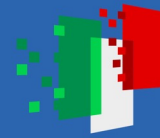




Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



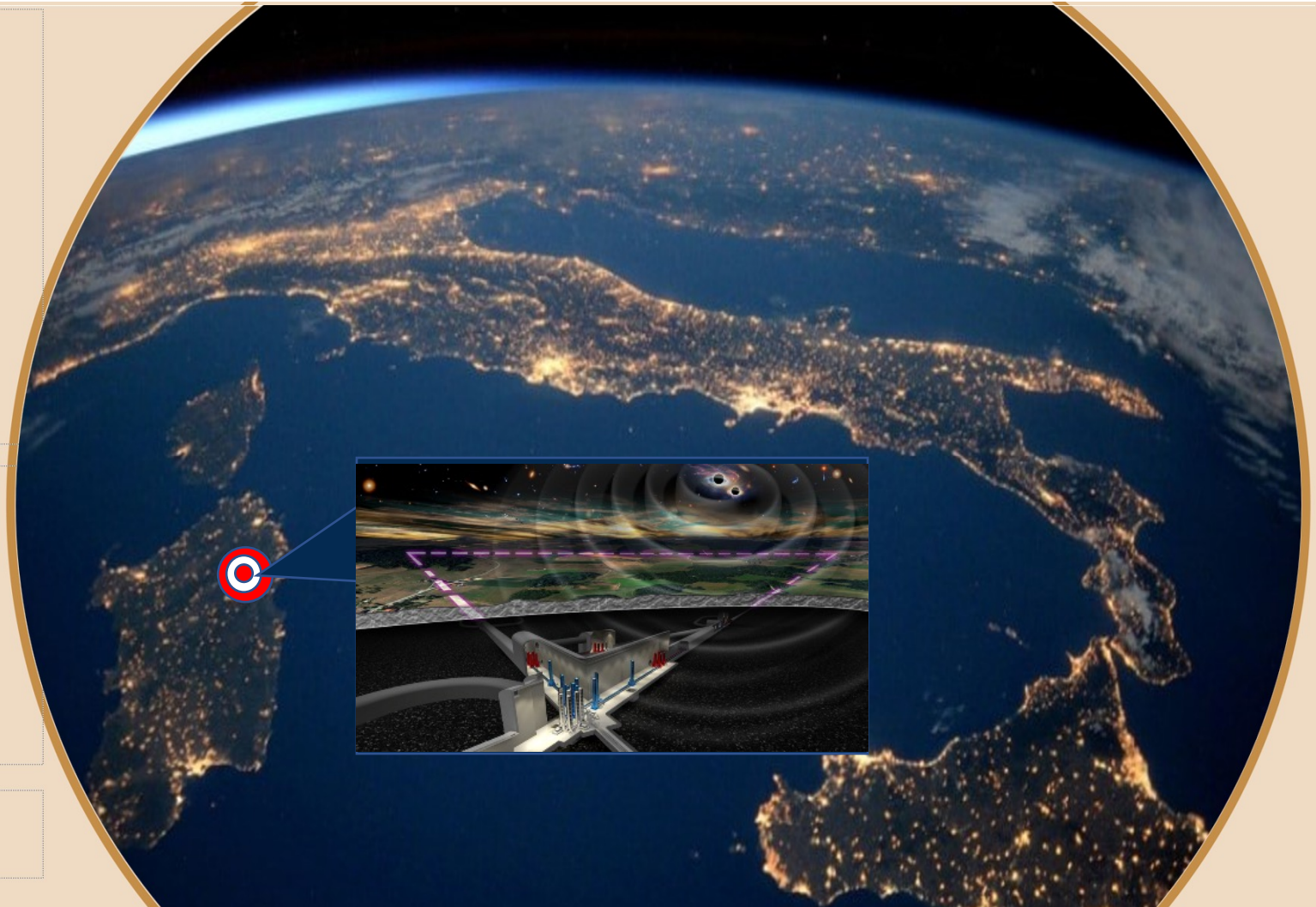
Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



# Advancements in Encoding Gravitational-wave Sky Localizations: Virtual Observatory Standards and New Challenges for the Einstein Telescope

Giuseppe Greco

INFN - Perugia

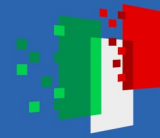




Finanziato dall'Unione europea  
NextGenerationEU



Ministero dell'Università e della Ricerca



Italiadomani  
PIANO NAZIONALE DI RIPRESA E RESILIENZA



## Member Organizations

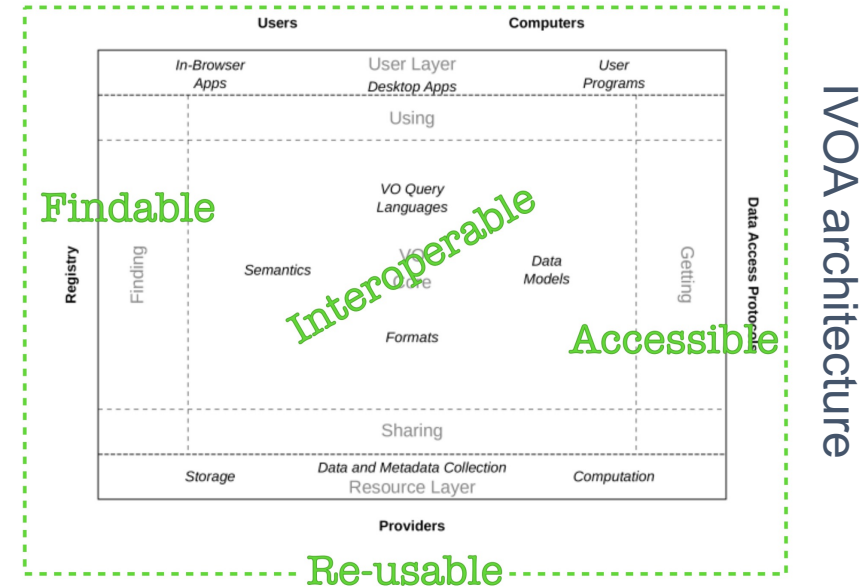


- Argentine Virtual Observatory
- Armenian Virtual Observatory
- AstroGrid, United Kingdom
- Australian All-Sky Virtual Observatory
- Brazilian Virtual Observatory
- Chinese Virtual Observatory
- Canadian Virtual Observatory
- Chilean Virtual Observatory
- European Space Agency
- European Virtual Observatory
- German Astrophysical Virtual Observatory
- Japanese Virtual Observatory
- Kazakhstan Virtual Observatory
- Netherlands Virtual Observatory
- Observatoire Virtuel France
- Russian Virtual Observatory
- Square Kilometer Array Observatory
- South African Astroinformatics Alliance
- Spanish Virtual Observatory
- Italian Virtual Observatory
- Ukrainian Virtual Observatory
- US Virtual Observatory Alliance
- Virtual Observatory India

Contacts for the IVOA Member Organizations

<https://ivoa.net/>

The Virtual Observatory (VO) envisions astronomical datasets and resources functioning seamlessly together. The International Virtual Observatory Alliance (IVOA) sets the necessary technical standards to achieve this vision. IVOA also serves as a hub for VO aspirations, facilitating the exchange of ideas and technologies, and promoting the VO globally.



Two interoperability meetings per year:

- 5 days around May.
- 3 days around Oct/Nov after ADASS (Astronomical Data Analysis Software & Systems).

*Previous Meeting: Sydney, Australia*

*Next Meeting: Malta*



# Encoding GW sky localization area with Multi Order Coverage map

 **Developments from 2014 to 2023**





- ❑ ASTERICS DADI ESFRI Forum & Training Event 1 – 3 & 4 December, 2015 – Trieste.
- ❑ ASTERICS DADI Technology Forum 2 – 7 & 8 March, 2016 – Edinburgh.
- ❑ DADI Meeting on Gravitational Waves – 31 May–1 June 2016 – Strasbourg.
- ❑ ASTERICS DADI ESFRI Forum & Training Event 2, 13 & 14 December, 2017 – Trieste.



**IVOA: Northern Spring 2016 Interoperability Meeting**



*Focus session from Mark Allen*







- ❑ AHEAD2020 WP12 F2F meeting 4 May, 2022 – Aquila.
- ❑ INFN–Perugia and SSC–ASI dedicated periodic calls.
- ❑ ESCAPE to the Future 25–26 October 2022 – Brussels.
- ❑ WP4 Technology Forum 3 – 15–16 March 2022 –online
- ❑ WP4 Technology Forum 2 – 13–15 April 2021 –online
- ❑ WP4 Technology Forum 1 – 4–6 February 2020 – Strasbourg

**+ Internal Virgo weeks and LVK teams calls**

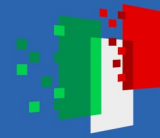
[Working with Gravitational-Wave sky localizations: new methods and implementations](#), *Greco et al.*, 2019

[Capability for Encoding Gravitational-wave Sky Localizations with the Multi Order Coverage Data Structure: Present and Future Developments](#), *Greco et al.*, 2020

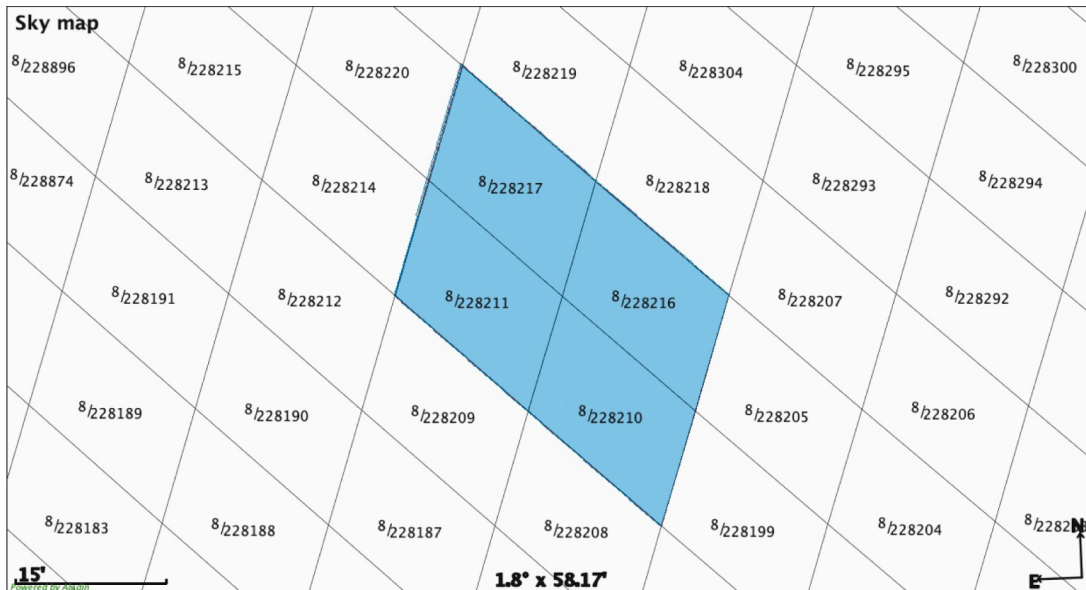
Based on the IVOA Recommendation

[MOC – HEALPix Multi-Order Coverage map Version 1.0 IVOA Recommendation 2 June 2014](#), *P. Fernique et al.*, 2014

*Slide from IVOA (Northern Spring) May 2023 Interoperability Meeting, Bologna*



## MOC in short



The MOC (Multi-Order Coverage) data structure is based on the HEALPix (Hierarchical Equal Area isoLatitude Pixelization) sky tessellation algorithm (Górski et al., 2005).

HEALPix divides the sky into curvilinear quadrilaterals, starting with twelve base pixels. Each pixel can be subdivided into four, increasing the resolution.

A MOC cell, which defines a unique sky region, is characterized by its hierarchy level and pixel index.

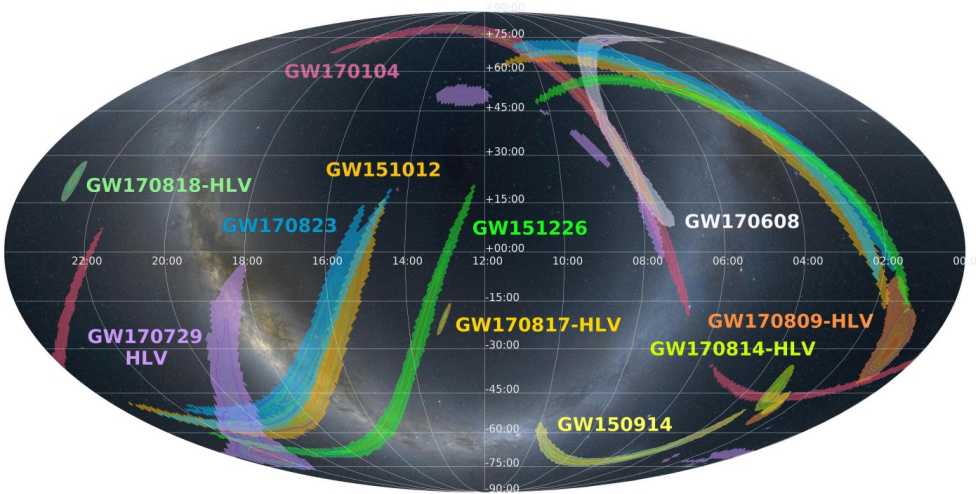
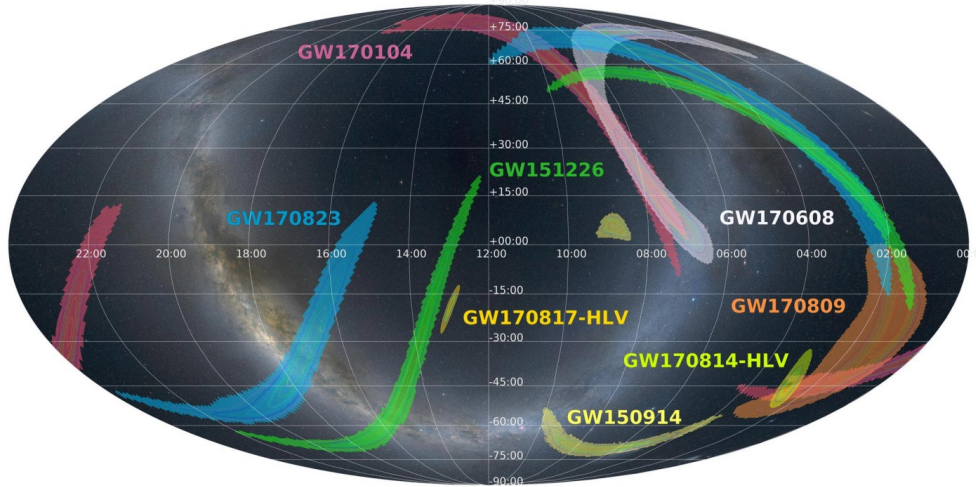
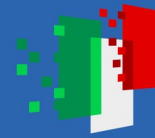
Using this hierarchical system, MOC efficiently represents complex sky regions and supports various astronomical applications.

## Serializations

**FITS**  $uniq = 4 \times (4^{order}) + npix$   
Flexible Image Transport System

**JSON**  $\{ "order" : [npix, npix, \dots], "order" : [npix, npix, \dots], \dots \}$ .  
JavaScript Object Notation





Generally, GW sky localizations are irregularly shaped and the Multi Order Coverage (MOC) IVOA standard offers

Fast mapping of localization areas even if there are separated regions.

Dedicated queries from the entire **IVOA collections\*** into that (GW) MOC.

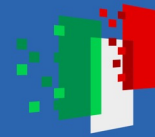
Comparisons between any sky region encoding in a MOC: neutrinos/GRBs localizations, references images.

Filtering catalogs and transient candidates.

Reactive planning to coordinate electromagnetic followup.

- \* → Available pixels  $5.72E+14$  (all HiPS resolutions, formats,  $1.18E+15$  with mirrors = 1181.0 thousands of billions pixels) (94.6% computed by CDS)
- (equivalent to a photo album of all inhabitants of the earth with one 393x393 picture per human)
- Nb catalog rows:  $3.28E+10$  = 32.8 billions of rows

<https://link.springer.com/article/10.1007/s41114-020-00026-9>



Aladin Desktop was created in 1999 by the CDS.

It is a popular software in astronomy that was the first to implement the construction of 2D credible regions for gravitational waves using the MOC data structure. The software is widely used in schools and tutorials.

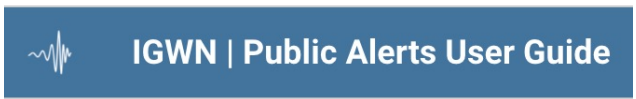


MOCpy is a Python library fully dedicated to the creation and manipulation of MOCs.

## Sky Map Visualizations and Credible Regions in Aladin

In this section, we demonstrate working with gravitational-wave sky localizations in [Aladin Desktop](#). 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](#)
- [Thumbnail View Generator](#)
- [Building a Spatial and Temporal Credible Region](#)
- [Spatial and Temporal Coverage Intersections](#)



<https://emfollow.docs.ligo.org/userguide/resources/aladin.html>

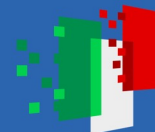




Finanziato dall'Unione europea  
NextGenerationEU



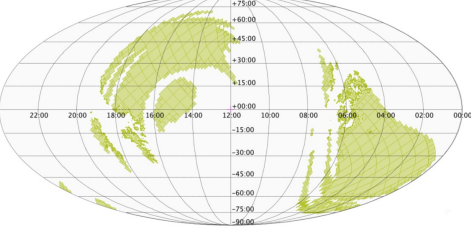
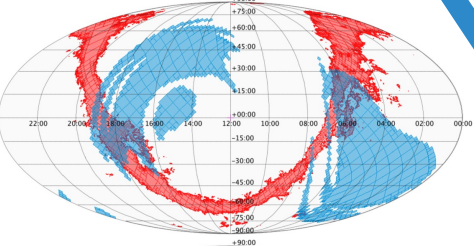
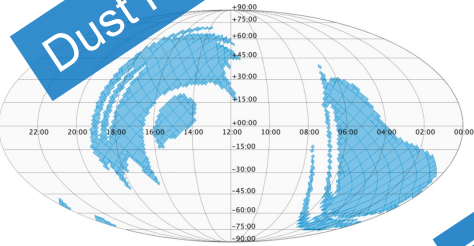
Ministero dell'Università e della Ricerca



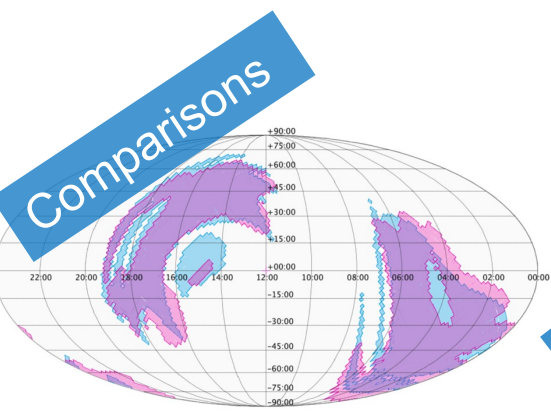
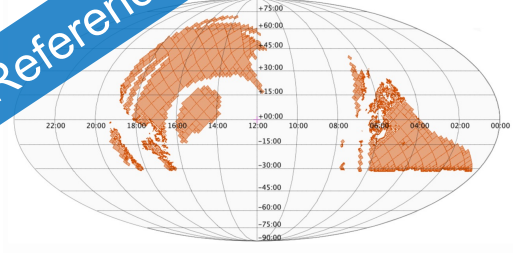
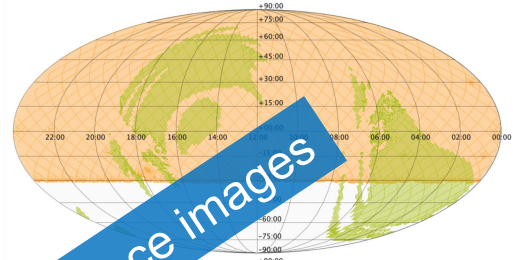
Italiadomani  
PIANO NAZIONALE DI RIPRESA E RESILIENZA



Dust regions

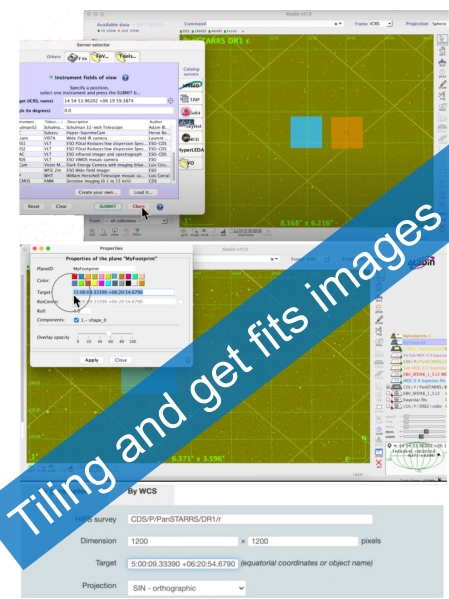


Reference images



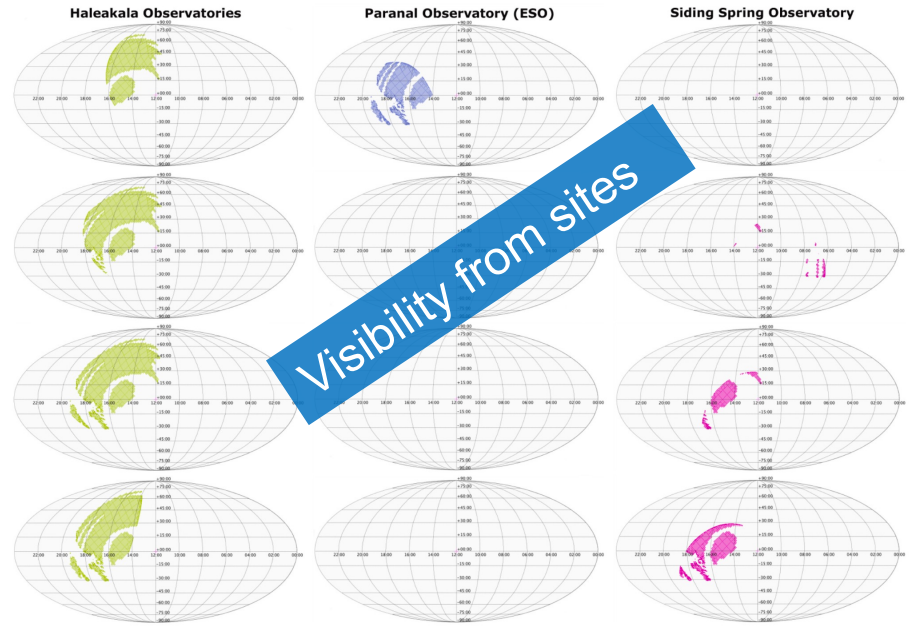
Comparisons

Tiling and get fits images



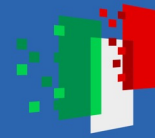
We demonstrated multiple applications for managing 2D sky maps from gravitational-wave transient event localizations using MOC data structures.

MOC data structures offer a flexible and interoperable methodology for planning multi-messenger observations, meeting various research needs in data comparison, access, and visualization in multi-messenger science.



Visibility from sites

*Multi Order Coverage data structure to plan multi-messenger observations, Greco et al., A&C, 2022*



<https://virgo.pg.infn.it/gladenet/catalogs/>

<https://virgo.pg.infn.it/maps/>

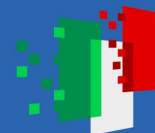
EDU version:

<https://virgo.pg.infn.it/soundmap/>

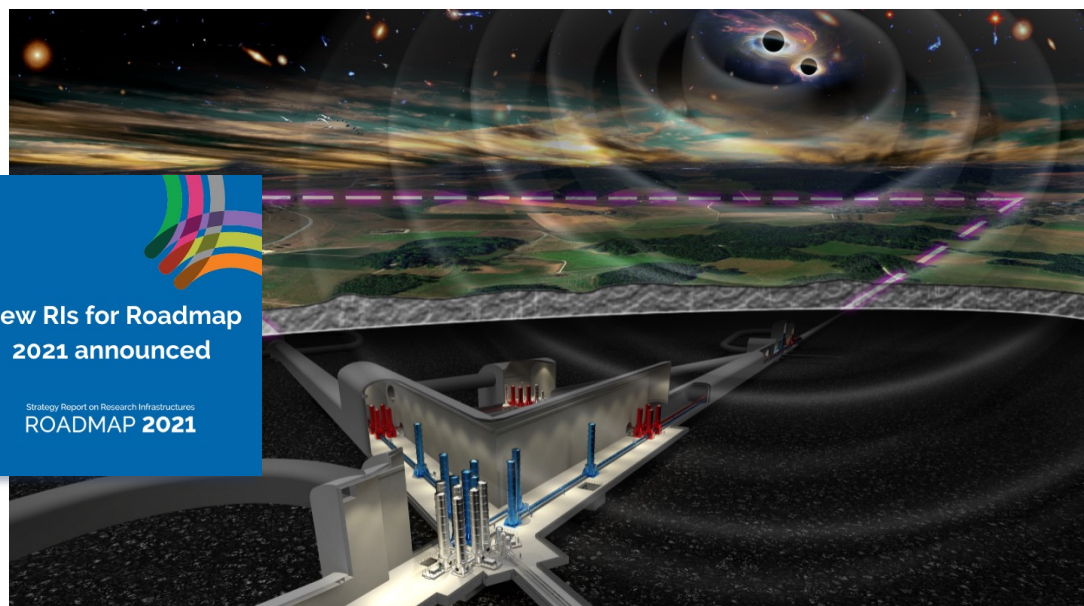


GW maps and GLADENet are web applications powered by Aladin Lite. GW maps allows for interactive visualization of credible regions. GLADENet, on the other hand, interactively displays galaxies within 90% of the credible volume using the GLADE catalog.



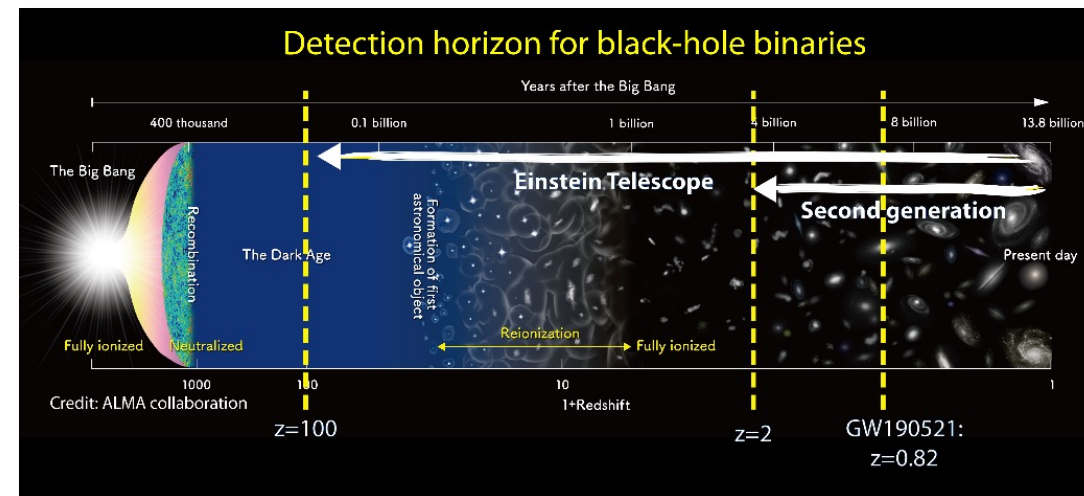


# ET: Einstein Telescope



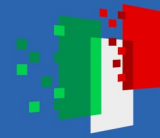
New RIs for Roadmap 2021 announced  
Strategy Report on Research Infrastructures  
ROADMAP 2021

**ET** - Einstein Telescope, the first and most advanced third-generation gravitational-wave observatory, with unprecedented sensitivity that will put Europe at the forefront of the Gravitation Waves research.



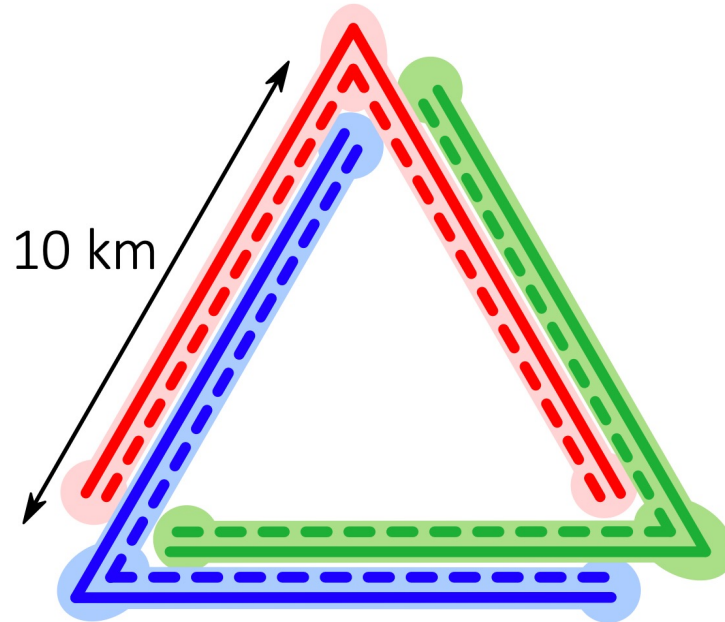
- Black hole properties: origin (stellar vs. primordial), evolution, demography.
- Neutron star properties: interior structure (QCD at ultra-high densities, exotic states of matter), demography.
- Multi-messenger astronomy: nucleosynthesis, physics of jets, role of neutrinos.
- Detection of new astrophysical sources of GWs: core collapse supernovae, isolated neutron stars, stochastic background of astrophysical origin.
- The nature of compact objects: near-horizon physics, tests of no-hair theorem, exotic compact objects.
- Dark matter: primordial BHs, axion clouds, dark matter accreting on compact objects.
- Dark energy and modifications of gravity on cosmological scales.
- Stochastic backgrounds of cosmological origin and connections with high-energy physics (inflation, phase transitions, cosmic strings, ...)

*Maggiore et al., 2020; Science case for the Einstein Telescope*

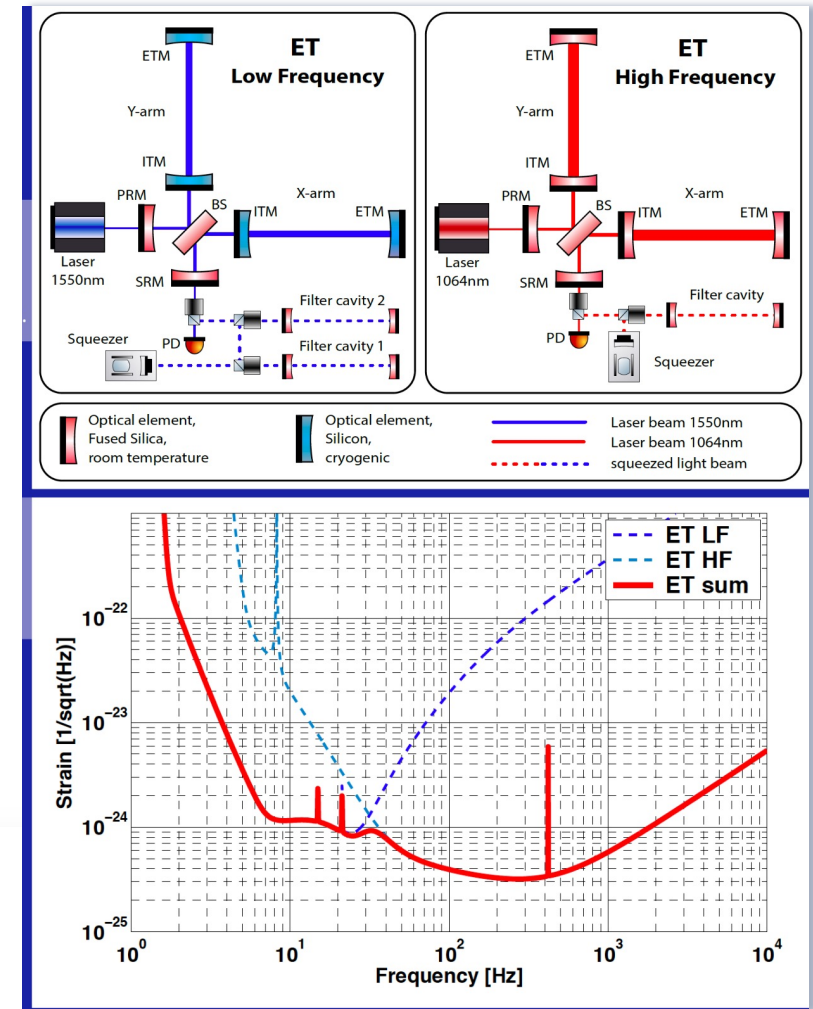


# ET in a Triangular Configuration

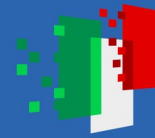
A possible Einstein Telescope configuration will consist of three nested detectors (shown in blue, green and red) in a triangular arrangement (Xylophone configuration).



Each detector consists of two interferometers, one optimised for low-frequency (solid) and one for high frequency sensitivity (dashed).







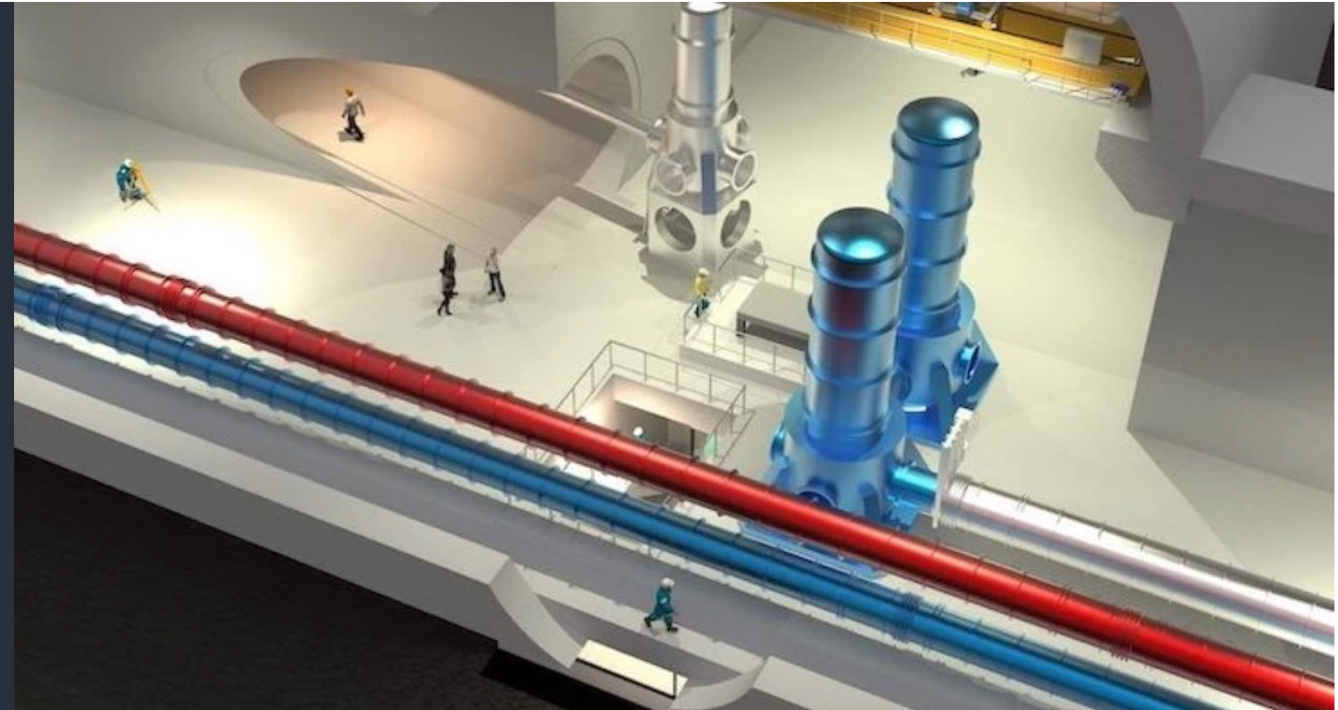
## Will the Einstein Telescope be split in two?

While Italy and the Netherlands prepare their bids to host the next gravitational wave observatory, the collaboration is considering an alternative design that would use both sites.

<https://www.nature.com/natitaly>

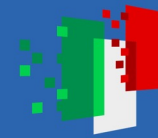
Chiara Sabelli

News | 18 April 2024

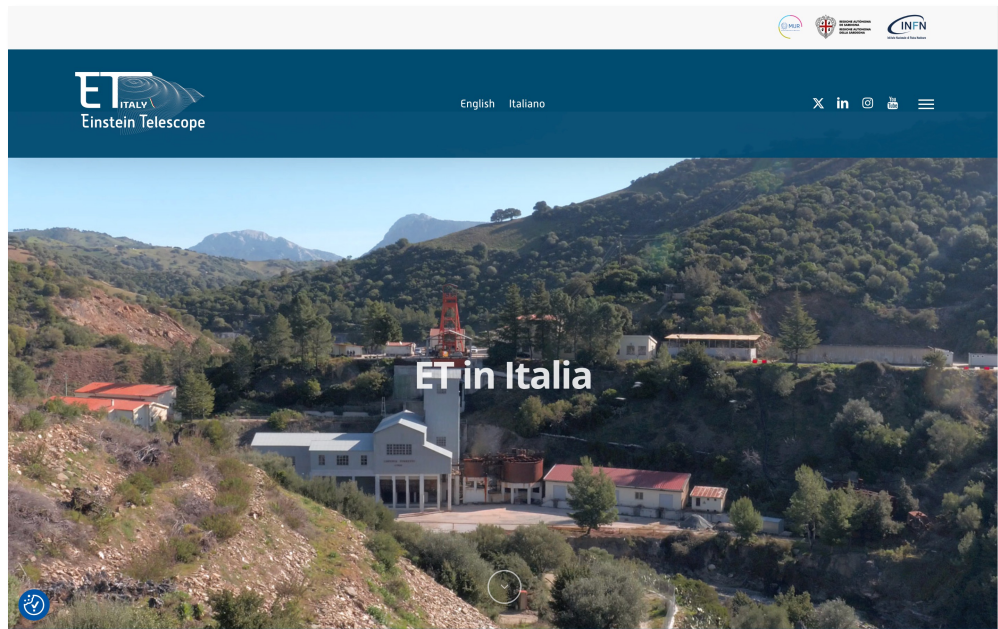


A recent study concluded that two L-shaped detectors would lead to better results. “For nearly all the science cases we have considered, two L-shaped detectors would be able to observe from two to three times the number of events that the triangle would see. That this design would also allow to better locate the source of each gravitational wave in the sky, which is critical for pointing optical telescopes in the right direction and observing the light emitted by merging neutron stars.

*[Science with the Einstein Telescope: a comparison of different designs, Branchesi et al., 2023](#)*



## ETIC: Einstein Telescope Infrastructure Consortium



ETIC, funded with 50 million euros by the PNRR (National Recovery and Resilience Plan) – Next Generation EU, under Mission 4 Education and Research and coordinated by the MUR (Ministry of University and Research), aims to support the international Einstein Telescope project.

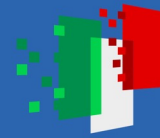
**Feasibility and Site Characterization Study of Sos Enattos:** Assessing the potential of Sos Enattos for the Einstein Telescope.

**R&D Laboratory Network:** Establishing and enhancing a national network of research and development laboratories at INFN locations, universities, and research institutes involved in the Einstein Telescope project.

### Technological Focus Areas:

- Seismic filtering systems and low-frequency control for optical suspensions.
- Low-noise cryogenic devices to reduce thermal noise in optics.
- Innovations in photonics, optics, and electronics.
- New materials for the construction of Einstein Telescope mirrors.





## MOC: Multi-Order Coverage map Version 2.0

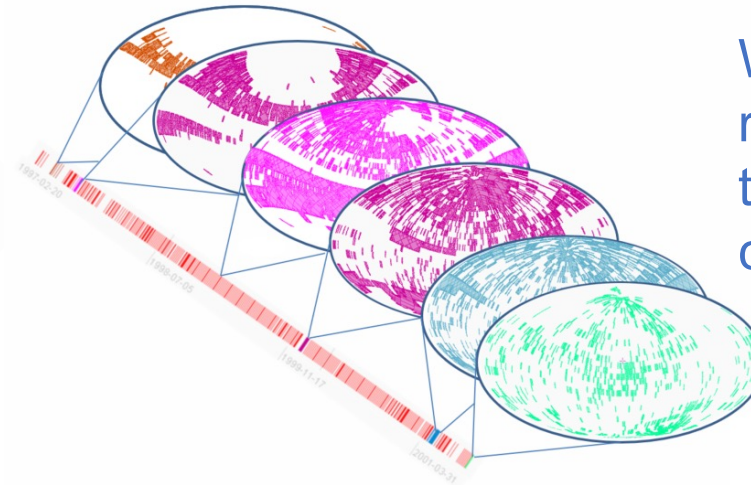
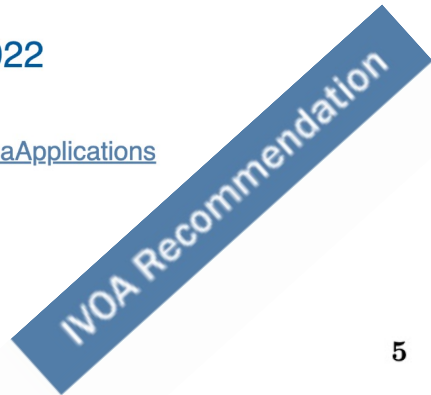
IVOA Recommendation 27 July 2022

Interest/Working Group:

<http://www.ivoa.net/twiki/bin/view/IVOA/IvoaApplications>

### Contents

<b>1 Introduction</b>	<b>5</b>
<b>2 The rationale</b>	<b>6</b>
2.1 Comparing the coverage of multiple datasets	7
2.2 Query databases using MOC	8
2.3 Gravitational Wave localisations	8
2.4 Space and Time MOC: Einstein Telescope and Early Warning Alerts	9
2.5 Multi-site positional and temporal search	10
<b>3 MOC principles</b>	<b>10</b>
3.1 Space MOC conventions	11
3.2 Time MOC conventions	14
3.3 Space and Time MOC conventions	15

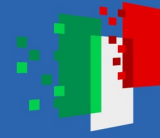


Within a specified time range, we can determine the corresponding spatial coverage.

### ST-MOC Queries and Operations

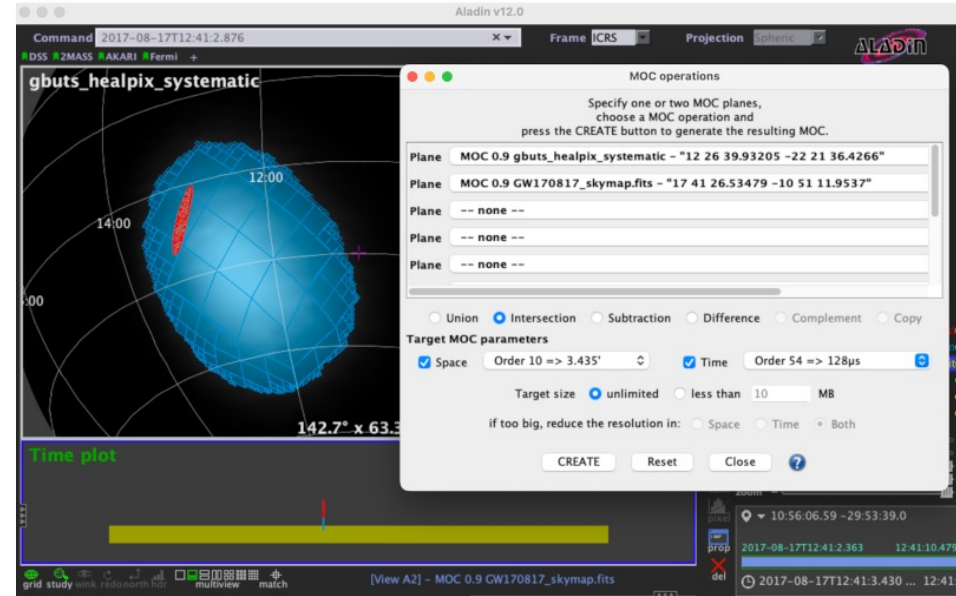
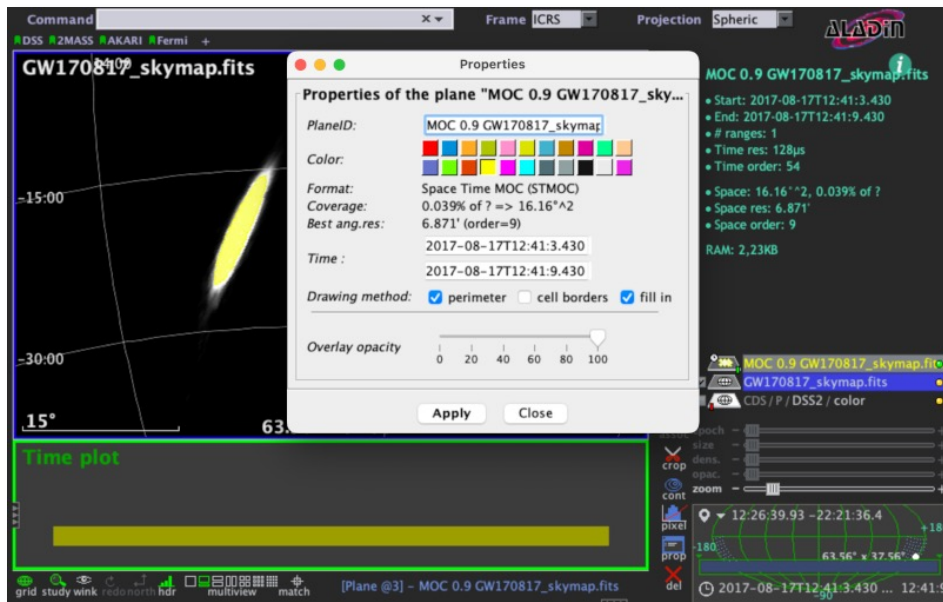
Enabling fast, real-time data access involves encoding ET/CE sky localizations into ST-MOC and querying them within specific time ranges. Transients can be ranked based on their positions within credible regions relative to the merge time.

Electromagnetic and neutrino surveys will dynamically explore ET sky localizations through multiple spatial and temporal intersections to investigate any signals associated with the inspiral, merger, or ring-down phases.



# GW170817/GRB170817

## Spatial and temporal coincident using ST-MOC



ST-MOC reference time systems. We opt for the TCB reference see [Rots and Bunclark et al., 2015](#) for details.

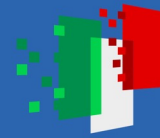




Finanziato  
dall'Unione europea  
NextGenerationEU



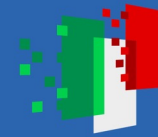
Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



**New Feasibility and Very Preliminary Studies to Handle the Enormous Number of Alerts Estimated at About  $10^6$  BH-BH Coalescences Per Year and Approximately  $10^5$  Neutron Star Coalescences in Binary Systems**



# MOC and Contextual Text

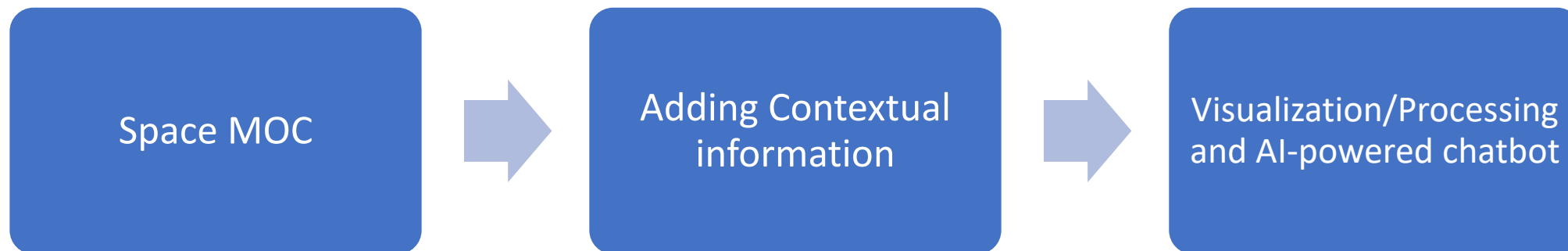
## General Idea:

We are experimenting with the integration of various texts related to GW credible regions into a MOC data structure.

The MOC coverage is managed using VO tools and the text by the OpenAI APIs.

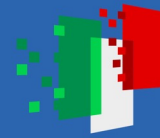
## Potential Use with GCN Circulars:

In this case, the text can be in the form of a GCN Circular—a human-readable bulletin submitted and distributed to community members worldwide—and is processed by an AI-powered chat bot with standard IVOA tools and library to visualize and process the MOC maps.



**Integrating Contextual information into Multi-Order Coverage Maps for AI-powered chatbot**





## Example of a Chatbot's Response to User Questions

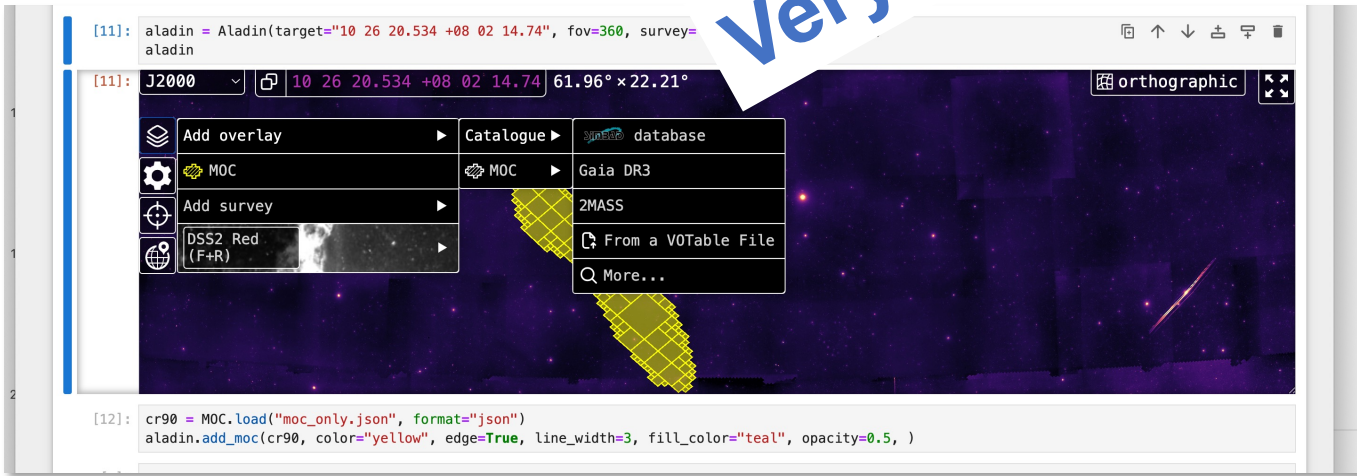
**Question:** Provide a list of all the instruments used here

**Answer:** The instruments used in the provided GCN Circulars are: 1. Dark Energy Camera (DECam) 2. EP-WXT instrument 3. T80S 0.8-m robotic telescope with T80S-Cam imager 4. Palomar 48-inch telescope with the 47 square degree ZTF camera 5. LIGO Hanford Observatory (H1) 6. LIGO Livingston Observatory (L1) 7. Virgo Observatory (V1) 8. Zwicky Transient Facility (ZTF) 9. Global Relay of Observatories Watching Events Happen (GROWTH) 10. Einstein Probe (EP) with the WXT instrument 11. Pan-STARRS template images 12. ATLAS 13. ZTF alert stream 14. Keck Observatory 15. Geminiwca 17. AMPEL 18. ZTFReST 19. Minor Planet Center 20. Transient Name Server 21. Lasair 22. Science Data Archive at NOAO These instruments are used for various observations, follow-ups, and analyses related to the gravitational wave event S240413p.

**Tokens used:** 6323

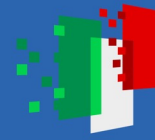
**Cost:** \$0.126460

Very preliminary!



We have developed a test function that utilizes the OpenAI GPT-3.5-turbo model to answer questions strictly based on the provided GCN Circular text embedded within a MOC JSON data structure.

Simultaneously, the localization areas can be visualized using ipyladin, enriching the chat conversation with MOC queries and functionalities.



# MocServer@CDS

## Meta data server

### i) MOC server

MOC server can also be queried to retrieve MOC rather than IDs or dataset records.

*The query must be an identifier or a mask of identifier (with wildcards), or a list of, comma separated.  
The resulting MOC will be the union (resp. intersection) of the matching MOCs, projected on the spatial dimension (smoc), or explicitly on the temporal dimension (anymoc). (If a physical dimension is required but missing, it is assumed to be present on the whole coverage.)  
The resolution of the resulting MOC can be reduced, either explicitly by setting the maximum order (1 value in the case of a SMOC or TMOC, or 2 values per maximum allowed size suffixed by 'KB' or 'MB'.*

ID=CDS/J/A+A/375\* & get=anymoc & op=union & order= & fmt=fits Go

### ii) Dataset record server

MOC server can also be used as a basic metadata server providing/updating dataset records for any remote client. With this form comparing them with an input ID[=TIMESTAMP] list.

*In case of empty list, all records are provided. If the list only contains one TIMESTAMP value, all records updated after the specified date will be provided. If the IDs are provided with a =TIMESTAMP suffix, only the records, amongs this list, updated after each specified date + the new records will be described above. The IDs removed or unknown by the MOC server will be returned with the dedicated field: MOCSERVER\_REMOVE = true.  
List of ID[=TIMESTAMP] must be coded in ASCII format, one per line and sent via POST method (multipartID: maj).*

Scegli file Nessun file selezionato & fields= & fmt=ascii Go

### iii) Property field list retrieval

MOC server may return the list of all used property key words (mainly ObsCore vocabulary), with a random example.

get=example & fmt=ascii Go

<https://alasky.u-strasbg.fr/MocServer/query>

The CDS MOCServer offers the ability to download and synchronize textual information along with the associated Multi-Order Coverage (MOC) for each dataset.

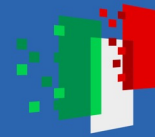
In addition, the python astroquery library offers various functionalities to query the MocServer

```
>>> from astroquery.mocserver import MOCServer
```



The next experimental step involves training a Recurrent Neural Network (RNN) with mixed MOC/text formats to create AI-driven automatic VOEvent alerts.





## Conclusions and Prospectives

Technological methods driven by scientific objectives are critical for advancing discoveries in multi-messenger astronomy. This importance will escalate with the advent of the third generation of interferometers and facilities like the Vera Rubin Observatory.

Developing shared standards for seamless data access from various facilities is crucial for advancing multi-messenger science. IVOA offers FAIR technologies.

The adoption and development of IVOA standards have had a significant scientific impact on the community and are supported and will continue to be supported by many other European projects such as ASTERICS, ESCAPE, AHEAD, ACME, ETIC, M2Tech and worldwide astronomical laboratories.

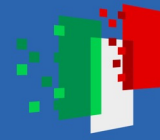
We will continue to support these standards and conduct feasibility studies to understand how they can be integrated into the latest AI models and Machine Learning techniques, planning a technical roadmap for the ET era [GW in the VO - ESFRI ET overview and EOSC connection](#).



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



**Thank you for your attention.**