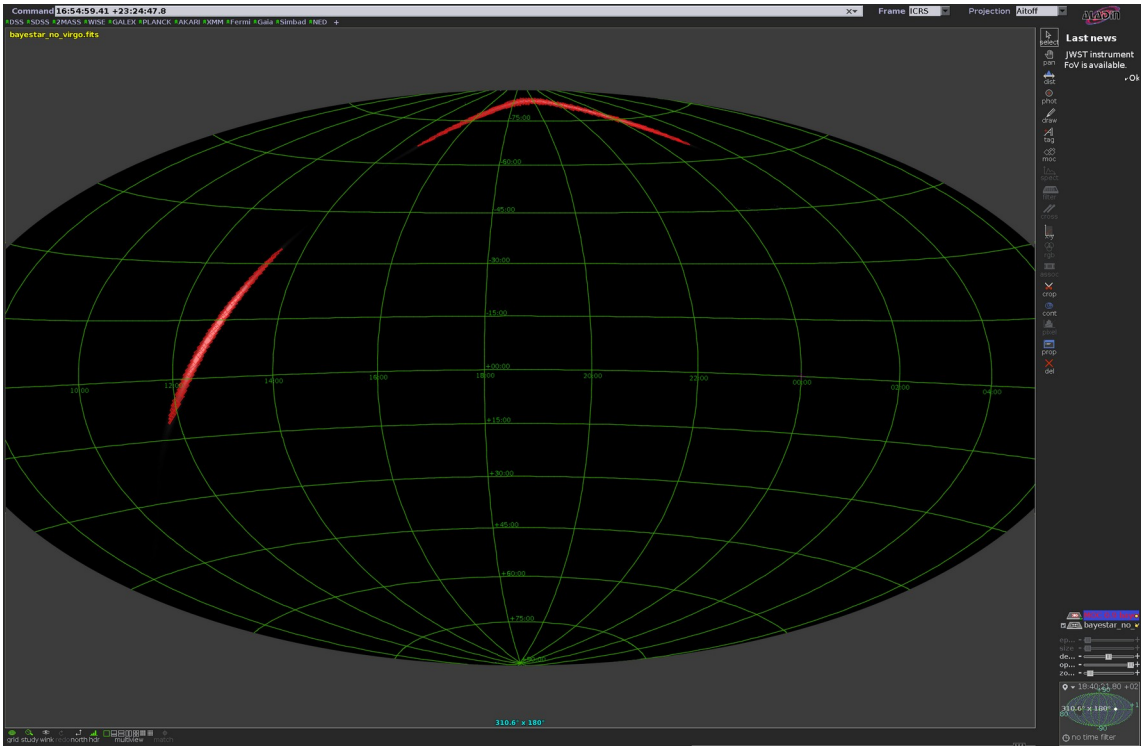


- Once the sky map has been uploaded in Aladin, the next step is to define the region covered by the sky map and determine its size. This is accomplished in Aladin as follows:

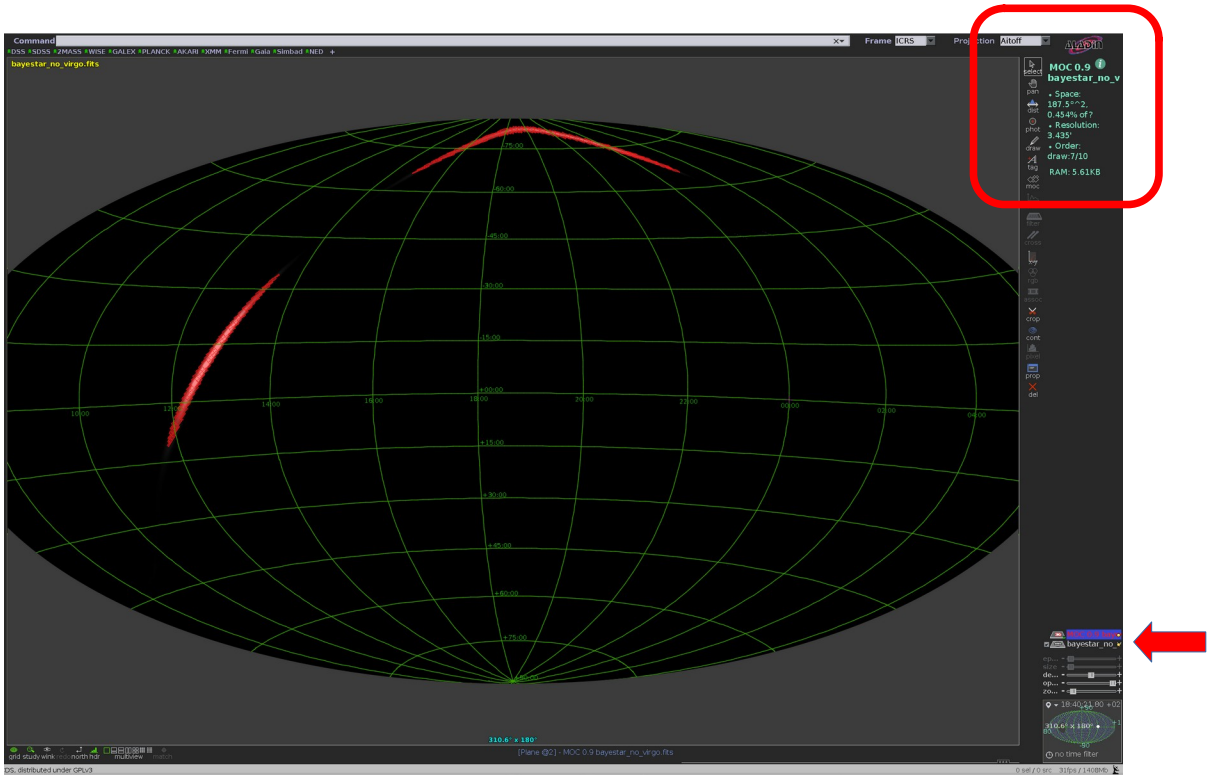
  - Coverage ⇒ Generate a spatial MOC based on ⇒ The current probability skymap

  - A new window (“MOC generation”) will pop up. The MOC generation window has three options: the probability sky map, the threshold, and the MOC resolution. Make sure that the GW sky map that we loaded in the previous step is selected in the Proba skymap box. Then enter 0.9 in the Probability threshold box. Do not change the MOC resolution. Finally, press the CREATE button. The MOC for the credible region is created and loaded in the Aladin Stack.





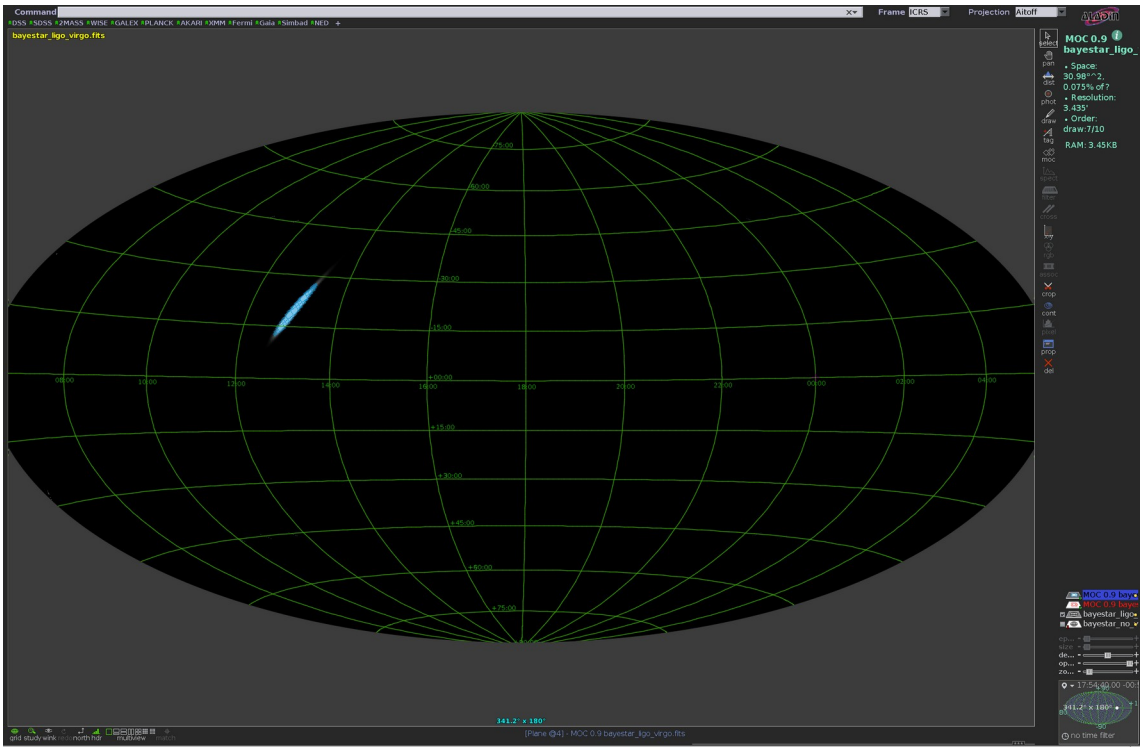
- One of the most important pieces of information is the size of the region. The area in square degrees and the percentage of the sky are reported in the top-right corner of the Aladin stack when you hover the cursor over the MOC name.



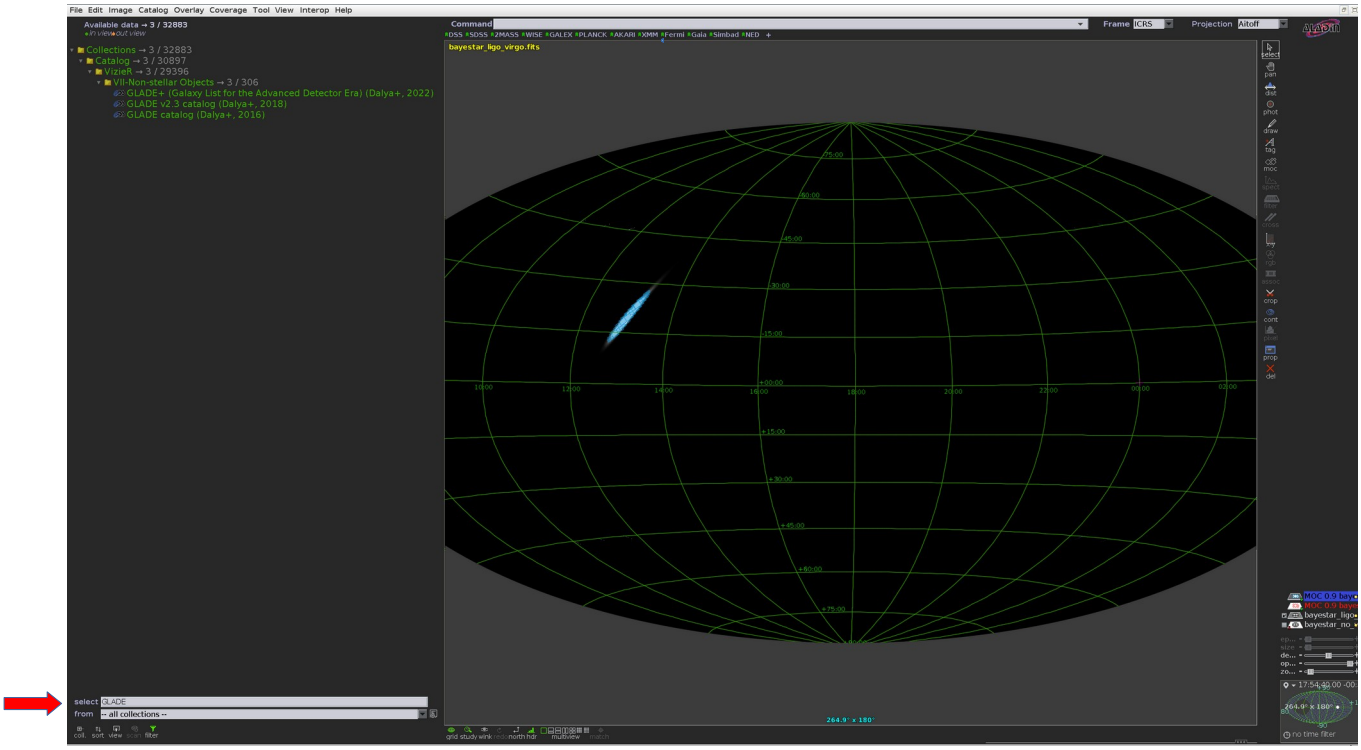
- Alternatively, to visualize the area of a credible region, you can click on the MOC plane in the Aladin stack and click "*Properties*" from the column of

icons shown on the right.

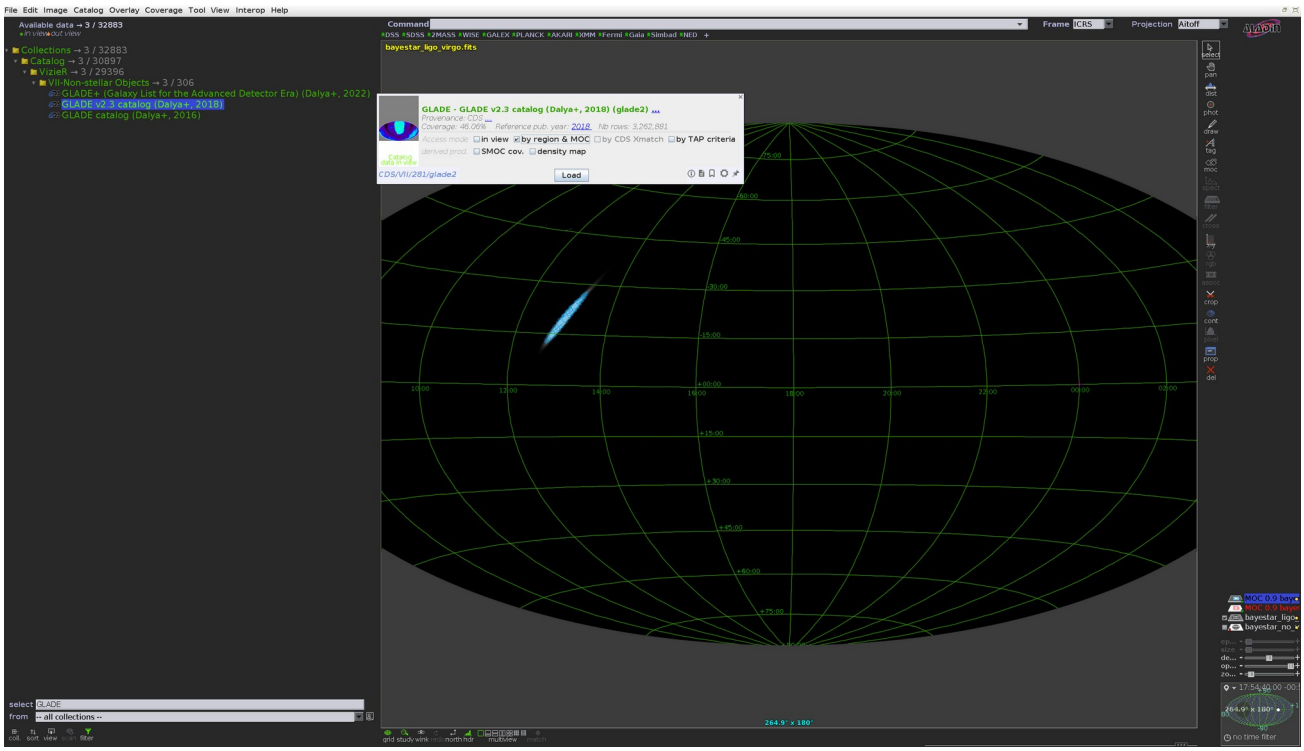
- The sky map region can be reduced if the VIRGO and LIGO data are combined.
  - Load in your computer the sky map generated using data from the two LIGO and VIRGO interferometers:
    https://dcc.ligo.org/public/0146/G1701985/001/bayestar.fits.gz
  - In the Aladin window: File --> Load local file. The LIGO-VIRGO sky map will appear in the Aladin window.
  - Generate a MOC for this new sky map following the same steps as before. We can see how the size of the region has decreased from 187.5 sq deg. to 30.98 sq deg.



- **Overplotting catalogues**
  - Pick out the catalogue of galaxies of our interest from the Aladin data collection tree.
    - Any of the > 30,000 catalogs published in the Virtual Observatory can be retrieved from the data collections tree in the left panel of the main Aladin window.
    - GLADE is catalog of galaxies specially suited for multimessenger searches. To load GLADE in Aladin, type *GLADE* in the *select* box (bottom left).

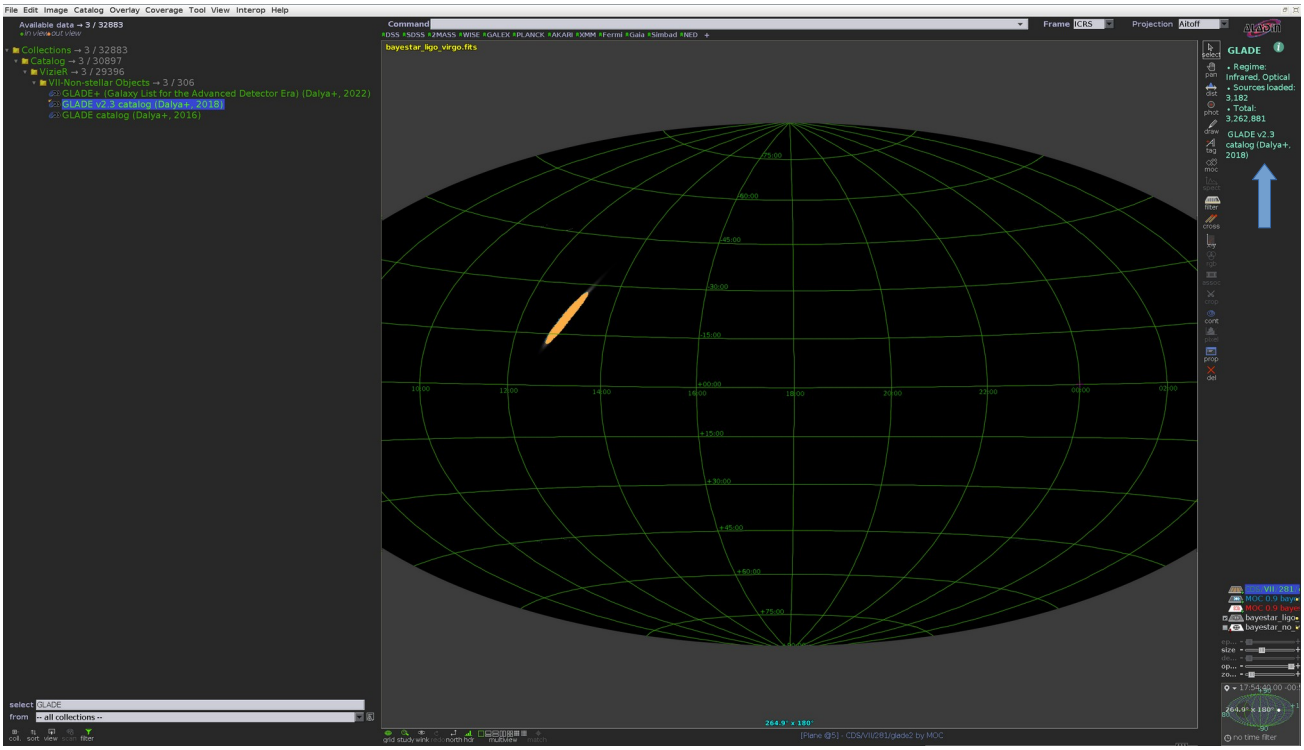


- In the data collections tree, click on GLADE v2.3 catalog (Dalya+, 2018). Then, in the popup window, click the *by region & MOC* checkbox in order to keep only those galaxies lying on the region of the sky covered by the MOC.



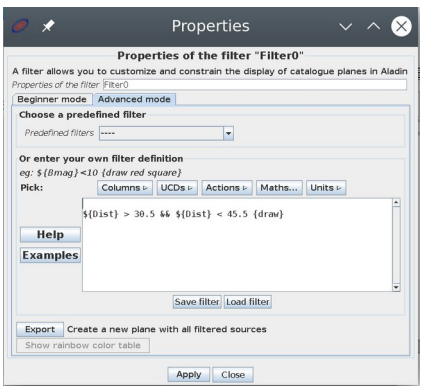
- Press the *Load* button. A new plane (CDS/VII/281/glade2 by MOC) is loaded in the Aladin stack. This plane contains a subset of 3182 galaxies (the GLADE catalogue contains more than 3 million galaxies) that are overplotted

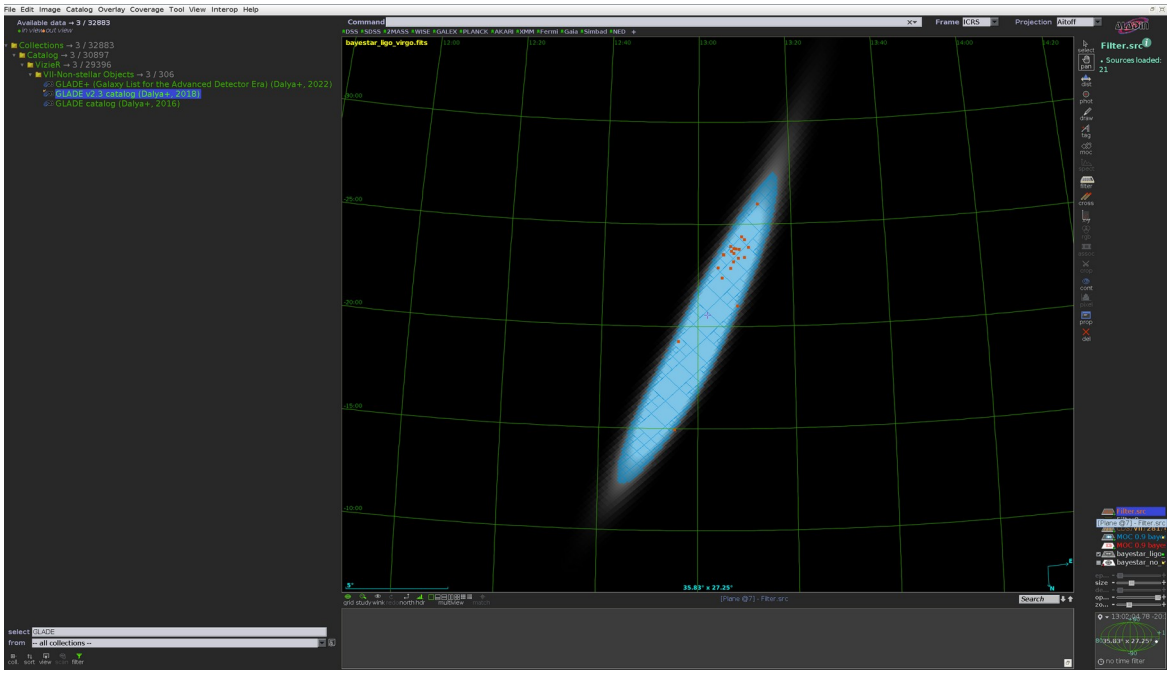
on the MOC region.



- **Filtering the catalogue by distance:** GW170817 is located at a distance of 38.0 +- 7.5 Mpc. To keep only GLADE galaxies in this range of distances we have to proceed as follows:

  - Click on the *CDS/VII/281/glade2 by MOC* plane.
  - In the Aladin Menu bar: *Catalog → Create a flilter*. A new window called "Properties" will pop up.
  - Select the Advanced mode tab and copy the following text into the filter definition box: ${Dist} > 30.5 && ${Dist} < 45.5 {draw}
    - This is an expression for a 1-sigma cut on distance in the Aladin filter syntax. Dist is the column in the GLADE catalog corresponding to the distance in Mpc.
  - Click on *Apply* and then on *Export* to create a new plane in the Aladin stack with just the galaxies fulfilling the filtering condition (21 sources).





- Once the list of potential host galaxies has been obtained, follow-up campaigns both from ground-based telescopes and space-based satellites can be conducted. In this paper you can find a description of the discovery of the optical counterpart of GW170817 using the Dark Energy Camera (see figure below).

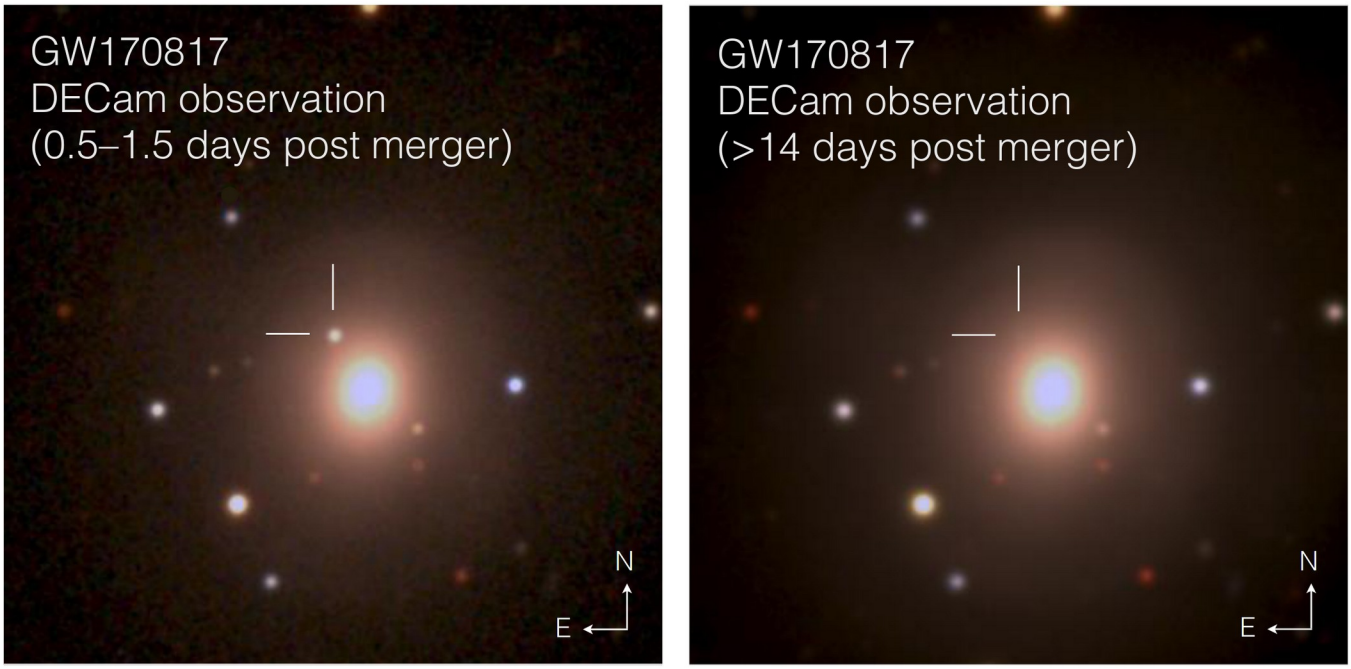


Figure 1. NGC4993 *grz* color composites (1.5'×1.5'). Left: Composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at RA,Dec = 197.450374, –23.381495. Right: The same area two weeks later.