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Localizations of electromagnetic counterparts and gravitational-wave signals: a new Python plug-in for Aladin

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Abstract. We describe a new plug-in for the Aladin Desktop software to analyze 3D sky maps of gravitational-wave sources. Aladin is the most used VO (Virtual Observatory) software for digitized astronomical images and gravitational-wave sky maps visualizer. Extending its functionalities is challenging and helps in developing astronomical technical standards, as IVOA (International Virtual Observatory Alliance) promotes.

Here, a Python algorithm has been developed to allow any Aladin user to immediately receive information about the probability distributions of having a gravitational-wave source along a line of sight in any given position of the sky map, just by clicking on that pixel.

1. Introduction

On 14 September 2015, the LIGO and Virgo Collaborations (LVC) detected a gravitational -wave (GW) transient, GW150914 (Abbott et al. 2016), for the first time in history. A binary black hole (BBH) merger was observed and no confirmed electromagnetic (EM) nor particle emission have been associated with the phenomenon, according to the popular theoretical expectations (Abbott et al. 2016). Remarkably, the first discovery of gravitational waves from the coalescence of two neutron stars in a binary system, GW170817 (Abbott et al. 2017a), happened during the second observational run of LVC (Abbott et al. 2019). The identification of its electromagnetic counterpart, GRB170817 / AT2017gfo, has ushered the science community in the era of multi-messenger astronomy (Abbott et al. 2017b).

With the ongoing urgent request of efficient multi-messenger tools, the role of the Virtual Observatory (VO) appears to be fundamental. VO is the quickest solution to astronomical imaging and data elaboration, led by the International Virtual Observatory Alliance[1] (IVOA).

[1]https://ivoa.net/about/what-is-vo.html

IVOA (Berriman et al. 2022) encourages the development of technical standards to ease astronomical research projects, to promote the VO and *science platforms* and their open sharing methods (Allen et al. 2004).

The purpose behind this paper is to illustrate a new algorithm which extends the functionalities of the Aladin Desktop software (Bonnarel et al. 2000). To date, the VO standards are not designed to manage 3D sky localizations for gravitational wave sources[2]. Here, an interactive approach is proposed. Just by clicking on whichever pixel on the sky map, our plug-in shows the probability of having a gravitational-wave source along a line of sight.

2. 3D Volume Reconstruction

All sky images produced by the pipelines that analyze gravitational-wave data, taken by the Advanced LIGO (The LIGO Scientific Collaboration 2015) and Virgo (Acernese et al. 2014), are stored using the HEALPix (Hierarchical Equal Area isoLatitude Pixelation) tessellation (Górsky et al. 2005). Each pixel represents a specific value ρ of the 2D posterior probability of having a gravitational-wave source in that position of the sky.

Furthermore, Singer et al. (2016a) developed a rapid algorithm for obtaining joint 3D estimates of sky location and luminosity distance from observations of binary compact object mergers. That means, we can derive the probability that a source is within a pixel at a certain distance.

The plug-in described here makes use of the new HEALPix-based file format for 3D localizations of gravitational-wave transients (Singer et al. 2016b).

3. Aladin software and SAMP protocol

Aladin is a VO tool, based on Java technology, developed at the Centre de Données astronomiques de Strasbourg (CDS), to provide an interactive sky atlas (Bonnarel et al. 2000). Aladin is regularly updated to be compatible with existing or emerging VO standards[3]. The user-friendly graphical user interface is shown in the left panel of Figure 1.

Aladin is also designed to implement a mechanism for connecting to other independent applications in order to interoperate with all the available VO software, furnishing a complete data analysis.

The interoperability between different tools is achieved through use of the SAMP (Simple Application Messaging Protocol) (Taylor et al. 2012). SAMP has an hub based architecture, in which each VO software is associated to a *client* identification. To collaborate, clients have to register to the same hub. Through SAMP, Python tools can exchange data and execute commands with other running desktop clients, thanks to the implementation *astropy.samp* module[4] from *astropy* library Astropy Collaboration (2013).

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

[3]https://aladin.u-strasbg.fr/java/nph-aladin.pl?frame=downloading

[4]https://docs.astropy.org/en/stable/samp/index.html

4. The plug-in: concept and design

The plug-in provides dedicated plots and interactive visualizations to manage a 3D gravitational-wave source localization.

Just by clicking on whichever spot of a gravitational-wave sky map, an interactive window displays the conditional distance distribution along a line of sight and the probability density per unit distance integrated over the entire sky. Figure 1 shows the final result.

The algorithm relies on the SAMP messaging connections to enable Python environment and Aladin to communicate with each other by exchanging dedicated Aladin script commands[5] and information contained in the file header of the gravitational-wave sky localization from LIGO, Virgo and KAGRA collaborations.

The GUI (Graphical User Interface) is created using the Tkinter module[6] in which a `Matplotlib` (Hunter 2007) figure is embedded.

The complete code is reported in a public GitHub repository, in which a Jupyter Notebook, including all of the Python modules necessary for this analysis, is provided.[7].

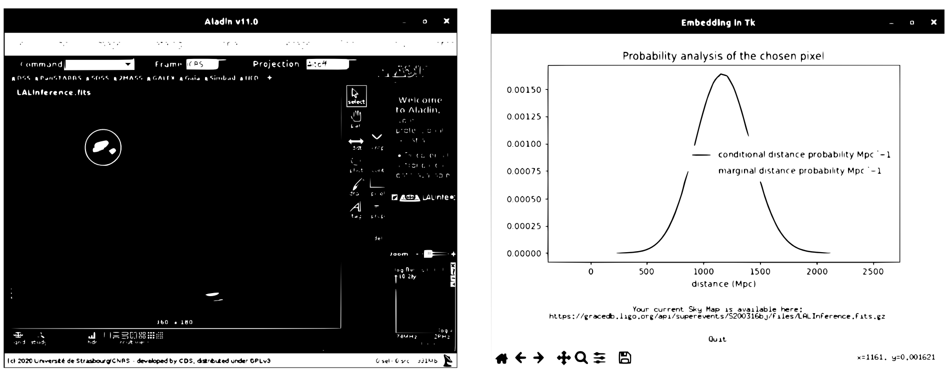

Figure 1. *Left:* A gravitational-wave sky localization, issued by the LIGO, Virgo and KAGRA Collaborations, is visualized in the Aladin Desktop. The clicked position is highlighted by a light blue circle and a purple pointer. *Right:* As one clicks on a spot, a pop-up window is shown up, plotting, in blue, the probability density per unit distance integrated over the entire sky and, in orange, the conditional distance distribution along a given line of sight.

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[5] https://aladin.u-strasbg.fr/java/AladinScriptManual.gml

[6] https://docs.python.org/3/library/tkinter.html

[7] https://github.com/ariannabartolomei

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