Interoperable multi-messenger approach for GW sky localization and EM follow-up

practical tools and methods supported by the ESCAPE project

Giuseppe Greco for ESCAPE/CEVO ESA/ESO SCIOPS 2019 WORKSHOP







EGO - Virgo





ASTERICS and ESCAPE



The inclusion of the data of the

ESFRI facilities from astronomy and astroparticle physics in the VO is already well advanced thanks to the collaboration between ESFRI pathfinders and European VO teams in the ASTERICS Data Access, Discovery and Interoperability (DADI) Work Package since 2015. ESCAPE European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

> ESCAPE is a project supported by the European Commission Framework Programme Horizon 2020 Research and Innovation programme of the European Union. The ESCAPE project will address the challenges in open science and data accessibility faced by European researchers.



Work Package 4 of ESCAPE, "Connecting ESFRI (European Strategy Forum on Research Infrastructures) projects to EOSC (European Open Science Cloud) through VO framework". CEVO plans to make the seamless connection of ESFRI and other astronomy and astroparticle research infrastructures to the EOSC through the Virtual Observatory framework.



<u>Multi Order Coverage Map</u>

- The MOC data structure is based on the HEALPix (Hierarchical Equal Area isoLatitude Pixelation) tessellation (Gorski et. al 2005) to map <u>irregular and complex</u> <u>sky regions</u> into <u>hierarchically grouped predefined cells</u>.
- The <u>operations</u> between the MOC maps (union, intersection, subtraction, difference) are <u>very fast</u> 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.



MOC Basic Algorithm

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

The NUNIQ scheme defines an algorithm for packing an (*order, ipix*) pair into a single integer for compactness:

uniq = 4x4^{order}+ipix



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.





ALADIN Desktop

MMA Section

A live demo at the end of presentation



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



Fourth ASTERICS School

International Virtual Observatory school

Observatoire Astronomique de Strasbourg, France

DADI: Data Access Discovery and Interoperability

Electromagnetic follow-up of gravitational-wave events

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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

<u>GW170814</u> 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

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 <u>VLT</u> Survey Telescope (VST) equipped with <u>OMEGACAM</u>. 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.

LIGO and Virgo User Guide



Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

Navigation

- Getting Started Checklist Observing Capabilities Data Analysis Alert Contents Sample Code Additional Resources
- ligo.skymap: Advanced
 Python Tools for Probability
 Sky Maps
- Sky Map Visualizations and Credible Regions in Aladin
 Gravitational Wave Events iOS App

← ligo.skymap: Advanced Python Tools for Probability Sky Maps | Gravitational Wave Events iOS App →

Sky Map Visualizations and Credible Regions in Aladin

In this section, we demonstrate working with gravitational-wave sky localizations in <u>Aladin</u> <u>Desktop</u>. The following main topics are addressed.

MOC and GW Sky Localizations

- Running Aladin Desktop
- Loading a GW Sky Localization
- Building a Credible Region
- Area Within a Credible Region
- Querying and Filtering a Galaxy Catalog

MOC and GW Sky Localizations

The enclosed area within a given probability level contour of a GW sky map can be effectively described with a Multi-Order Coverage (<u>MOC</u>) map []]. MOC is a standard of the Virtual Observatory which provides a representation of arbitrary regions on the unit sphere using the <u>HEALPI</u>s sky tessellation.

The MOC data structure encodes irregular sky regions as a hierarchy of HEALPix pixels. Each MOC call is defined by two numbers: the hierarchy level (HEALPix order) and the nixel index



Fublic Alerts

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+ Additional Resources | Sky Map Visualizations and Credible Regions in Aladin

ligo.skymap: Advanced Python Tools for Probability Sky Maps

The ligo.skymap Python package includes a number of advanced tools for working with GW probability sky maps.

 Publication-quality astronomical mapmaking built on Astropy (ligo.skymap.plot.allsky)



- ligo.skymap mainly developed by Leo Singer.
- We discussed a merge request to create credible regions using the MOC data structure for interoperability. MOCpy module will be used.

SpaceTime MOC

http://www.ivoa.net/documents/stmoc/20190515/NOTE-stmoc-1.0-20190515.pdf

SpaceTime of GW sky localizations

- The next Aladin releases will provide the GW credible regions in the space-time MOC data format.
 - Filtering EM candidates according with the trigger time reported in the image header.
 - Space-time intersection with the existing surveys.



TimeSpace MOC to have simultaneously space and time coverage.

In progress



https://alasky.u-strasbg.fr/hips-image-services/hips2fits

HiPS : Hierarchical Progressive Surveys

Hierarchical scheme for the description, storage and access of sky survey data. The system is <u>based on hierarchical tiling of sky regions</u> at finer and finer spatial resolution which facilitates a progressive view of a survey, and supports multi-resolution zooming and panning. HiPS uses the HEALPix tessellation of the sky as the basis for the scheme.

HIPS2FITS: Educational

- The hips2fits service enables generation of FITS (JPEG) images cutouts of arbitrary size and resolution from a given HiPS.
- IVOA Interop, Groningen, Apps 2 (Boch et al., 2019)

Q onde gravitazional



Virtual Reality tour

https://poly.google.com/view/0Jipgrriskn

Panoramic images in Facebook





Il tour mostra 5 eventi (su un totale di 11) riportati nel primo catalogo di Onde Gravitazionali della collaborazione LIGO e Virgo. Per questi eventi è mostrata la regione di localizzazione ed è associata la traccia audio che riproduce i dati registrati dagli interferometti (LIGO-Handford, LIGO-Livingston e Virgo) e il modello della forma donda utilizzato (template).

GW150914

GW170608

L'onda gravitazionale osservata l'otto giugno del 2017 è stata generata dalla fusione di 2 buch neri nu un sistema binario con masse di circo 11 e 8 volte la massa del Sole. La massa totale e di circo 18 masse solari, L'area di localizzazione (90%) è di 392 gradi quadrati. Il redshift z = 0.07



HIPS2FITS: sharing MMA data



If your HiPS is publicly available through HTTP (ie no access restriction, no password), it will be reachable by the hips2fits service and anyone with the HiPS URL will be able to generate FITS cutouts extracted from this HiPS. In progress

The approach could be useful for a fast data sharing. The user can get from the hips2fits only specific section of the image for analysis.



Aladin Lite for inclusive education

GW sky 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 constellations as well as the GW sky localizations are sonorized with a chord and a mp3 file description.

An automatic tour is added using the Aladin Lite Plugin developed by Tamara Civera.

In progress

Interactive Detection Skymap 0-844

turn to the Virgo homepage Go to the LIGO Open Science Center

e interactive skymap shows the localizations of the gravitational waves reported in the Gravitational-Wave Transient Catalog of Compared Binary Mergers (GWTC-1). The interactive sky map is sonotized. A specific chord is played when the raor enters or leaves the coverage of the gravitational-wave sky localization. The frequency is mapped to the galactic latitude of the mouse cursor location with a stereo spatialization (leftright speaker) for the galactic longitude. e sonotization starts when a Localization checkbox is selected and is deactivated when the Label and **Poy-up** into checkbox is are choosen. The sonotization can be completely disabled from the checkbox *Sonorization* on the top of the

Tweet G Share



Using the skymap

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

Detection	Sky localisation	Label	Pop-up info
GW170818 - GWTC-1 skymap			
GW170817 - GWTC-1 skymap			
GW170814 - GWTC-1 skymap			
GW170809 - GWTC-1 skymap			
GW170608 - GWTC-1 skymap	0	0	0
GWI-50914 - GWITC 1 skymag	~		
And - Andromeda/Andromeda	•		0
Ant - Antila/Macchina pneumatica	3		
Aps - Apus/Uccello del paradiso	•	0	
Aqr - Aquarius/Acquario	9	0	
Aql - Aquila/Aquila	9	0	
Ara - Ara/Altare	3	0	
Ari - Aries/Ariete		0	
Aur - Auriga/Auriga		0	
Boo - Bootes/Bootes	9		
Cae - Caelum/Bulino		1	-

Under tests in the Virgo/EGO events



Conclusion

- Five years in testing and implementation to support the GW credible region in MOC data format
- Supporting in the VO (Virtual Observatory) and LVC (LIGO and Virgo Collaboration) schools and tutorials
- Outreach and EPO (Facebook photospheres, VR tours, Google Poly)
- Space-time MOC implementation for GW MOC region in progress
- Hips2fits as a new approach for sharing data in MMA under testing

THANKS!



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