Working with Gravitational-Wave sky localizations: new methods and implementations

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Asterics
Astronomy ESFRI & Research Infrastructure Cluster

Data Access, Discovery and Interoperability (DADI)

First GRAVI-GAMMA Workshop
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Gravitational Wave Sky Localizations & the Multi Order Coverage map method

The GW sky localizations are irregularly shaped. In particular cases the sky regions can be fitted by an ellipse.

GW source sky localizations are encoded as HEALPIX projection in FITS file format.

The value stored at each pixel is the probability that the gravitational-wave source is within that pixel.

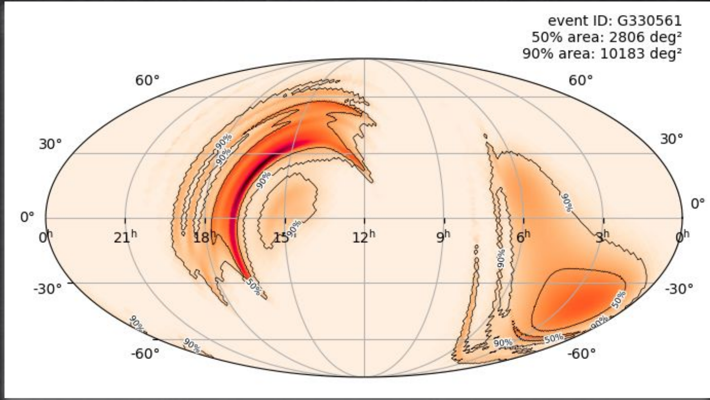
We can represent the GW credible region using the Multi Order Coverage Map.

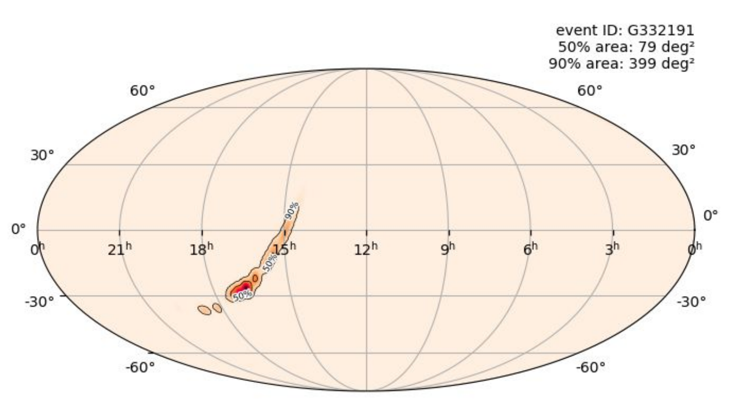
Discussed in ASTERICS DADI Technology Forum 2
7 & 8 March, 2016 - Edinburgh

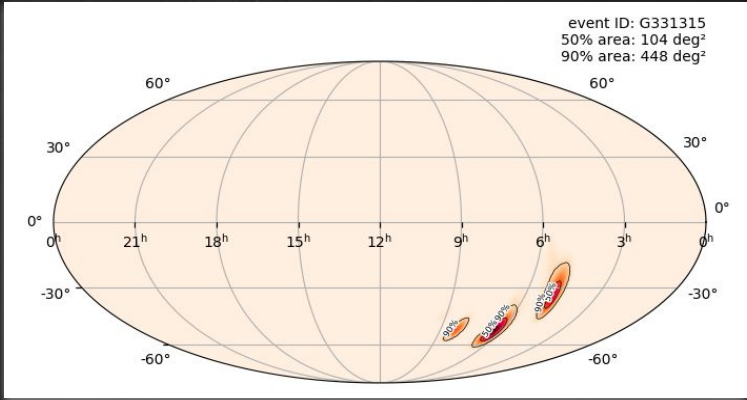
O3 GW Sky Localizations: a few examples

The irregular and complex shapes of the GW sky localizations represent a new challenge for observational astronomers, who need to work with

- Fast tiling
- Catalog queries
- Transient localizations
- Visibility
- Skymap comparisons







Multi Order Coverage MAP

- The MOC method is based on the HEALPix tessellation algorithm (Gorski et. al 2005) and it is essentially a simple way to map irregular and complex sky regions into hierarchically grouped predefined cells.

- The operation between the MOC maps (union, intersection, subtraction, difference) are very fast even for very complex regions.

- Some dataserver, such as VizieR, can be queried by MOC in order to return data (galaxy catalogs/list of images) only inside the MOC coverage.

Fernique et al., 2014

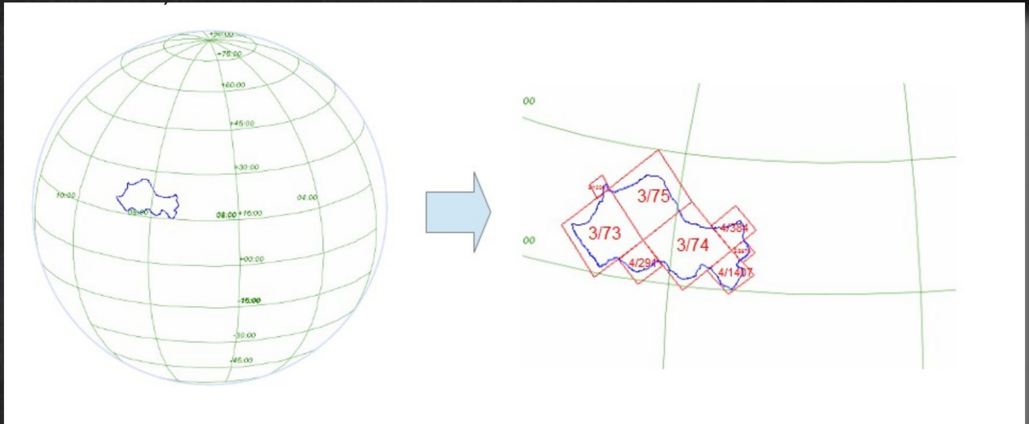
MOC Basic Algorithm

Each MOC cell is defined by two numbers: the hierarchy level (HEALPix order) and the pixel index (HEALPix npix).

The NUNIQ scheme defines an algorithm for packing an (ORDER, NPIX) pair into a single integer for compactness:

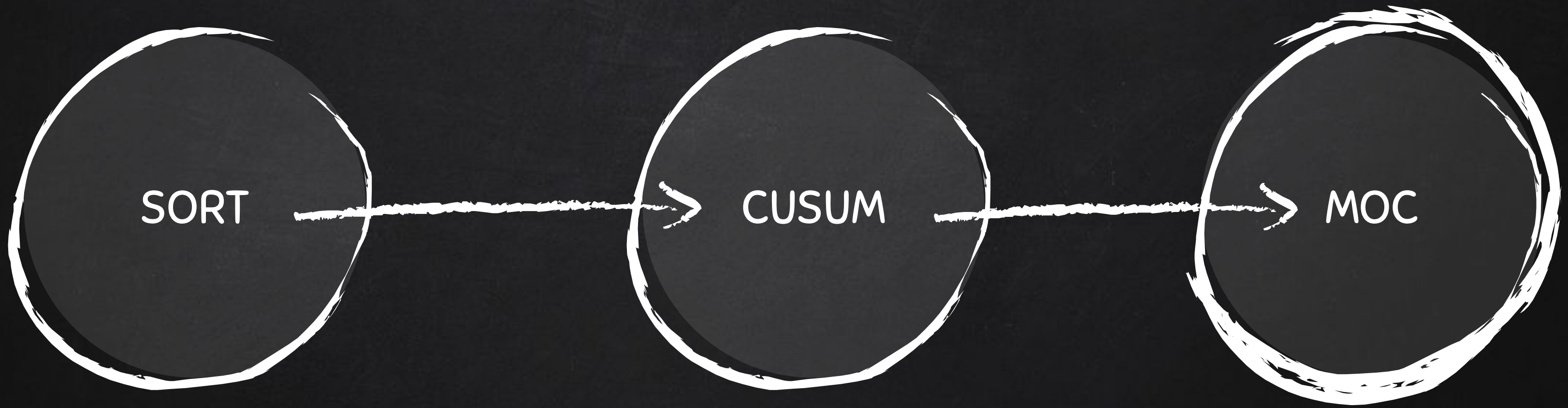
$$uniq = 4 \times 4^{order} + npix$$

Fernique et al., 2014



A MOC can thus be represented as a flat list of integers (in this example, 8 of them) and stored in a single-column FITS table.

GW Sky localization area is the confidence region that encloses a given percentage of the localization probability.



More details about the computational time in slide 13.

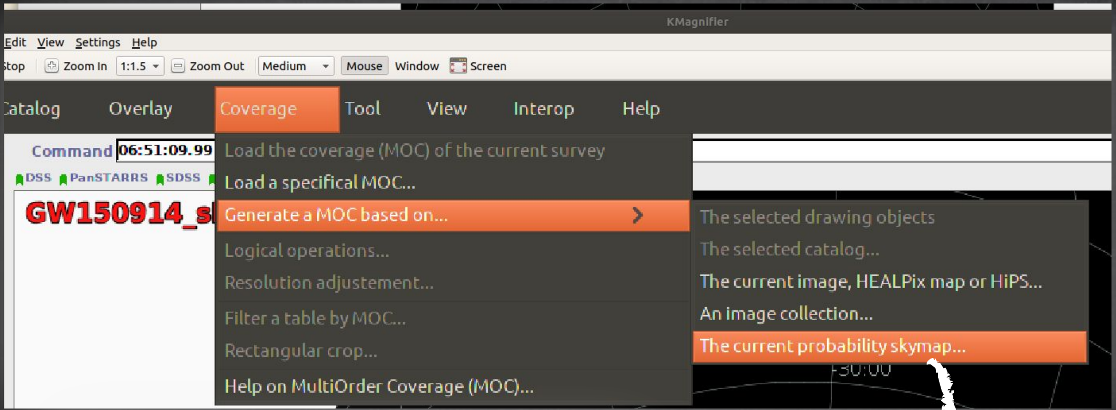
CDS

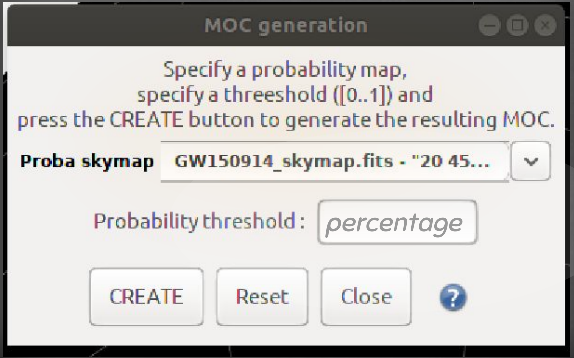
Aladin Desktop

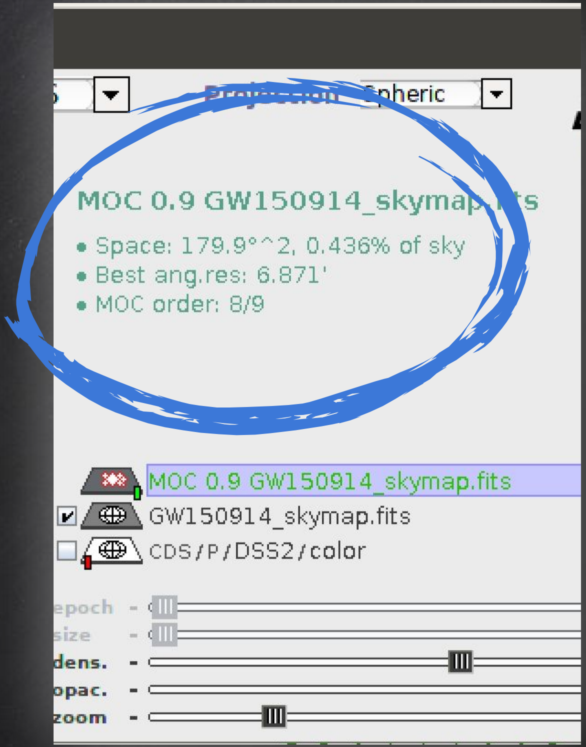
MMA Section

From credible region(s) to galaxy catalog queries

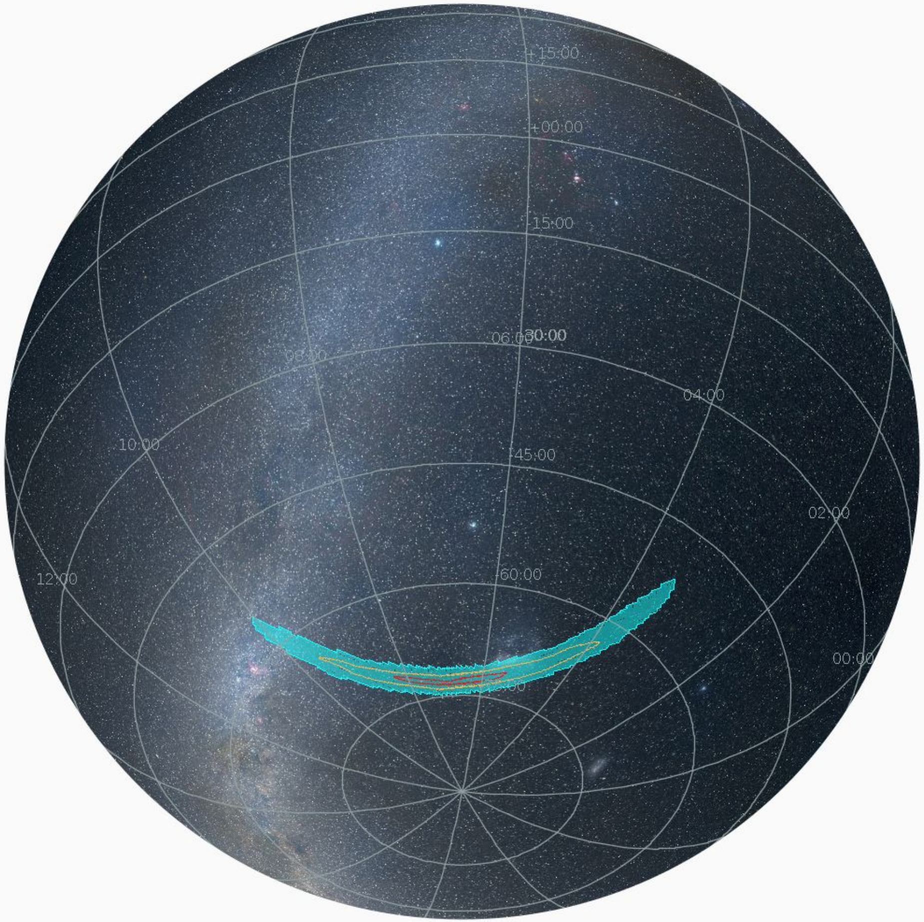
1. Confidence level(s)



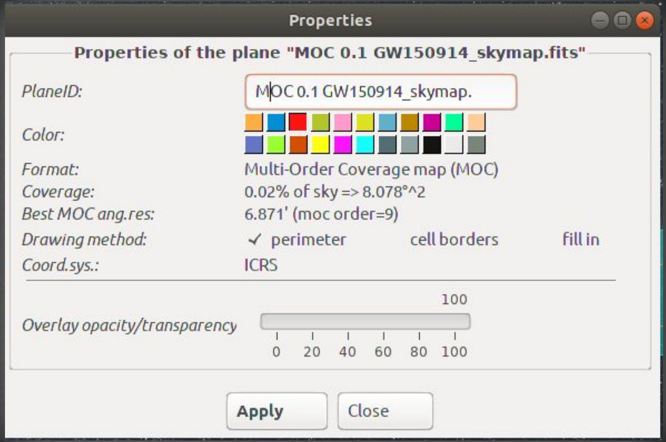




By leaving the cursor on the plane, the enclosed sky area in sq. deg. is quoted in the Aladin stack (see "Space" on the top right)



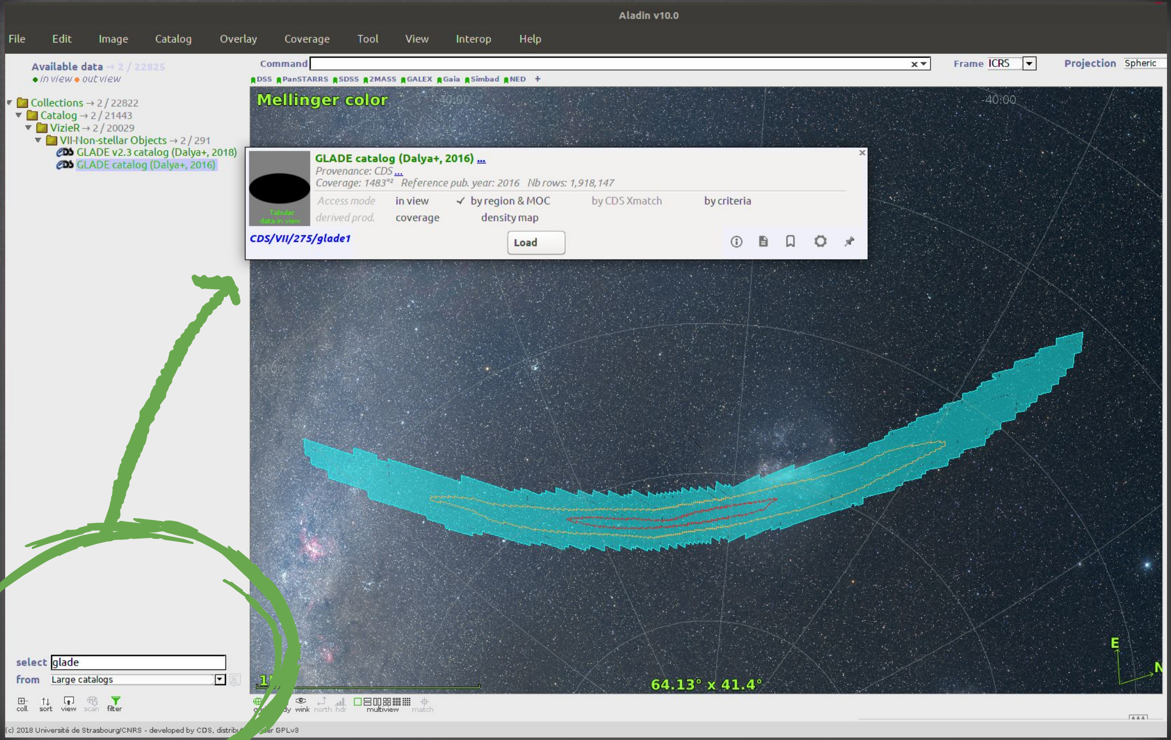
2. Properties



Display multiple confidence levels selecting "perimeter" as Drawing method

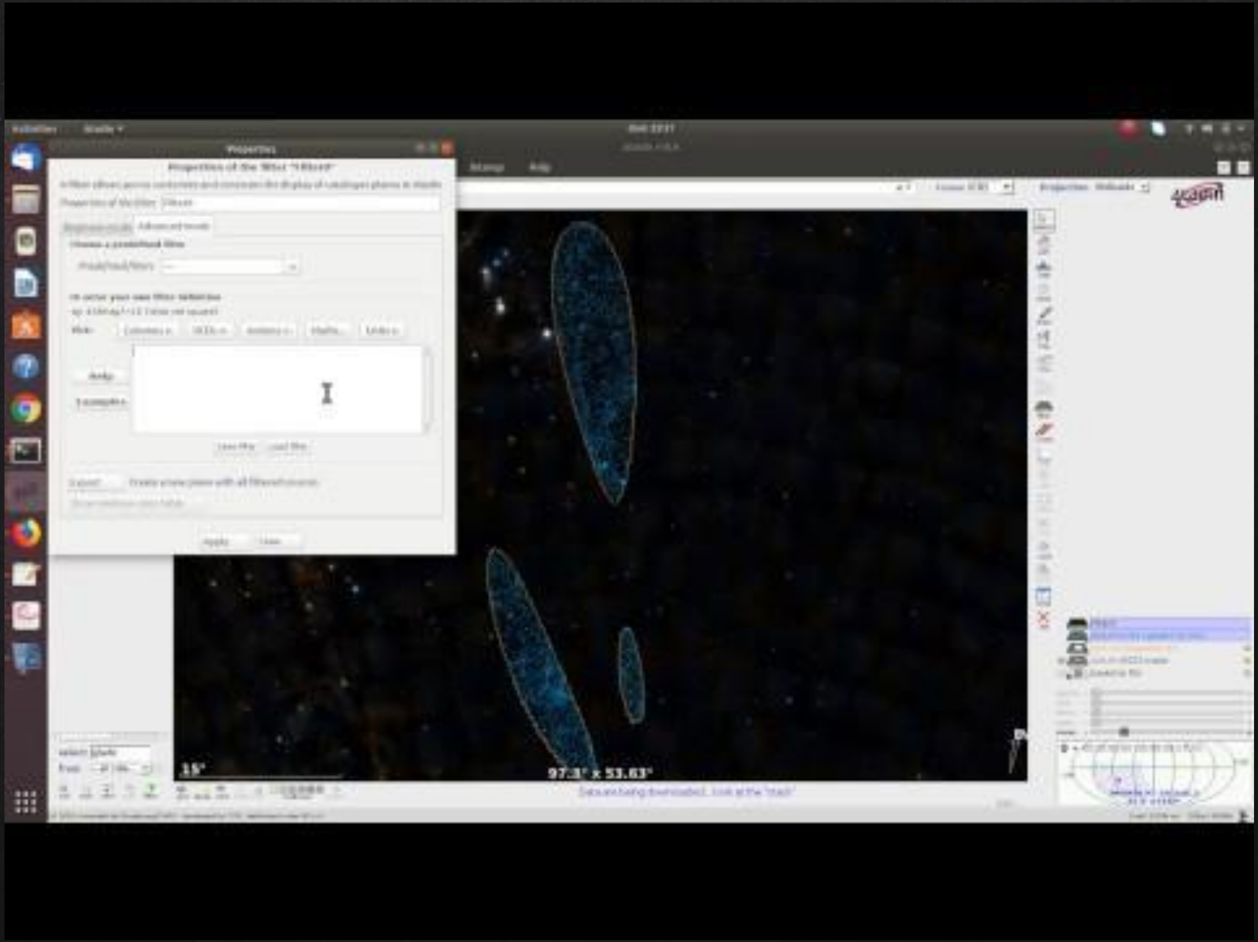
3. Queries

The Aladin data collections tree provides access to a large data collections.



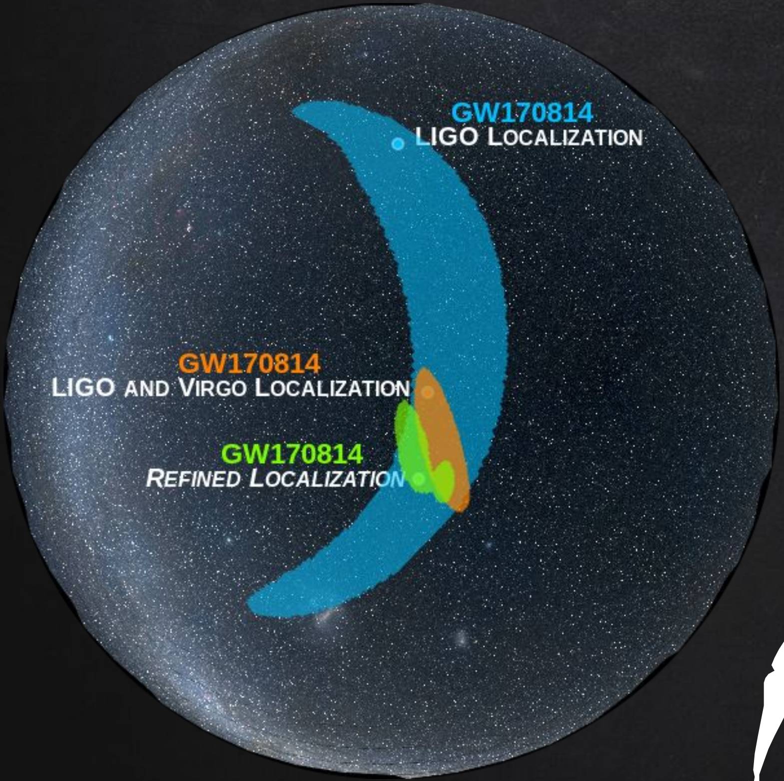
For catalogues, you can load all sources in the GW sky localization (at any confidence regions).

For image surveys, you can access the HiPS images.

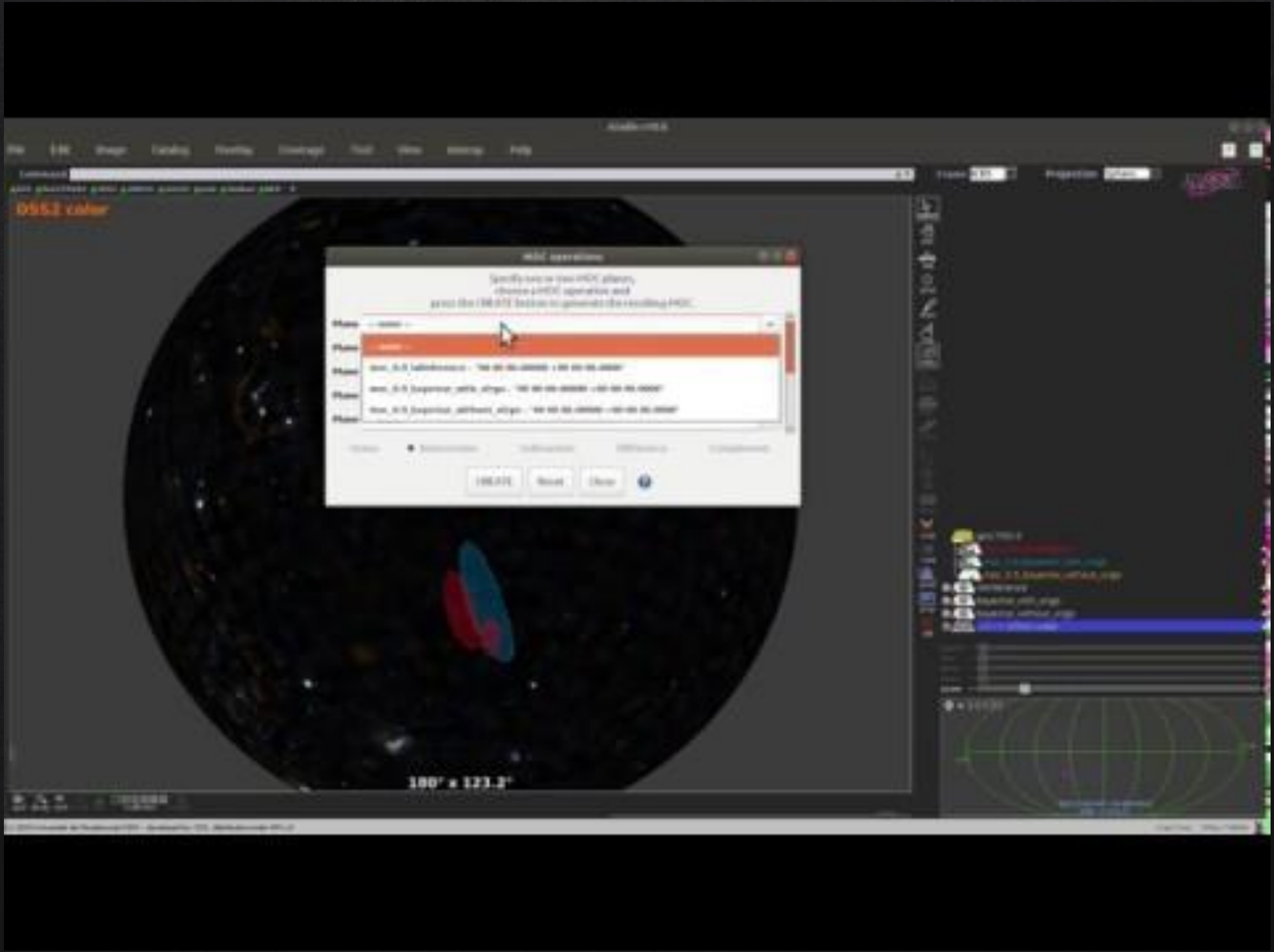


https://drive.google.com/file/d/1JIWwjI7_9-RtHE4UlL_beAjaXQIB3PNB/view?usp=sharing

4. Quantitative Comparisons



Union or the intersection of the data sets coverages and skymaps comparisons can be provided.



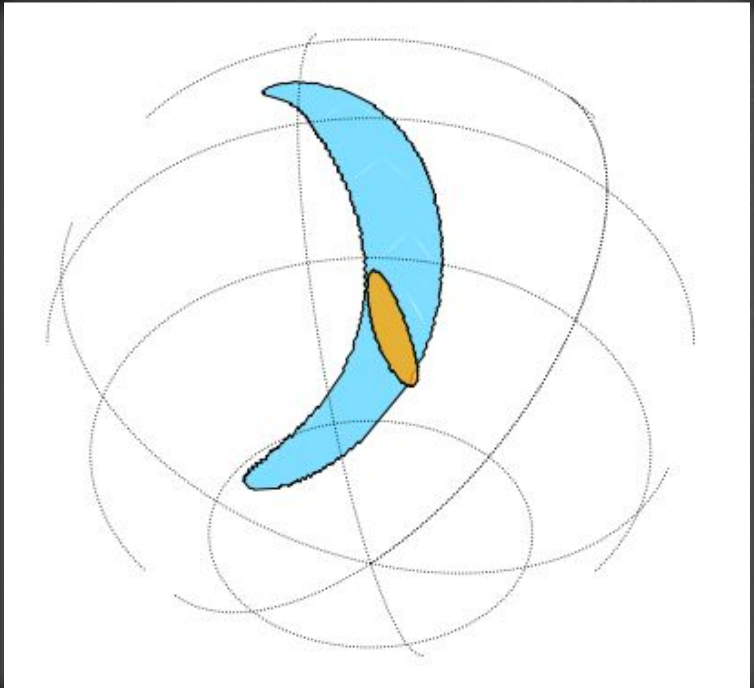
https://drive.google.com/file/d/1mx5RetcALoJmVwWn8_cj7dDNTfW6PG-x/view?usp=sharing

MOCpy

Python MOC

Matplotlib support

Perimeter function in mocpy



The last version of mocpy supports "perimeter" as Drawing method linked the popular matplotlib library.

mocpy.moc.MOC.get_boundaries()
The borders are returned as a list of SkyCoord

Asterics DADI Tutorial

https://www.asterics2020.eu/tutorials/overview

Astronomy ESFRI & Research Infrastructure Cluster

Fourth ASTERICS School

International Virtual Observatory school

Observatoire Astronomique de Strasbourg, France

Electromagnetic follow-up of gravitational-wave events

by G. Greco giuseppe.greco@uniurb.it, E. Chassande-Mottin ecm@apc.univ-paris7.fr and M.Branchesi marica.branchesi@gmail.com and many others

1. Working with the sky localizations of GW150914, GW151226 and GW170104

The probability sky maps are produced using a sequence of algorithms with increasing accuracy and computational cost. Here, we compare three location estimates: the prompt cWB and/or the rapid BAYESTAR localizations that were initially shared with observing partners and the final localization from LALInference.

2. GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

GW170814 is the fourth published detection of gravitational waves. As was the case with the first three published detections, the waves were generated by the coalescence of a pair of stellar-mass black holes. When we compare its position reconstruction in the Universe with the previous events, the sky localization of GW170814 is the narrowest. This new and exciting result was reached through a triple-coincident detection, coordinated by a body of more than 1,000 international scientists forming the LIGO and Virgo Collaboration (LVC).

3 VST tiling of GW170814

You are at ESO-Paranal Observatory in Chile and your team are planning to observe the LIGO and Virgo trigger G297595 (confirmed as GW170814), with the VLT Survey Telescope (VST) equipped with OMEGACAM. The observations are divided in 9 regions - 3° x 3° - centered on the following coordinates RA, Dec (ICRSd):

4. GW 170817: sky localizations of the *golden binary*

Fig.7 shows the localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows a projection of the 90% credible regions from LIGO (light green), LIGO-Virgo (dark green), triangulation from the time delay between Fermi and INTEGRAL (light blue), and Fermi GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hours after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right).

5 Verrecchia et al., in preparation: An AGILE Science Case: using MOC within AGILE procedure

An AGILE Science Case of interface between L-V GW skymap with AGILE data to look for gamma-ray counterpart to GW event.

VO in the OPA Era

Virtual Observatory and Ligo and Virgo Open Public Alert

The resolution of a GW sky localization with 3 detectors can reach a resolution too large (NSIDE=2048) for running the MOC in a normal pc!

↓

You need to sort the values in order to scan the higher elements. If your memory cannot contain all your values, the sort can not be done easily and the time of computation explodes.

Aladin Beta integrates a more powerful algorithm to extract MOC from an HEALPix map.

The HEALPix is converted in HiPS (for splitting the data in tiles) before applying the MOC method.

The preliminary tests show a high performance by computing several MOC confidence regions just allocated 1 gigabytes of memory to the Aladin section.

Discussed in ASTERICS DADI ESFRI Forum & Training Event 2, 13 & 14 December, 2017 - Trieste

MMA Support

Visualization & Sonification

Interactive Detection Page

www.virgo-gw.eu/skymap.html

Interactive Detection Skymap

J2000 11 01 32.208 -40 26 29.44

FoV: 180°

Using the skymap

Click on the various options below to display information relating to each detection.

Detection	Sky localisation	Label	Pop-up info
GW170817 - H1 only	☑	☑	☑
GW170817 - L1/H1 only	☑	☑	☑
GW170817 - L1/H1/V1	☑	☑	☐
GW170817 - Refined skymap	☐	☐	☐
GW170817 - (GRB170817A) Initial Fermi GBM localization	☑	☑	☑
GW170817 - (GRB170817A) Final Fermi GBM localization	☑	☐	☐
GW170817 - SSS17a/AT2017gfo Transient sky position		☑	☑
GW170814 - H1/L1	☐	☐	☐
GW170814 - H1/L1/V1	☐	☐	☐
GW170814 - Refined skymap	☐	☐	☐
GW170608 - Refined LIGO localization	☐	☐	☐
GW170104 - Refined LIGO localization	☐	☐	☐

Backgrounds

If you want to see the extension of these sky regions through the constellations you can

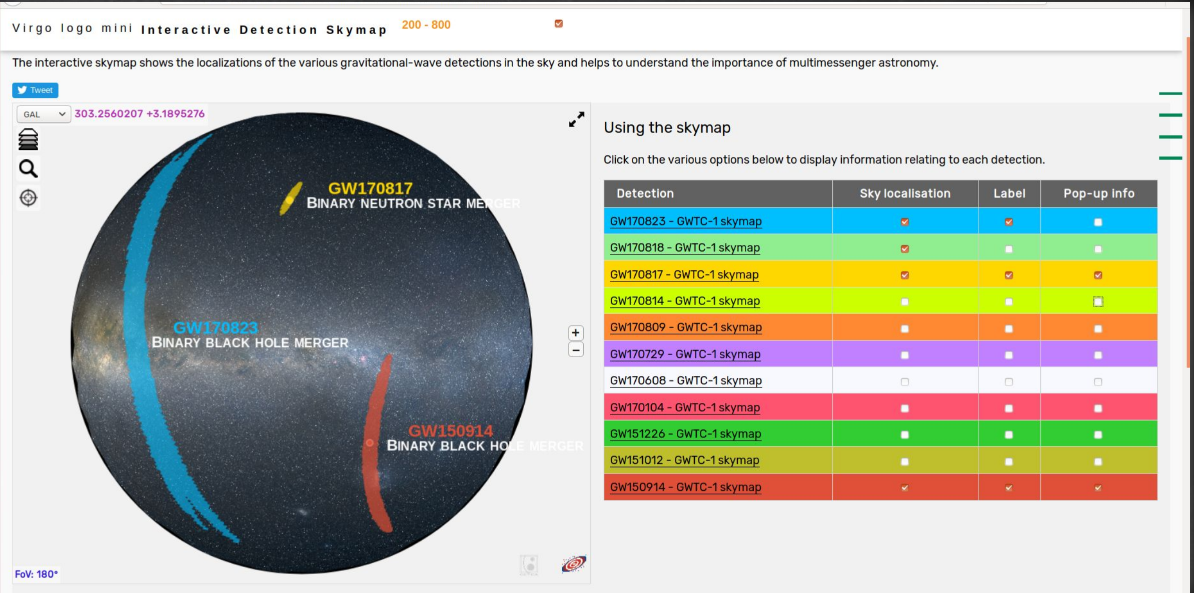
Sonification Project

The frequency is mapped to the galactic latitude of the mouse cursor location with a stereo spatialization (left/right speaker) for the galactic longitude.

A specific chord is played when the cursor enters or leaves the coverage of the sky localization.

An audio file is added to explain the nature of each event and the main properties.

The user can modify the frequency range or exclude the sound system with a check button.



An automatic tour will be added using the AladinLite Plugin developed by Tamara Clvera.

CDS

GraWITA
Gravitational waves @ INAF

FUTURO IN RICERCA

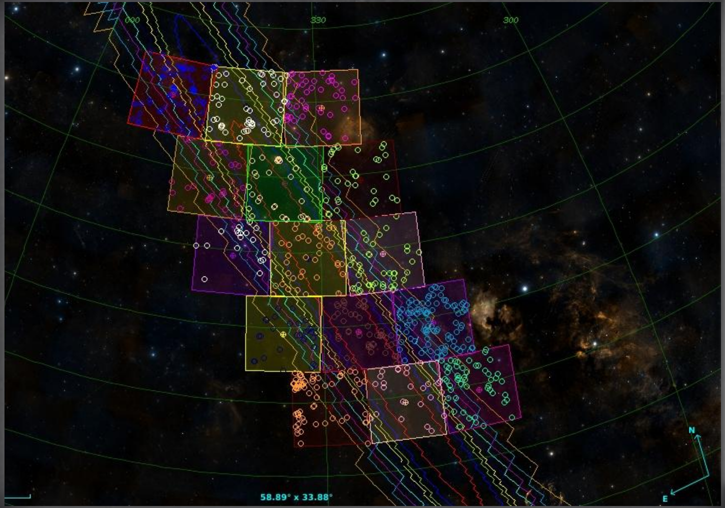
GWsky

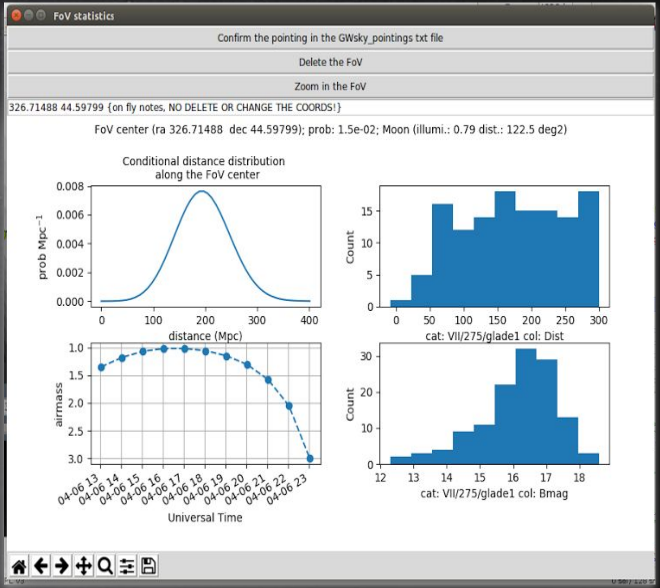
Skymap tiling

MOC Visibility

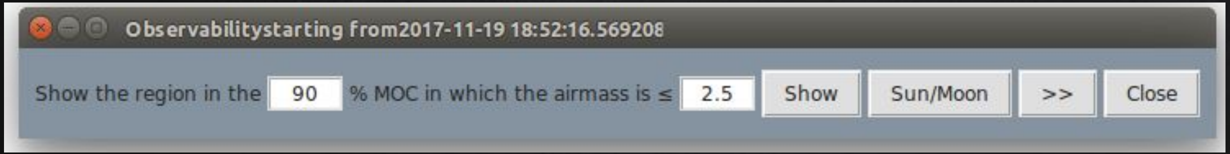
GWsky

- Skymap Tiling

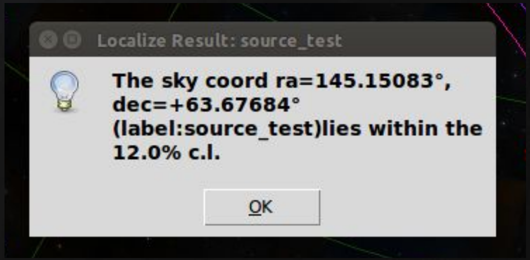




- MOC Observability

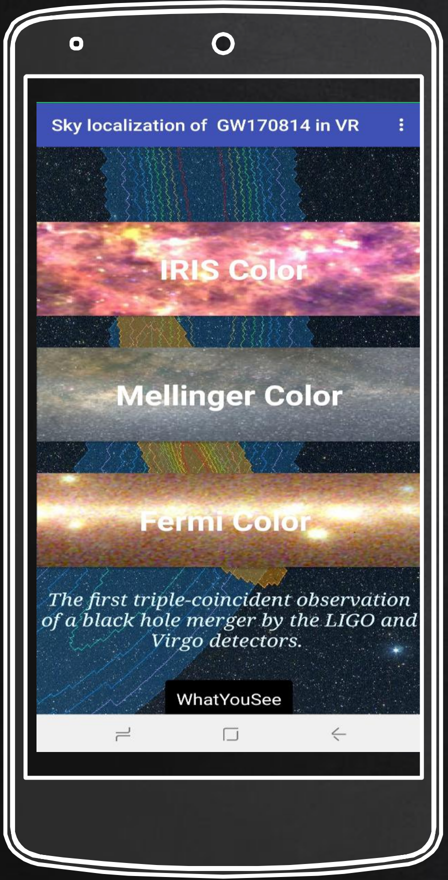


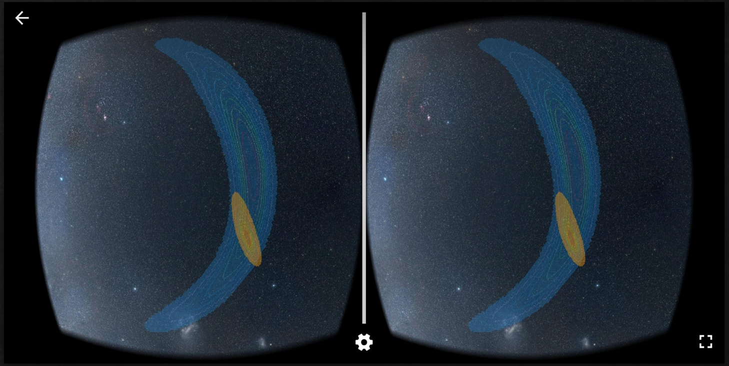
- Source localization

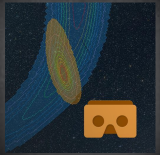


Discussed in ESFRI Forum & Training Event 1, 3 & 4
December 2015, Trieste

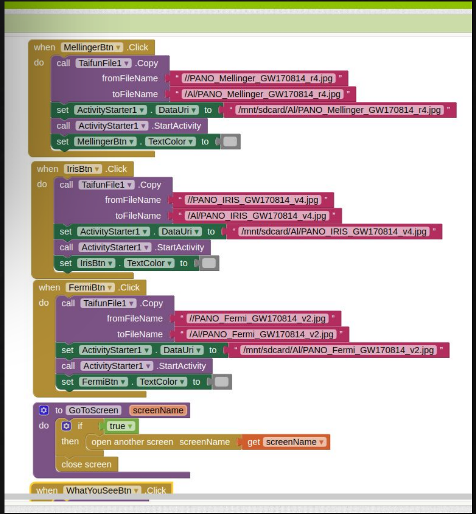
Virtual Reality App using HIPS Photospheres







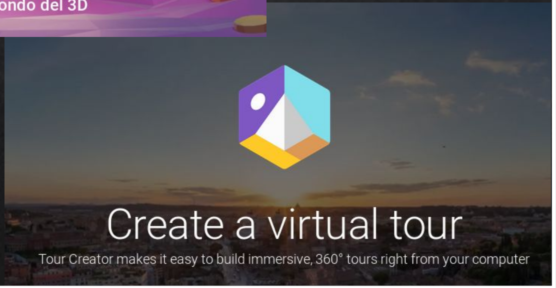
From GOOGLE PLAY download&install GWsky 170814



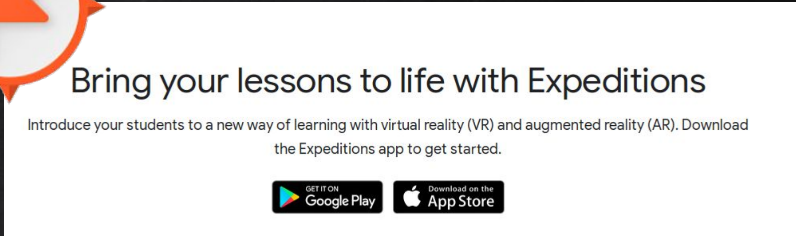
Develop using the educational App code MIT APP Inventor

Tour Creator, Poly and Expeditions Google App

Immersive GW sky localizations in the GOOGLE educational tools



https://poly.google.com/u/0/view/dQIX2GhQ1eL



Tutorial

https://dcc.ligo.org/LIGO-G1900764/public

THANKS!