

# GLADEnet : a progressive Web App for Multi-messenger Cosmology

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# GLADEnet role in the multi messenger context

## Why GLADEnet ?

- **Localization problem:** big 3D volumes for GW events, a lot of possible galaxies
- **Big deal** for GW+EM events (*Standard Sirens*) and a really **big problem** for GW events only (*Dark Standard Sirens*)
- Rapid and effective follow up campaign (also with narrow field view telescopes)

**Multi-  
messenger  
Issues**

- **Catalogs are important:** use the *Catalog-Based Search* to reduce the observing region
- Galaxies targeting for multi messenger purposes
- With GLADEnet **we visualize in real time** the GLADE+ completeness in the 3D sky locations
- Promote dedicated campaigns to **increase** catalogues completeness
- Calculate **Hubble's constant** in *dark standard sirens* case

**Improvements**

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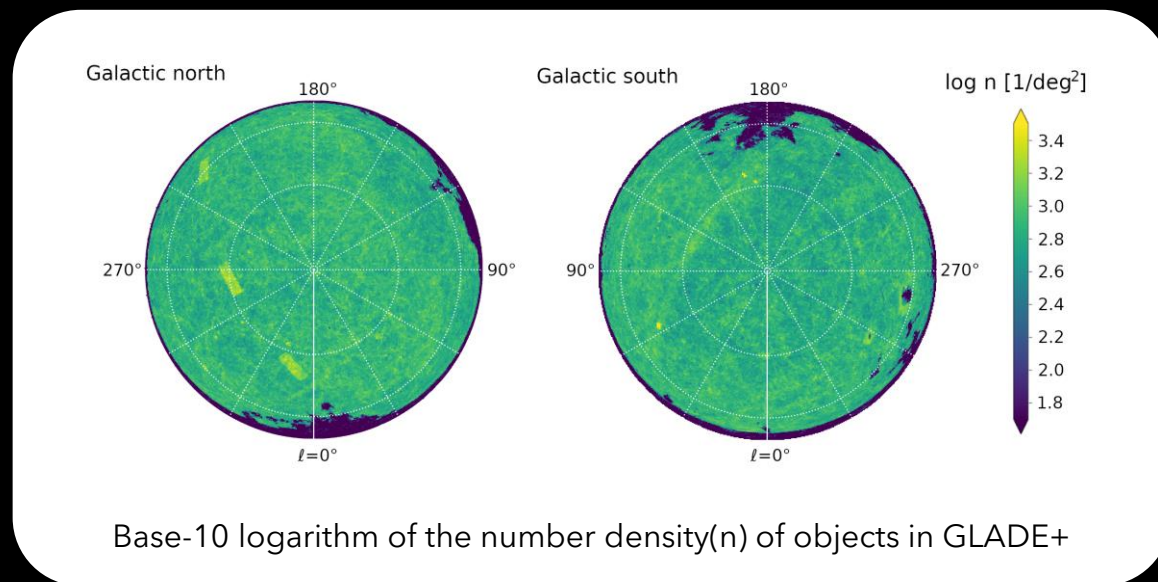
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**Improvements**

# GLADE+ galaxy catalogue

- GLADE+ is the last version of the GLADE catalogue (**G**alaxy **L**ist for the **A**dvanced **D**etector **E**ra) developed by Dàlya et al.
- Includes ~22,5 million **galaxies** and ~ 750 thousand quasars
- The latest version is formed by **cross-matching** six different astronomical catalogues: GWGC, 2MPZ, 2MASS XSC, HyperLEDA, WISExSCOSPZ and SDSS-DR16Q
- GLADE+ is **complete** up to  $d_L = 47^{+4}_{-2}$  Mpc (cumulative B-band luminosity) ----->

*Dàlya, G., Galgóczi, G., Dobos, L., et al. 2018*



It contains all of the brightest galaxies contributing to 90% of the total B-band luminosity up to  $d_L \cong 130$  Mpc

# Schechter function parameters evaluation

Schechter proposed a model for a galaxy number density in a given comoving volume with a given luminosity

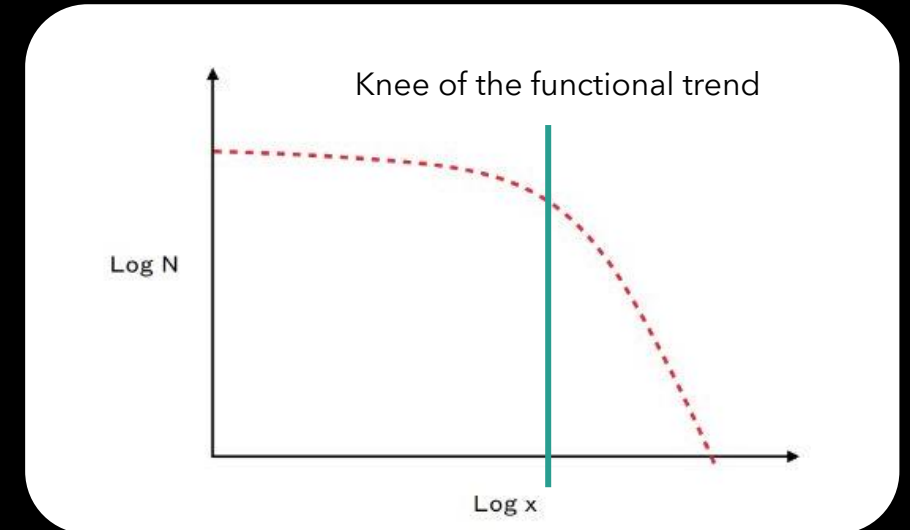
↓  
**Schechter function**

$$\phi = \rho_{\text{gal}} dx = \phi^* x^\alpha e^{-x} dx$$

$\phi^*$  : normalization factor

$$x = L/L_B^* \quad \text{with} \quad [L_B^*] = 10^{10} h^{-2} L_{B,\odot}$$

↓  
characteristic luminosity where the power-law truncates



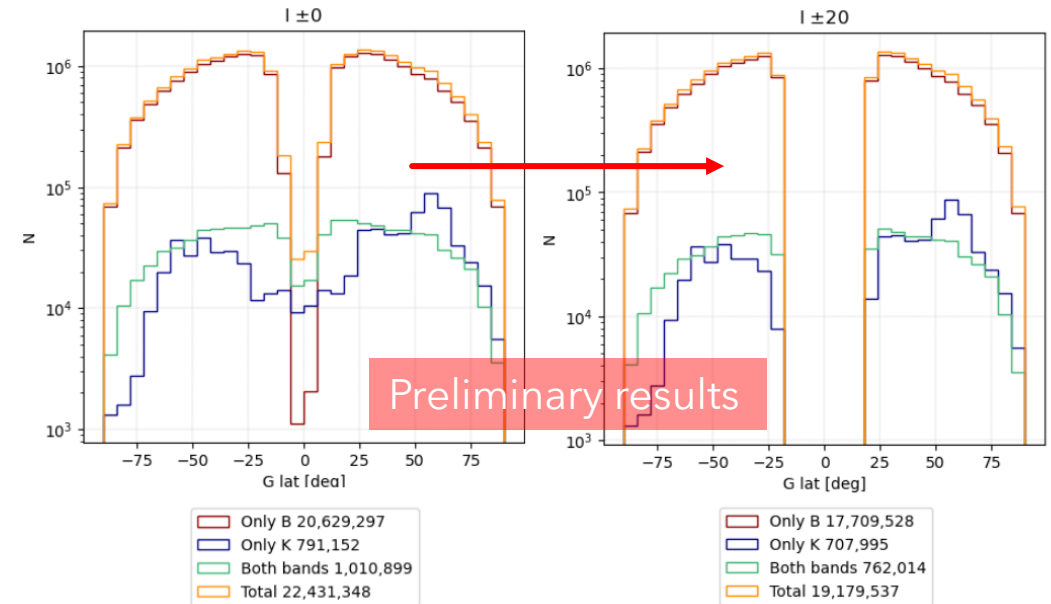
From luminosity to absolute magnitude :  $\Phi(M) = 0.4 \ln_{10} \left( 10^{0.4(M^* - M_i)} \right)^{(\alpha^* + 1)} e^{-10^{0.4(M^* - M_i)}}$  ( $M_i^*$ : absolute magnitude)

Parameters we need to fit :

$$M_{GLADE+}^* \quad \alpha_{GLADE+}^* \quad \phi_{GLADE+}^*$$

# Schechter function parameters evaluation

- Galactic Plane latitudes **cut off**:  $|b| > 20^\circ$
- Three **volume shells**: 25, 50, 75 Mpc
- Only B-band magnitude selected
- Curve\_fit* method from Scipy library



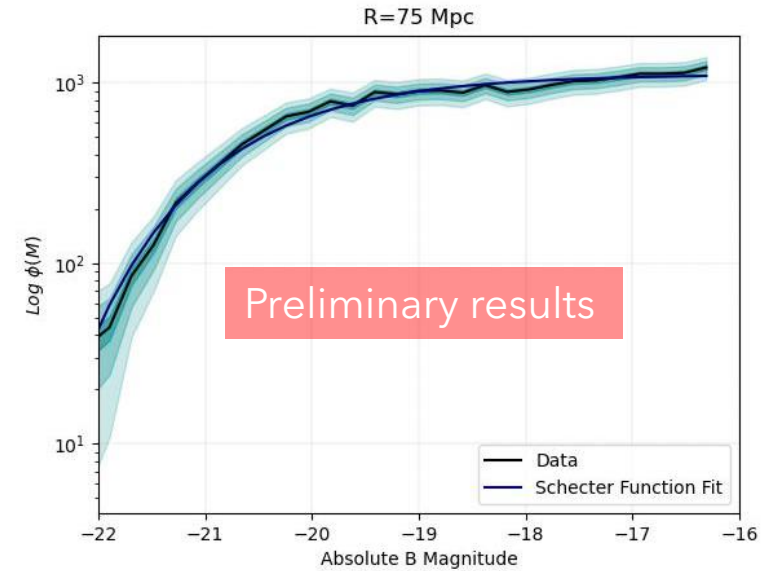
M.L. Brozzetti et al.: GLADEnet: a progressive web app for multi-messenger and follow-ups (under submission)

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## Parameters evaluation



Schechter function fitting for GLADE+ up to 75 Mpc. B-band filter. The galaxy distribution is in black with  $1\sigma$ ,  $2\sigma$  and  $5\sigma$  error bands in light blue.

Bands	$\phi^*$ [ $h^3 \text{ Mpc}^{-3}$ ]	$\alpha^*$	$M^*$ [mag]
<b>B</b> (our work)	$(1.69 \pm 0.38) \times 10^{-2}$	$-1.03 \pm 0.03$	$-20.59 \pm 0.08$
<b>B</b> (Gehrels et al.)	$(1.6 \pm 0.3) \times 10^{-2}$	$-1.07 \pm 0.07$	$-20.47$

M.L. Brozzetti et al.: GLADEnet: a progressive web app for multi-messenger and follow-ups (under submission)

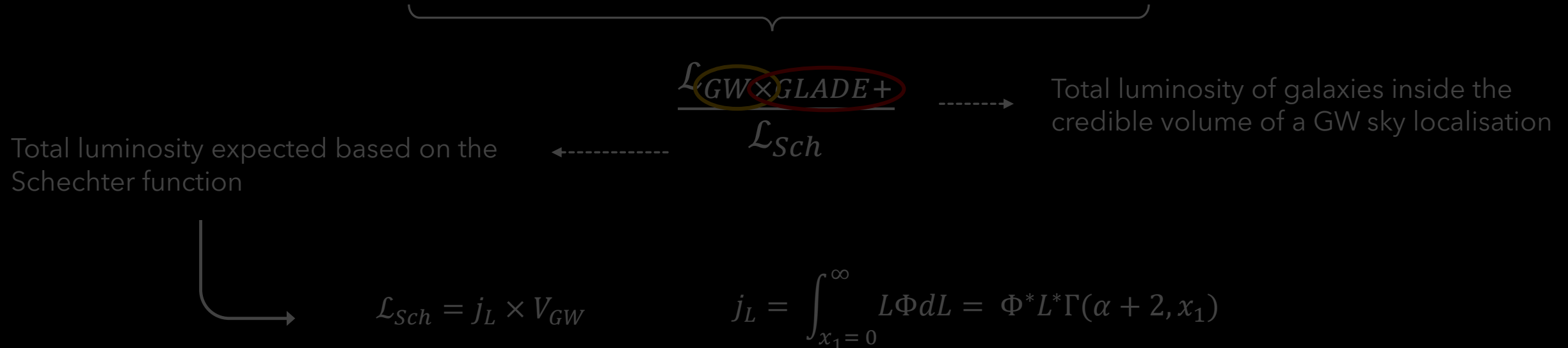
# The Completeness Coefficient $\mathcal{C}$

## GW event signal

- 3D skymap credible volume with  $dP/dV < 90\%$
- Different waveform models (SEOBN, PHENOM, Mixed...)
- Data from GWTC-1, GWTC-2.1 and O4 alerts

## Cross match with GLADE+

- Number of galaxies in the credible volume
- Summing the  $L_B$  of each galaxy in the 3D gw event





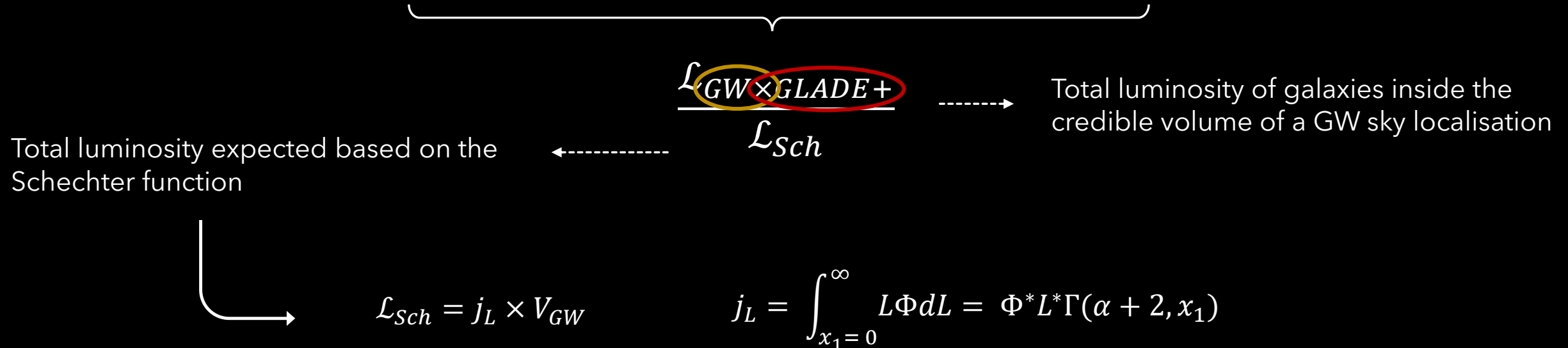
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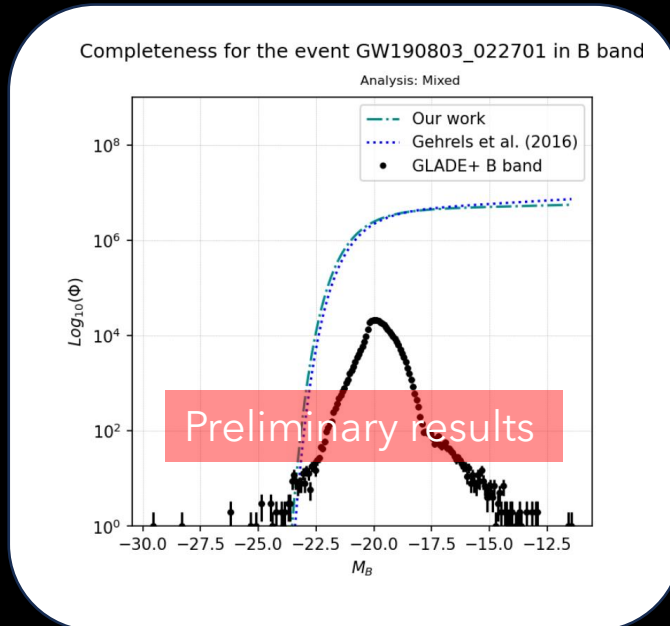
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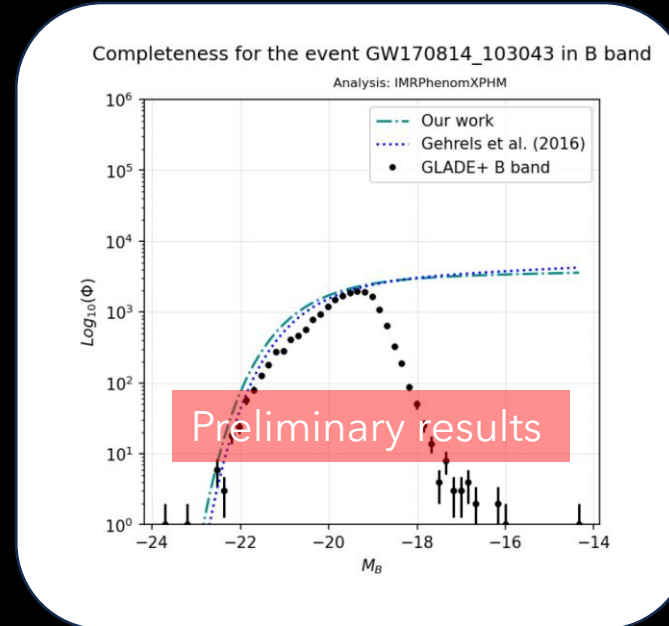
# The Completeness Coefficient $\mathcal{C}$

For each event GLADEnet computes the completeness of the catalog in that precise localization volume and gives the relative plot to the user

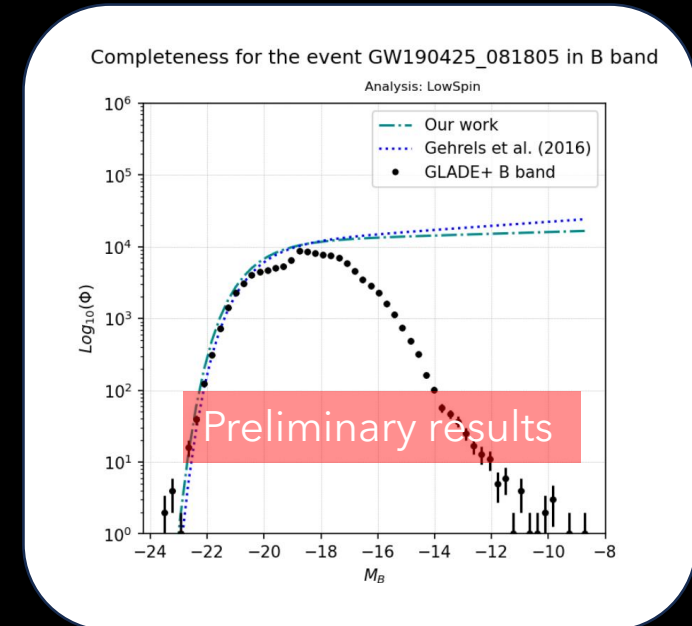
Result of our work :



Volume [Mpc<sup>3</sup>]:  $1.16e^{+10}$   
 $\mathcal{C}$  :  $3.30e^{-03}$



Volume [Mpc<sup>3</sup>]:  $3.80e^{+06}$   
 $\mathcal{C}$  :  $4.99e^{-01}$



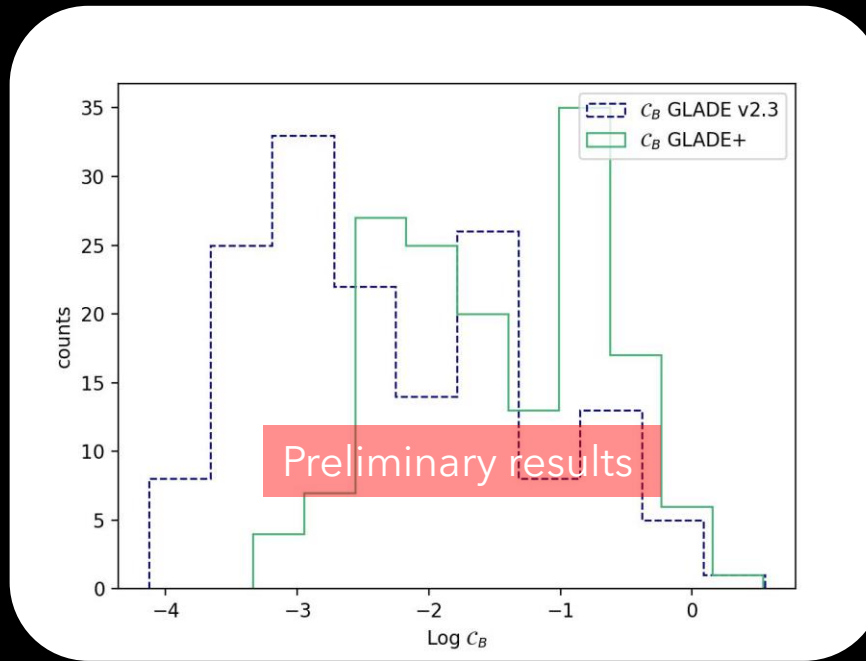
Volume [Mpc<sup>3</sup>]:  $9.03e^{+06}$   
 $\mathcal{C}$  :  $6.98e^{-01}$

*M.L. Brozzetti et al.: GLADEnet: a progressive web app for multi-messenger and follow-ups (under submission)*

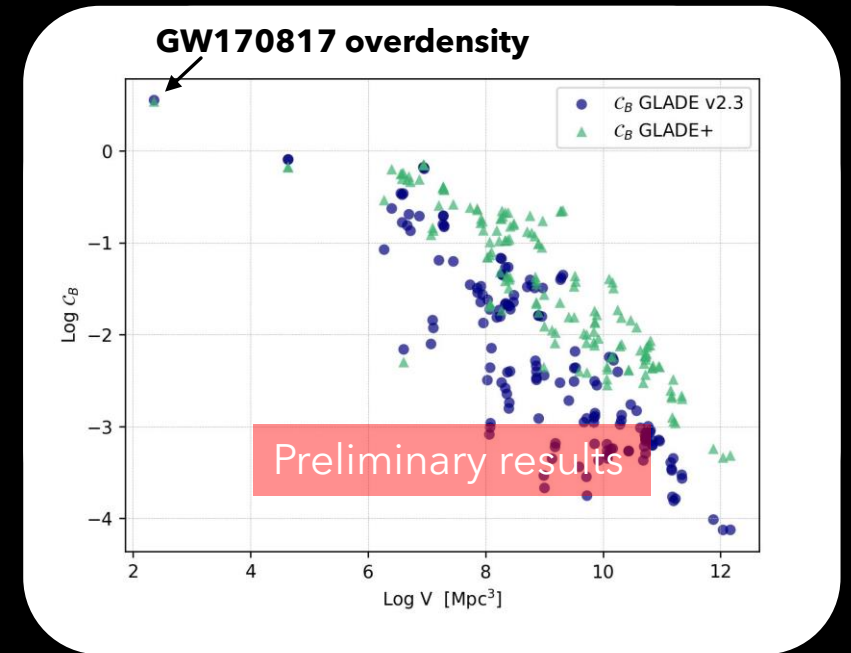
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M.L. Brozzetti et al.: GLADEnet: a progressive web app for multi-messenger and follow-ups (under submission)

Result of our work :



Completeness coefficient distribution for GLADE+ and the previous version GLADE v2.3



Scatter plot of  $\mathcal{C}_B$  dependency on localization volume for GLADE+ and GLADE v2.3

GLADE v2.3  
 $\mathcal{C} \sim 10^{-4}$        $\longrightarrow$       GLADE+  
 $\mathcal{C} \sim 10^{-3}$

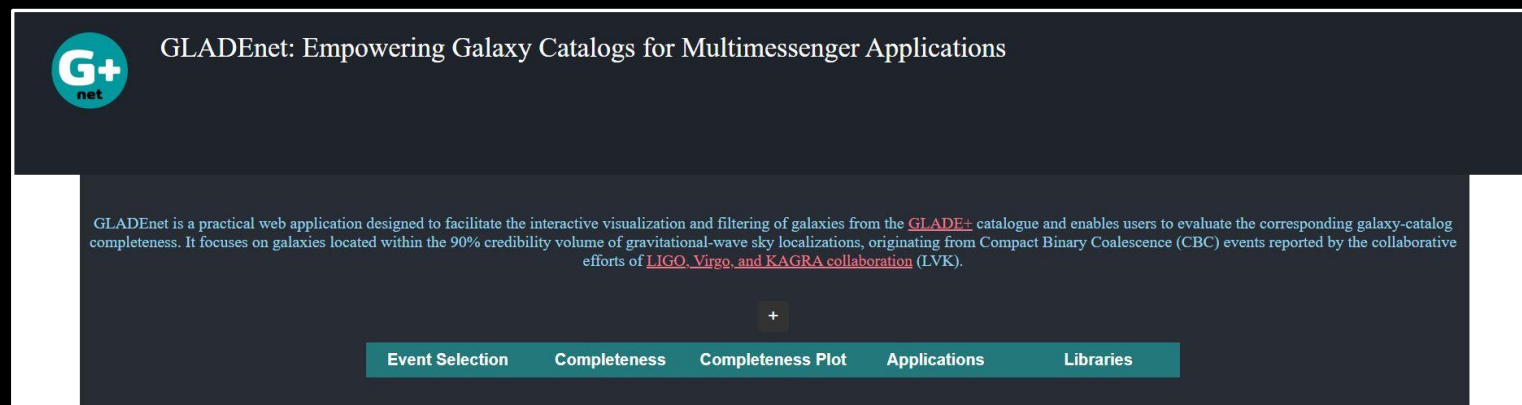
Completeness decrease as the volume  
(and so the distance) increase

# GLADEnet – web App

A Progressive Web App with **REACT JS** and the **Virtual Observatory** standards



- ReactJS is a declarative, efficient, and flexible **JavaScript library** for building reusable UI (User Interface) components.
- It is an **open-source**, component-based front end library. It was initially developed and maintained by Facebook and later used in products like WhatsApp, Instagram, Netflix etc.
- It looks very **promising to create MMA applications** for push notifications in connection with the NASA GCN



# GLADEnet – web App



## GLADEnet: Empowering Galaxy Catalogs for Multimessenger Applications

GLADEnet is a practical web application designed to facilitate the interactive visualization and filtering of galaxies from the [GLADE+](#) catalogue and enables users to evaluate the corresponding galaxy-catalog completeness. It focuses on galaxies located within the 90% credibility volume of gravitational-wave sky localizations, originating from Compact Binary Coalescence (CBC) events reported by the collaborative efforts of [LIGO, Virgo, and KAGRA collaboration](#) (LVK).

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Event Selection

Completeness

Completeness Plot

Applications

Libraries

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### Event Selection

GLADEnet includes a dropdown menu for event selections, which consist of two options.

If the chosen event corresponds to one from the Gravitational-Wave Transient Catalogs (GWTCS), labeled as **GW**, you can further select the waveform family used. In the case of a candidate event sent in low latency, they are denoted as **S**, and the user can choose the sequence of LVK alerts sent for that specific event.

The waveform banks used in the post-processing analysis are specified in the publications related to the Gravitational-Wave Transient Catalogs. You can find more information in [GWTC 1](#) and [GWTC 2.1](#).

The timeline of alerts issued for the gravitational-wave event candidates and the corresponding information on the source parameters released at different times with respect to the merger are fully described in the [IGWN Public Alerts User Guide](#), specifically in the [Data Analysis section](#).

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### Completeness

The Completeness coefficient  $\mathcal{C}$  is determined as the ratio of the total luminosity of galaxies inside the credible volume of a gravitational-wave sky localization,  $\ell_{\text{GW} \times \text{GLADE+}}$ , to the total luminosity expected based on the Schechter function,  $\ell = j_L \times V_{\text{GW}}$ , where  $j_L$  is the value obtained by integrating the Schechter function over luminosity.

Here, we computed the luminosity density (with the integral bounds  $x_1$  and  $\infty$ ) using the following equation:

$$j_L = \int_{x_1}^{\infty} L \Phi dL = \Phi * L * \Gamma(\alpha+2, x_1),$$

where  $\Gamma(\alpha+2, x_1)$  is the incomplete gamma function.

The Completeness coefficient,  $\mathcal{C}$ , is evaluated as:

$$\mathcal{C} = \ell_{\text{GW} \times \text{GLADE+}} / \ell$$



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**Completeness Plot**

For enhanced data visualization, we create a plot that highlights the completeness within the credible localization volumes of a gravitational-wave event. This completeness plot is presented within a dedicated resizable box upon selection from the dropdown menu.

**Plot Details:**

- Black dots represent the distribution of GLADE+ galaxies in the B-photometric band within the 90% credible volume.
- The expected Schechter function, calculated in Brozzetti et al. (A&A submitted), is displayed as a green dashed-dotted line.
- Parameters from the literature in [Gehrels et al. 2016](#), are represented by blue dots.

**Optimal Histogram Bin Width:**

To ensure accurate representation, we determine the optimal histogram bin width using [Knuth's rule](#).

Knuth's rule is a Bayesian method implemented in the [Astropy](#) library ([knuth\\_bin\\_width](#)), which helps in choosing the most suitable bin width for the histogram by considering a fixed-width approach.



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### Applications

1. **Choice of the Observational Strategy:**

GLADEnet will assist in selecting the observational strategy based on galaxy completeness. For instance, it may recommend covering the entire sky region with wide-field telescopes when the completeness coefficient is low or targeting galaxies with smaller fields of view telescopes when the completeness coefficient is high.

2. **Promotion of Punctual Surveys and Maximization of Follow-up Campaigns:**

GLADEnet can identify sky regions that are currently less observed or incomplete and suggest them as targets for survey observations to increase catalogue completeness.

3. **Uploading New Data:**

After observation campaigns to increase catalogue completeness, the new data can be uploaded directly to the VizieR data server. The VizieR catalogue upload service [VizieR catalogue upload service](#) is dedicated to this purpose. The Centre de Données astronomiques de Strasbourg (CDS) provides a full description of the standard conventions used, available at <http://cds.u-strasbg.fr/doc/catsid.htm>.

4. **Search Efficiency Estimates:**

The completeness evaluation by GLADEnet can be used to correctly estimate the probability that observed galaxies are the actual hosts of the GW source.

5. **Support the Hubble Constant Estimate:**

GLADEnet provides an appropriate evaluation of completeness, crucial for accurately evaluating the Hubble constant using dark sirens.

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### Libraries

GLADENet is developed using ReactJS. You can learn more about ReactJS at <https://react.dev/>

To obtain the galaxies within the 90% credible volume, we utilize the `crossmatch` function provided by the `ligo.skymap` library. You can find more information about the `ligo.skymap` library at <https://lscsoft.docs.ligo.org/ligo.skymap/>.

GLADENet is powered by the Virtual Observatory (VO) standard and tools supported by IVOA (International Virtual Observatory Alliance). You can learn more about the IVOA at <http://www.ivoa.net/>

# GLADEnet - web App



GLADEnet: Empowering Galaxy Catalogs for Multimessenger Applications

Select catalog (GW) or candidate event (S):

GW190413\_134308

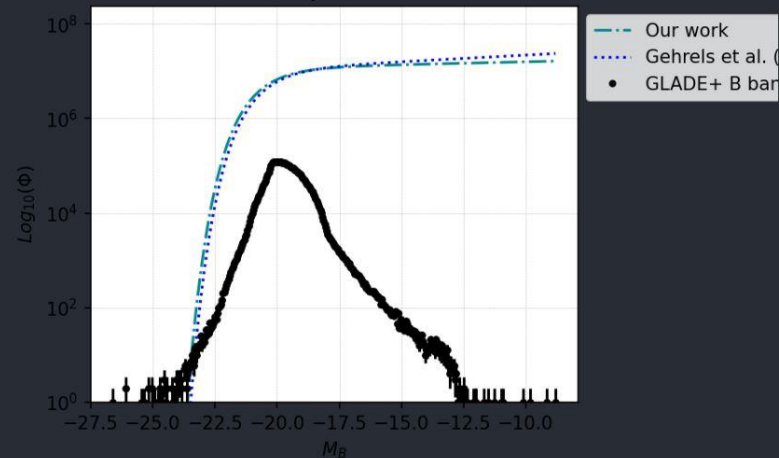
Select waveform analysis or alert type:

C01:SEOBNRv4PHM

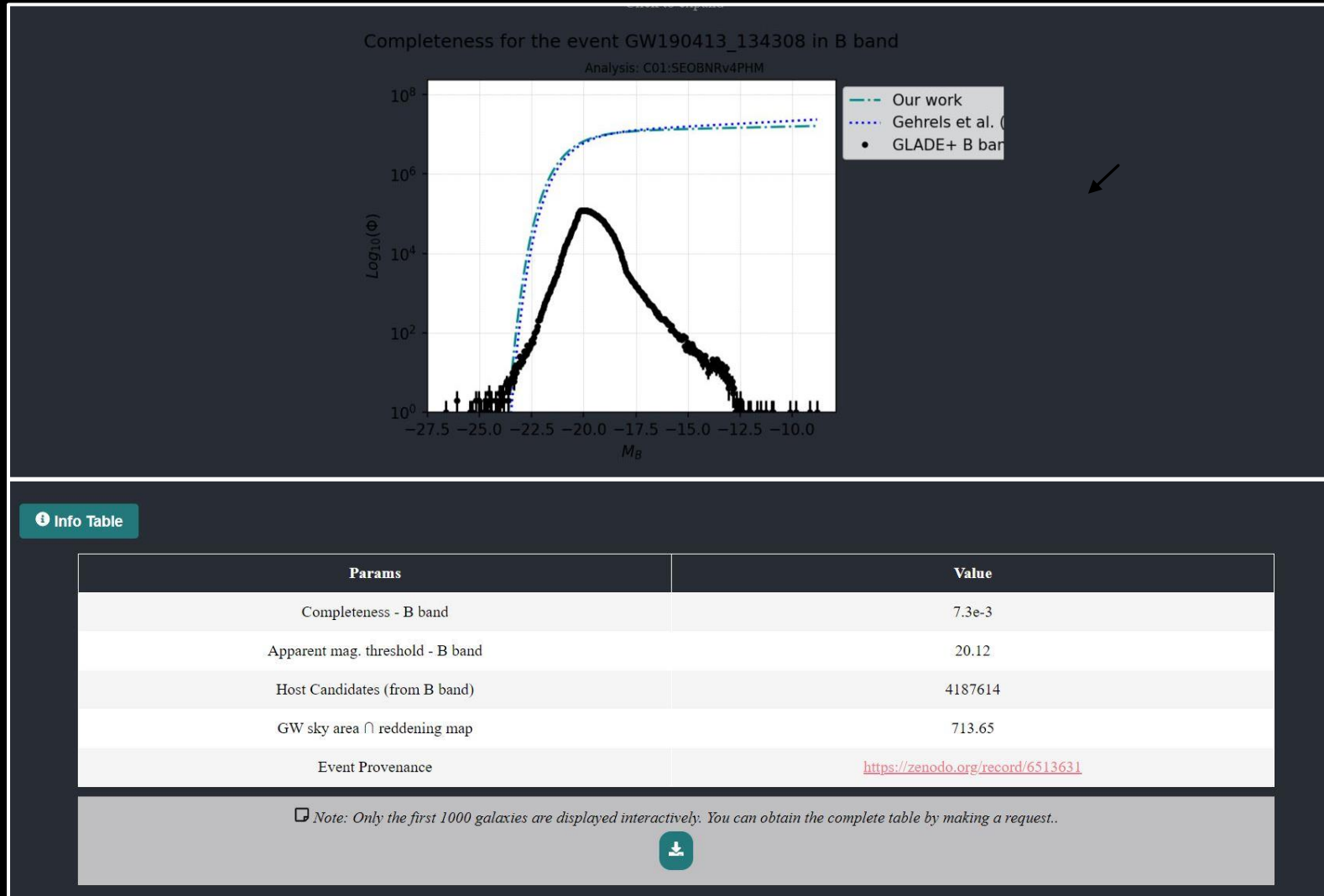
Click to expand

Completeness for the event GW190413\_134308 in B band

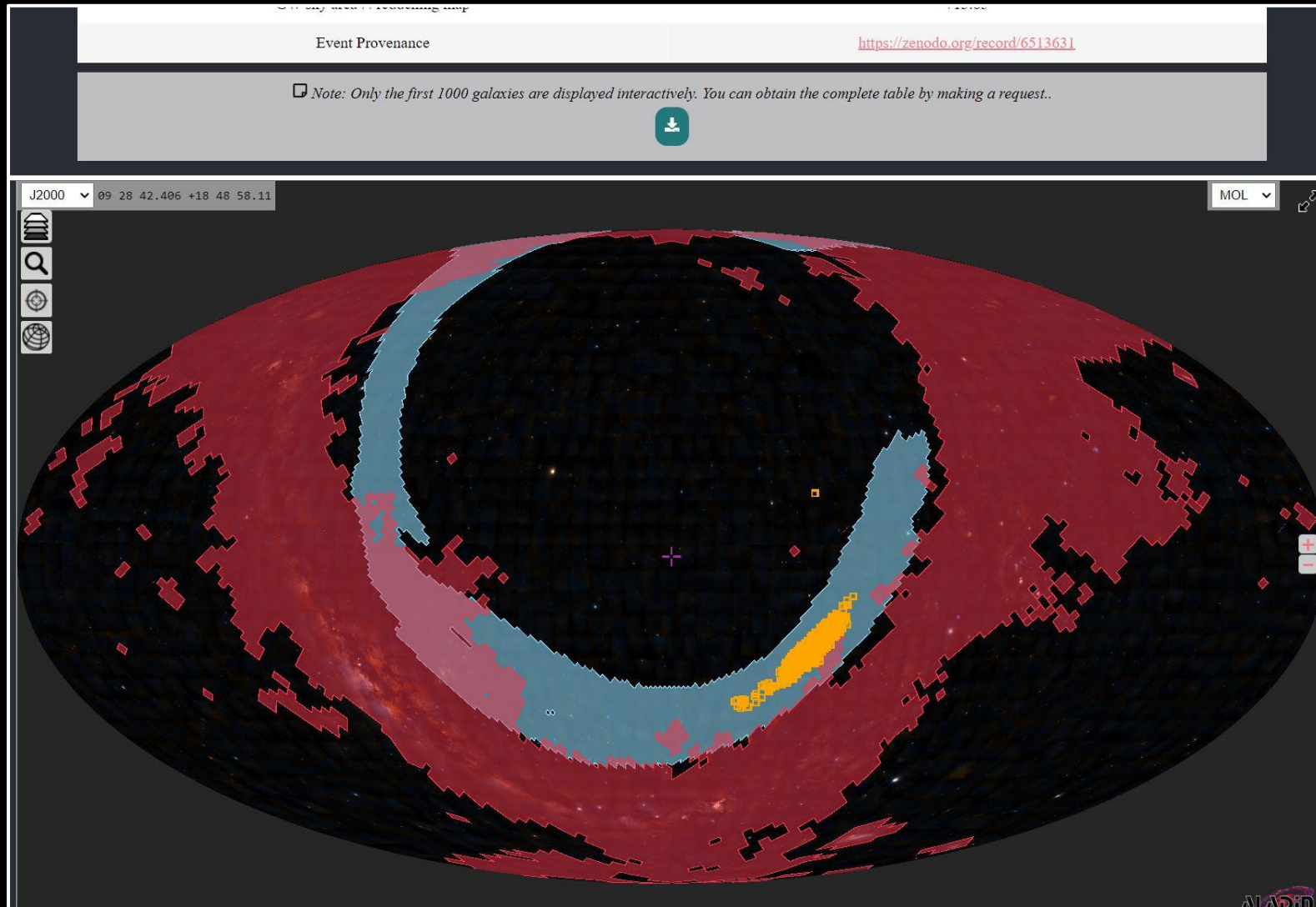
Analysis: C01:SEOBNRv4PHM



# GLADEnet - web App



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# Outlook for the future

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It is just a **step**, many **more** have to come!

- Technical **upgrades** to add features on GLADEnet
- We want to include also other electromagnetic band in the analysis (as K-band)
- Help the **Pre-selection** of gw-events in future observing runs
- Extend this method to other catalogues
- Use the completeness evaluation to support the **Hubble constant** estimate
- Insert the **redshift** ( $z$ ) dependency of Schechter function and study its implications
- Add simulated events to develop observational strategies for upcoming runs

# ***Thanks for your attention***

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