Challenges in Multimessenger Astronomy in the ET Era:

From Interoperability to Multimodal Generative/Agentic AI Systems

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EINSTEIN TELESCOPE

Finanziato dall'Unione europea NextGenerationEU

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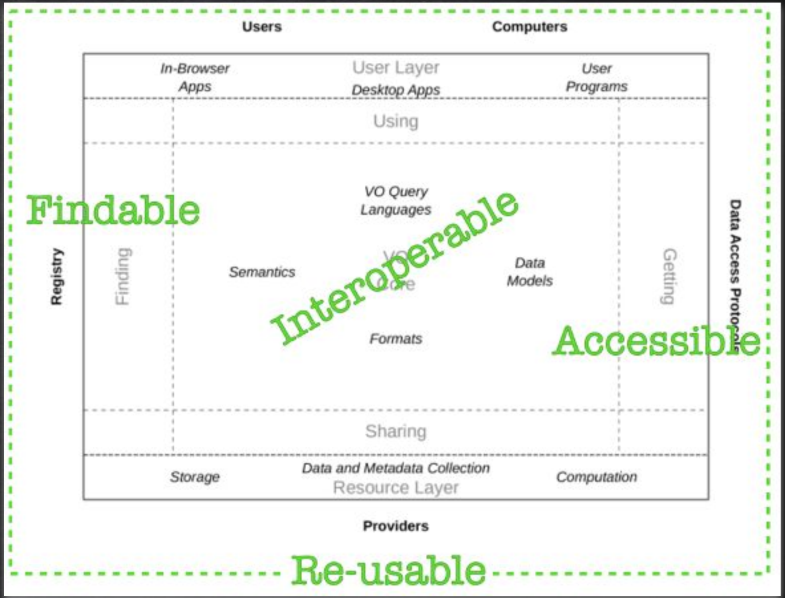
IVOA



IVOA June 2025 Interoperability Meeting

1–6 Jun 2025
Edward St. John Learning and Teaching Center (ESJ)
US/Eastern timezone

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.

How we can build AI systems from VO standards and tools?

A few Idea Use Cases (VO + AI Integration)

🧠 Language Models (LLM)

📊 Train LLMs using high-quality datasets from IVOA services like VizieR.

🤖 Build a RAG (Retrieval Augmented generation) framework for semantic search over vector databases.

👁️ Vision Models

🛰️ Fine-tune visual models using HiPS to collect and visualize astronomical surveys.

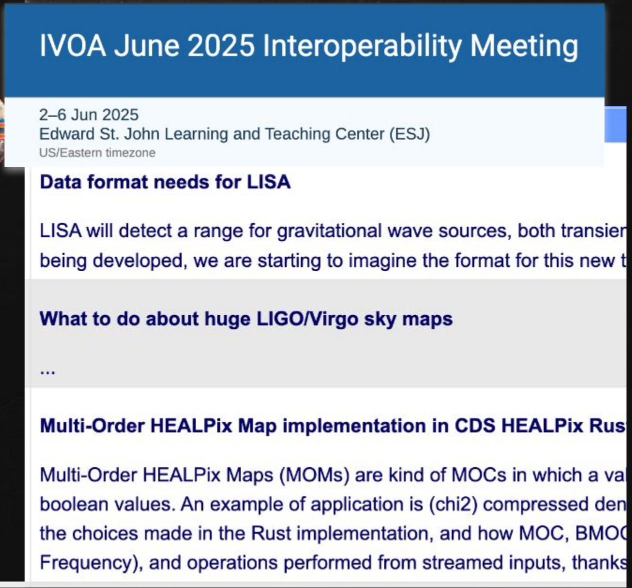
💬 Conversational Agents

🧾 Develop a SQL RAG agent to process natural language questions over TAP (Table Access Protocol) services.

🗣️ Translate natural language to ADQL (Astronomical Data Query Language) and return enriched, human-readable answers.

🧭 Multimodal Queries

🌌 Enable spatial, temporal, textual and visual queries simultaneously for scientific exploration using MOC data structure.



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Data format needs for LISA

LISA will detect a range for gravitational wave sources, both transien
being developed, we are starting to imagine the format for this new t

What to do about huge LIGO/Virgo sky maps

...

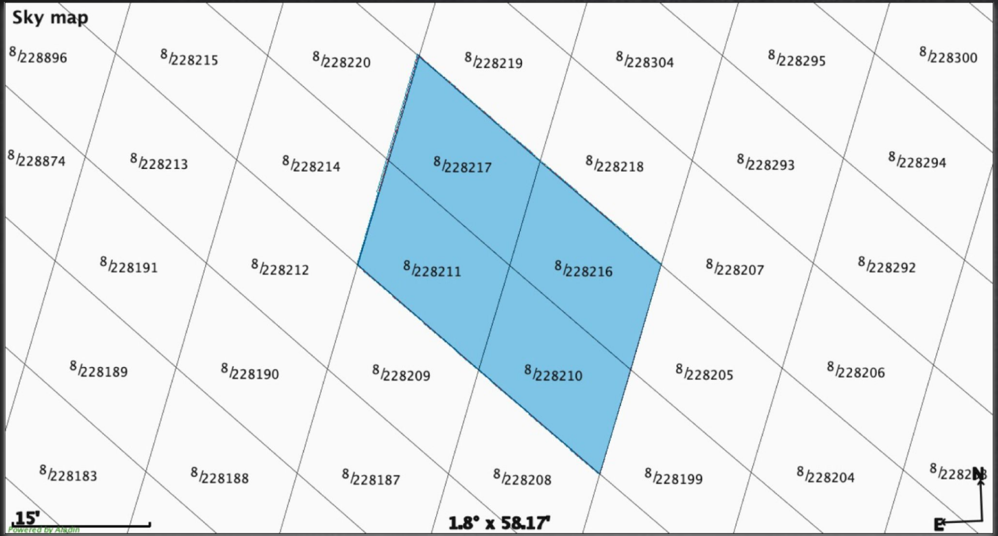
Multi-Order HEALPix Map implementation in CDS HEALPix Rus

Multi-Order HEALPix Maps (MOMs) are kind of MOCs in which a va
boolean values. An example of application is (chi2) compressed den
the choices made in the Rust implementation, and how MOC, BMOC
Frequency), and operations performed from streamed inputs, thanks

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

We present an experimental discussion on how to optimize IVOA MOC standards for the use in multimodal generative AI. A basic tutorial is provided to initiate discussions, with a focus on skymap encoding.

Multi Order Coverage Map



Json and FITS serializations

$$\{"order" : [npix, npix, \ldots], "order" : [npix, npix \ldots], \ldots\}.$$

$$uniq = 4 \times \left(4^{order}\right) + npix$$

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

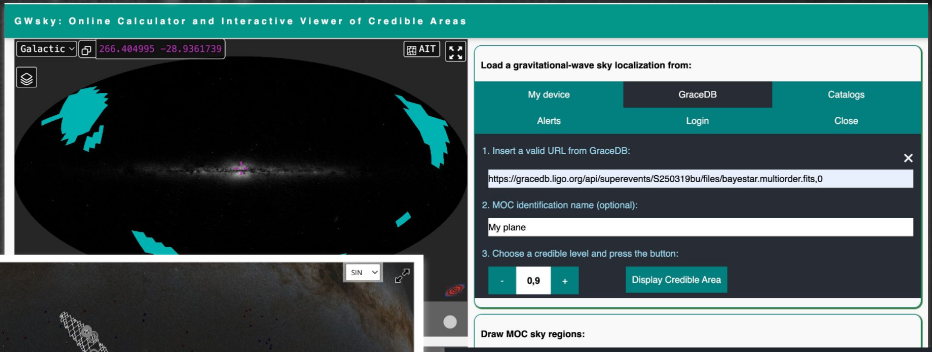
HEALPix divides the sky into curvilinear quadrilaterals, starting with twelve base pixels. Each pixel can be subdivided into four, increasing the resolution.

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

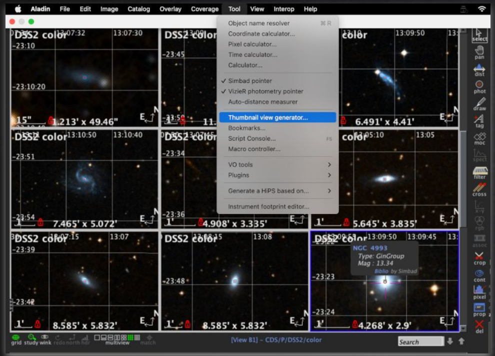
Using this hierarchical system, MOC efficiently represents complex sky regions and supports various astronomical applications (*Fernique et al, 2014*).

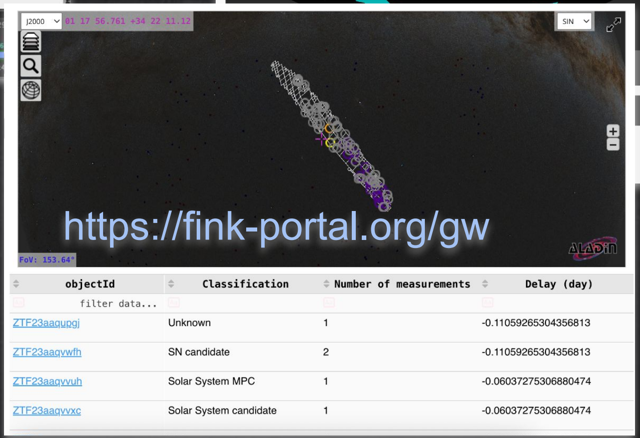
Multi Order Coverage Map in LL/MMA

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

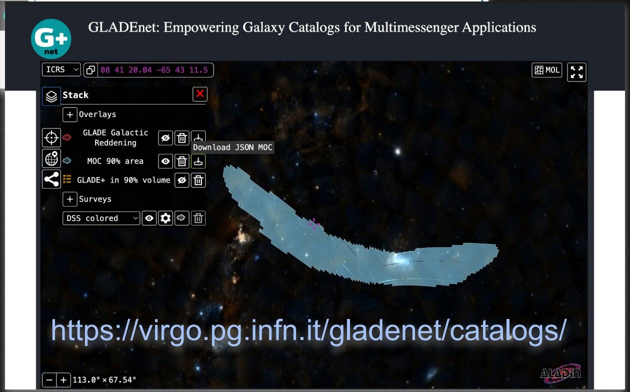


see Poster section





https://fink-portal.org/gw



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

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

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

Experimental Standards

Text and Semantic MOCs

Encoding sky regions and textual piece of information for simultaneously semantic and sky space operation – including multimodal Generative AI.

Basic JSON structure of a Space MOC

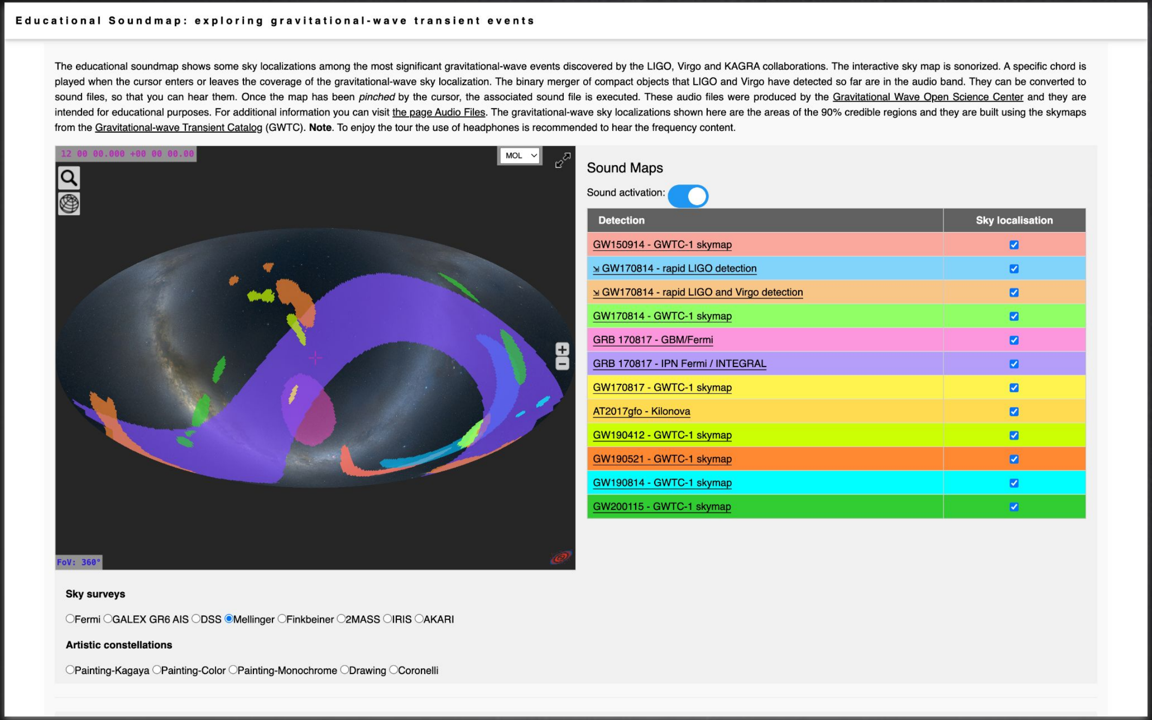
```
{
  "order_n": [npix_i | where npix_i uniquely
      defined integers],
  // ... continue for other orders ...
}
```

Adding new entries in the JSON MOC serializations

```
"text": "Your textual description here",
“multimedia” : “URL”
```

TEXTUAL MOC

Building Basic AstroGame: Sound GW skymaps



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

This educational soundmap showcases some of the most significant sky localizations of gravitational-wave events discovered by the LIGO, Virgo, and KAGRA collaborations.

The interactive sky map is enhanced with sound: a specific chord plays when the cursor enters or exits a gravitational-wave localization area.

Binary mergers of compact objects detected by LIGO and Virgo fall within the audible frequency range and can be converted into sound files.

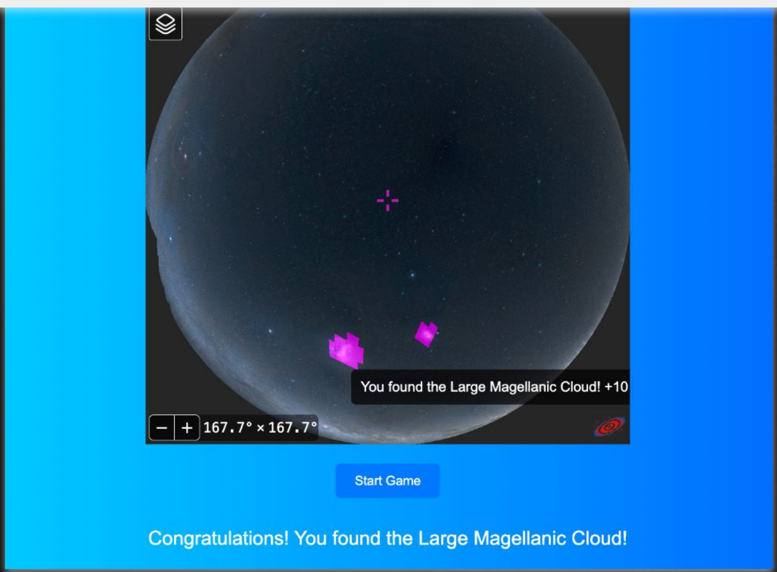
When a localization on the map is selected, the corresponding audio—produced by the Gravitational Wave Open Science Center—is played for educational purposes.

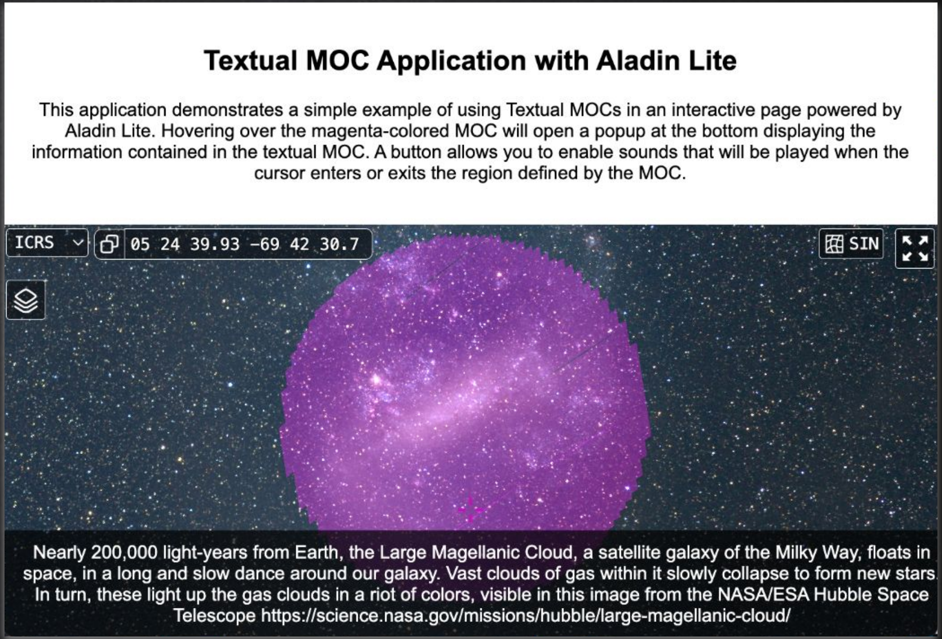
The highlighted sky areas represent 90% credible regions, based on skymaps from the Gravitational-wave Transient Catalog (GWTC).

TEXTUAL MOC

Building Basic AstroGame: Finding Galaxy and discovery objects

An interactive game using Textual MOCs within Aladin Lite helps users locate the Large Magellanic Cloud (LMC). The magenta-colored MOC marks the position of the LMC, and informational popups provide feedback as the user interacts with the map. Auditory cues enhance the user experience by signaling correct or incorrect selections.

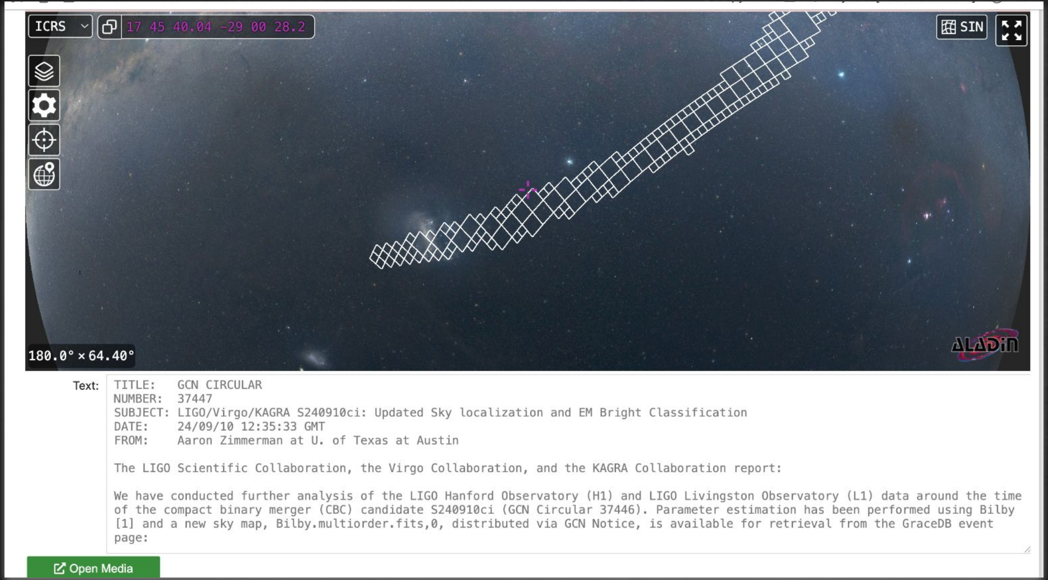




Tutorial code is provided with the associate article: Encapsulating Textual Content into MOC data Structure for Advanced Applications

TEXTUAL MOC

GW Skymap and GCN Circ.

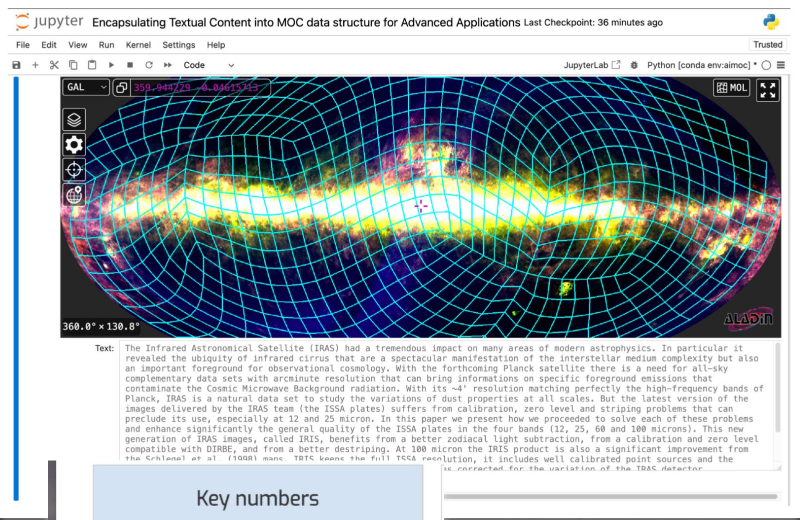


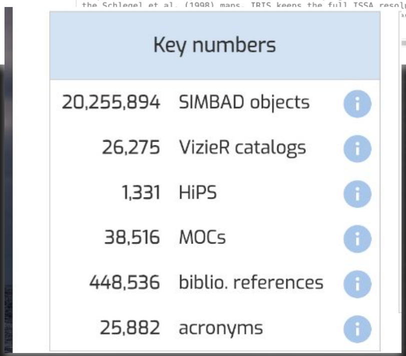
This use case shows how to display the 90% credible region of a gravitational-wave sky localization alongside LVK alerts via the General Coordinates Network (GCN). GCN Circulars are accessed in text or JSON format. Building on the method by Greco et al. (2022b), we enhance sky maps with Textual MOCs, linking each sky region with its related GCN Circular(s).

Other astronomical platforms can be utilized for the creation of Textual MOCs, such as the General Coordinates Network (GCN)10, the Transient Name Server (TNS) (Gal-Yam, 2021), the Astrophysical Multimessenger Observatory Network (AMON) (Ayala Solares et al., 2020) and follow-up pointings in the Gravitational Wave Treasure Map (Wyatt et al., 2020).

TEXTUAL MOC

MOCserver enables textual MOCs enriched with high-quality metadata curated by archival experts.





MOCserver, a server specifically dedicated to MOCs. In our context, this is particularly valuable as it allows us to create textual MOCs with metadata curated by archival scientists, ensuring both accuracy and reliability.
This service can be accessed remotely through an HTTP API. Additionally, a Python module is available on GitHub as part of the astroquery providing a convenient interface for integrating this functionality into Pythonbased workflows.

MOC-Set: A Local Mini-Server for MOC Management

Part of the cds-moc-rust library, MOC-Set allows users to manage MOC collections locally in a single binary file. It supports efficient querying, updating, and organization without relying on multiple FITS files. MOC-Set offers the foundational capabilities of a mini-server, mirroring centralized MOCserver features but at a more manageable scale. For setup and advanced features, see the official MOC-Set repository.

https://alasky.cds.unistra.fr/MocServer/query

Semantic MOC

Embedding

Textual MOCs are converted into semantic embeddings, which are compact numerical representations that encapsulate the meaning of the text within a multidimensional geometric space.

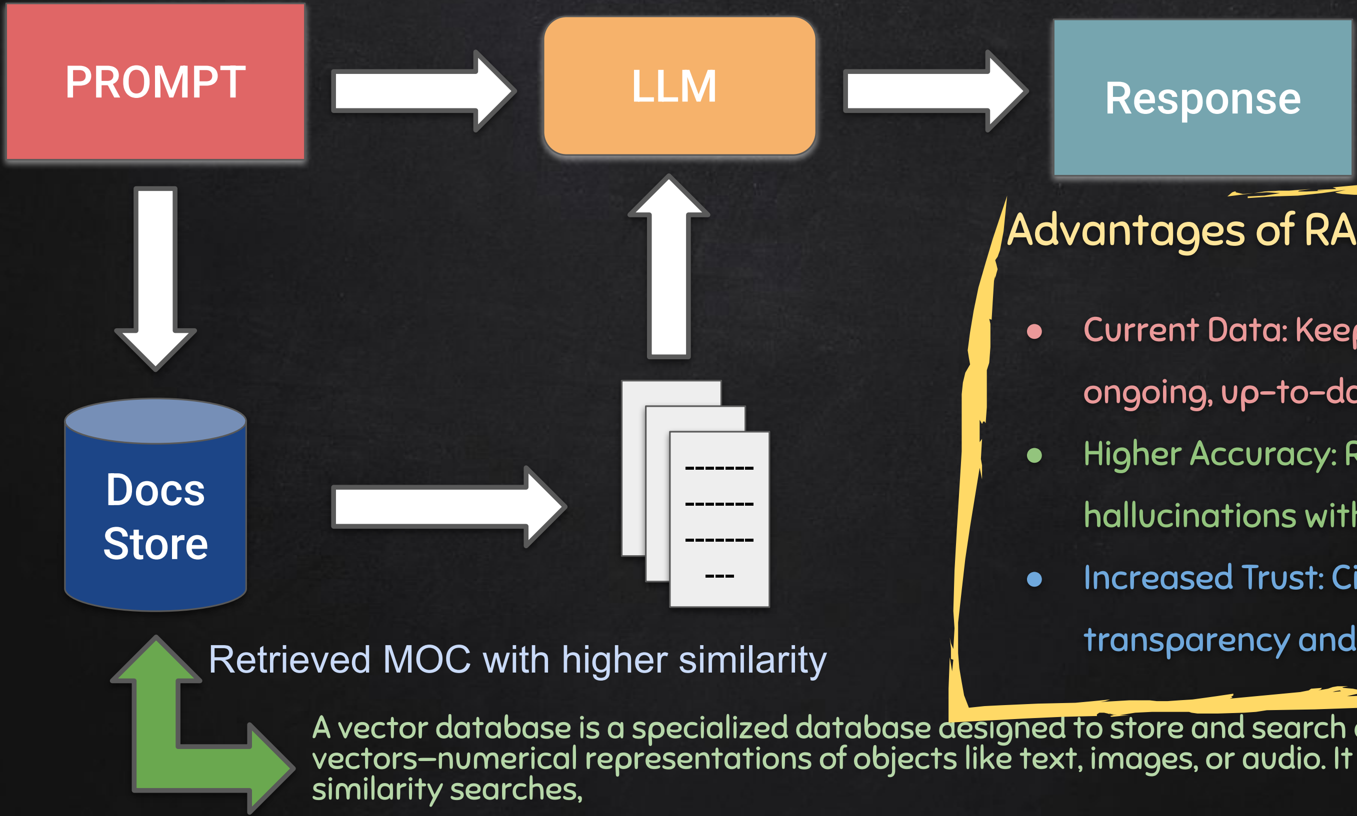
```
textual_moc.embedding_from_custom_text(embeddings_model="embedding model chosen")
```

The embedding field contains the numerical vector representation of the text, generated through a chosen text vectorization technique, encoding the semantic meaning in a compact form suitable for computational analysis. The model entry specifies the embedding model used to generate the vector representation.

```
"embedding": [text vectorization],
“model” : selected embedding model
```

Semantic MOC

Semantic MOC access using natural language prompts with Vector DB and RAG.



Advantages of RAG

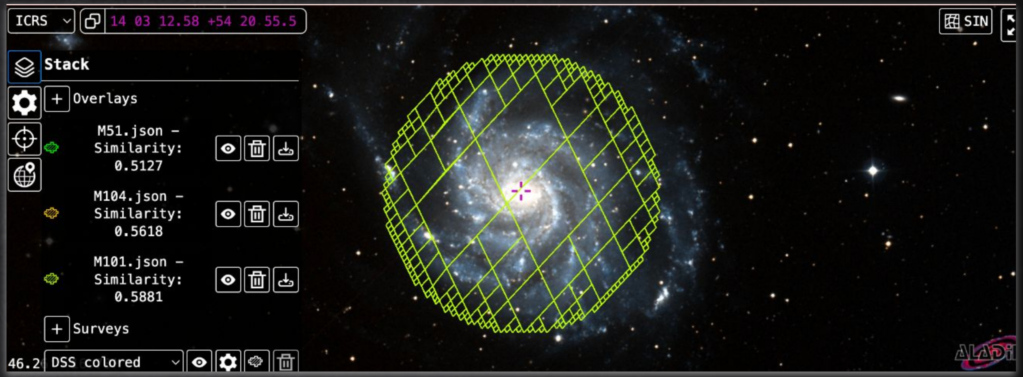
- Current Data: Keeps LLMs updated with ongoing, up-to-date relevant information.
- Higher Accuracy: Reduces errors and hallucinations with reliable data sources.
- Increased Trust: Citing sources fosters transparency and user confidence.

A vector database is a specialized database designed to store and search data represented as vectors—numerical representations of objects like text, images, or audio. It allows fast and efficient similarity searches,

Semantic MOC

Retrieve spatial, semantic, and visual data in a unified operation.

Figure shows the integration of a Retrieval-Augmented Generation (RAG) system within the ipyaladin visualization interface. The system retrieves and presents the most relevant information for astronomical objects, directly overlying the results onto the interactive sky visualization. Additionally, the similarity scores computed by the RAG system are clearly displayed alongside each astronomical object, enabling users to immediately evaluate the relevance and accuracy of the provided responses.



We optimize the use of these technologies by building a vector-based approach for storing the textual part of MOC files while simultaneously indexing their spatial attributes. This enables queries that seamlessly integrate semantic and spatial information.

Semantic MOC

Multimodal using HiPS

```
vision_llm = ChatOllama(model="llama3.2-vision", temperature=0)
```

```
prompt: str = "Does this image indicate possible interactions with a nearby galaxy? Do a short comment"
```

To enable models with vision capabilities in the context of the Semantic MOC, we add the image field optionally links a astronomical image. In this scenario, the hips2fits server is used to retrieve astronomical images through direct URL parsing, thus ensuring rapid and uniform data access. These images are appropriately referenced, each supported by a comprehensive and specific bibliography.

```
"image": "HIPS2FITS URL",
```

https://alasky.cds.unistra.fr/hips-image-services/hips2fits

===========================

🔭 VISION MODEL RESPONSES (llama3.2-vision):

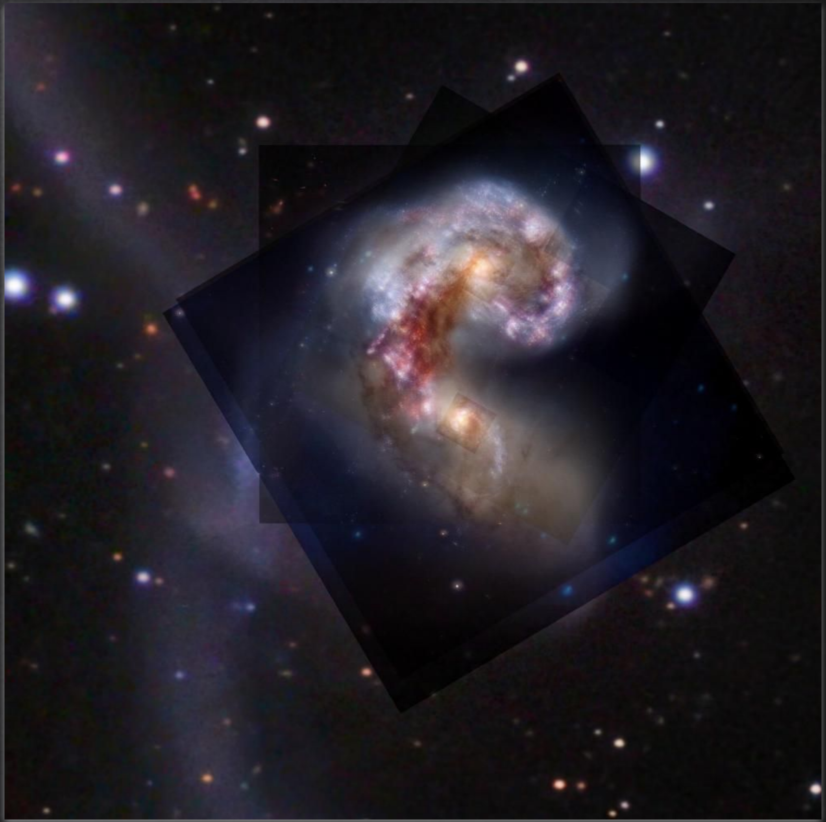
===========================

File: NGC_4038_4039.json

Vision Model Output: The image shows two galaxies in close proximity to each other, which could indicate that they are interacting or merging. The presence of distorted shapes and irregular features suggests that the galaxies may be experiencing gravitational forces from one another, leading to changes in their structure and composition.

⚠️

The verification of the validity of the multimodels is beyond the scope of this work, which solely illustrates how IVOA standards and tools can be used in the multimodal generative AI systems (training, fine tuning, RAG, CAG ecc)

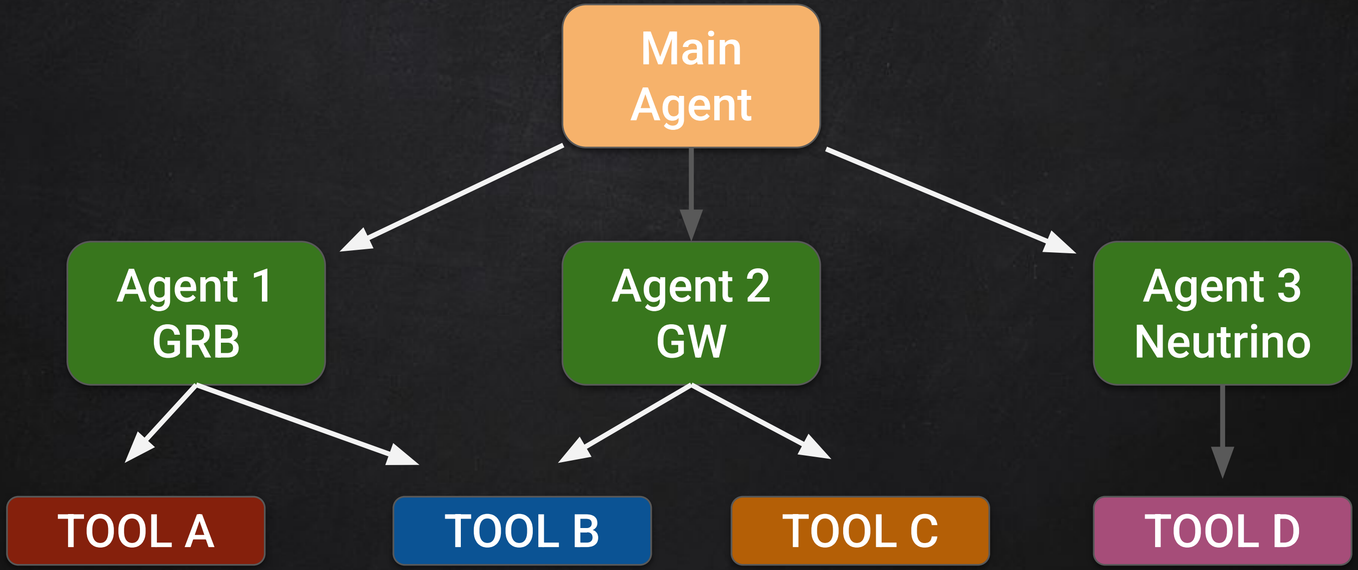


HiPS2FITS

https://alasky.cds.unistra.fr/hips-image-services/hips2fits?hips=CDS%2FP%2FHST%2FEPO&width=1000&height=1000&fov=0.1&projection=SIN&coordsys=icrs&rotation_angle=0.0&ra=180.4790760656&dec=-18.884864677&format=jpg

Towards AI (Skymap) Agentic Applications

Semantic MOCs provide a Structured Data Formats, making them well-suited for developing <u>multi agent-based applications.</u> These can be integrated into various multi-messenger activities in the Einstein Telescope era, enabling the evaluation of coincident events and the autonomous generation of alerts.



Tools based on mocpy for making MOC Operations

Key Challenges of Multi-Messenger Astronomy with ET

High Alert Volume: Massive number of GW triggers during inspiral and mergers requires scalable computing and real-time event management.

Dynamic Databases: Efficiently track and update a large number of transient candidates for prompt dissemination to the astronomy community.

Automated Prioritization: Events should be ranked automatically based on parameter estimation accuracy and scientific relevance.

EM Alert Listening Capability: ET should be able to receive and process alerts from electromagnetic , neutrino and high-energy gamma-ray observatories to identify spatial-temporal coincidences.

Signal Overlapping: Superimposed signals require innovative detection methods and integrated spatial-temporal analysis strategies.

Managing Large Custom Catalogs: Handling dedicated, massive catalogs to support counterpart searches.

Interoperability & FAIR Principles: Success depends on open standards enabling data sharing across diverse infrastructures.

Global Coordination & Standardization: Collaboration between observatories is essential to define protocols and support cross-domain integration.

To make all this happen!

MOC text and Semantic Tutorial

Encapsulating Textual Content into MOC data structure for Advanced Applications

The notebook is associated to the submitted paper **Encapsulating Textual Content into MOC data structure for Advanced Applications**. The notebook outlines the basic functionalities of a new approach that integrates textual descriptions directly into the JSON representation of MOC, enabling simultaneous semantic and spatial operations. After demonstrating some basic applications and its potential use for educational gamification, we will later showcase its applicative capabilities in generative AI (GenAI).

Version 0.0.2 - February 2025

The notebook is divided into the following sections.

Basic Methods for Handling Textual MOCs

Here are some basic applications of the **Textual MOC**, which enhances ordinary MOCs by encapsulating textual content. The `TextualMOC` class is designed to interact with a Multi-Order Coverage (MOC) object, enabling serialization, modification, and extension of MOC data with additional textual descriptions and multimedia links. The `__init__` method initializes the TextualMOC class with an optional MOC object. If a MOC object is provided, it is serialized into JSON format. Additionally, an `ipyaladin` widget is initialized for later use in visualizing the MOC.

For using methods that transform textual content into semantic embeddings, we recommend installing and running Ollama - https://ollama.com/.

The complete list of methods is provided below.

```
[1]: # Importing the necessary libraries
```

A tutorial will be published soon to encourage discussion, feedback, and new ideas.

Conclusions

- Standardization also impact the computing resources and capabilities required for low-latency and multi-messenger activities (LVK example about skymap production).

- ET MMA low-latency will provide real-time alerts but also support approaches to set real time strategies: tiling credible regions, catalog filtering, metadata to prioritize the observations, fast space and time operation between GW/neutrino/high energy alerts.

- The goal is not to develop a single tool, but to build standard libraries—similar to today's approach, where many MMA tools rely on VO technologies with distinct features. Full MMA tool coordination could be required, but full coordination in standardization is critical: a well-established best practice in astronomy remains the coordination around metadata and the development of shared standards.

- Even though all of this will unfold over the next decade, it is reasonable to expect that Generative AI (GenAI) will play a key role.

⌛ A ten-year timeframe may appear quite long, but considering the complexity of establishing standardized protocols, fostering cross-domain synergies, developing interoperable infrastructures, and assessing the role and impact of GenAI technologies, it is in fact rather constrained. <u>Early and coordinated action is essential.</u>