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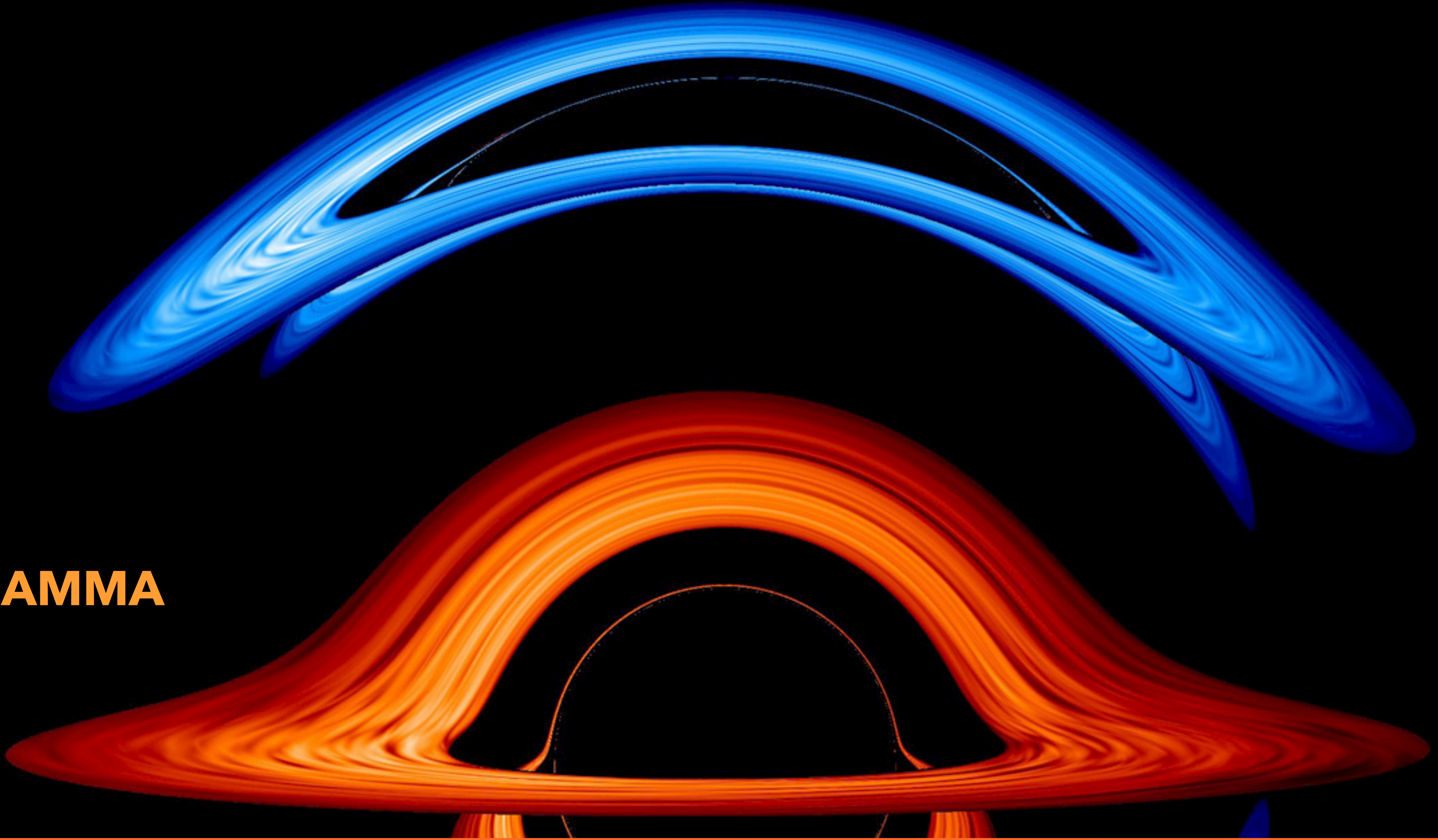


5-7 OTTOBRE 2022

THE THIRD GRAVI-GAMMA WORKSHOP

“EVALUATING CATALOGUES COMPLETENESS BY EXTENDING THE VIRTUAL OBSERVATORY FRAMEWORK TO ESTIMATE THE H_0 HUBBLE CONSTANT WITH DARK STANDARD SIRENS ”

M.L. BROZZETTI
G. GREGO
M. BAWAJ
M. PUNTURO

NASA Visualization Probes the Light-bending Dance of Binary Black Holes

INTRODUCTION

HUBBLE'S TENSION

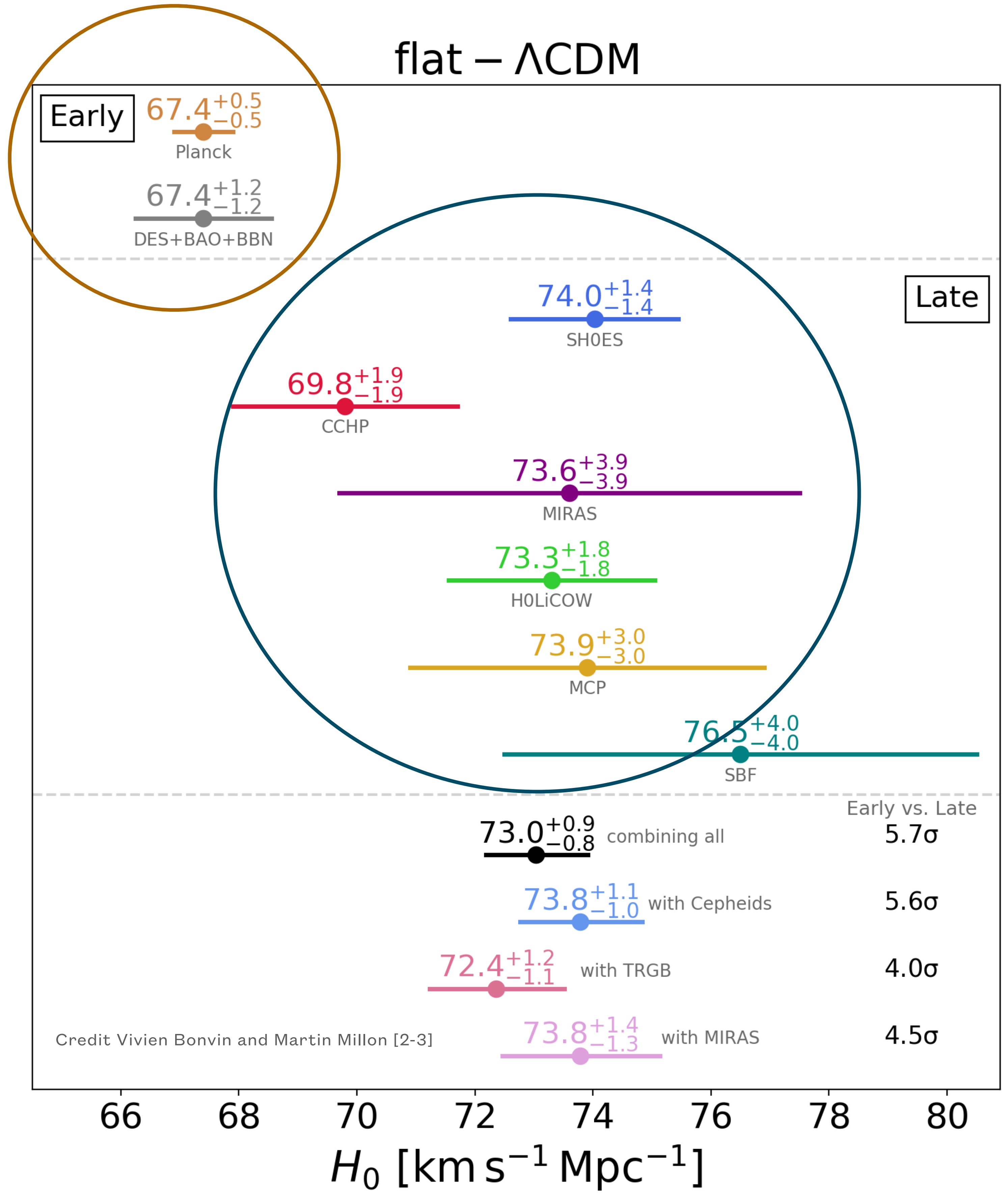
The discrepancy is about $\sim 4-6\sigma$ [7] between **late**- and **early**-time measurements.

- *Cosmic Microwave Background* (***CMB***): the latest Planck results give a Hubble constant value of

$$H_0 = 67.36 \pm 0.54\, km\, s^{-1}\, Mpc^{-1} \text{ [5]}$$

- Related to local expansion, the intrinsic luminosity from light curves of *Type Ia Supernovae* (SN Ia), making them usable as **standard candles** : SH0ES, Supernovae-H0-for the equation of State of Dark energy, led to

$$H_0 = 73.24 \pm 1.44 km\, s^{-1}\, Mpc^{-1} \text{ [6]}$$



INTRODUCTION

HUBBLE'S TENSION

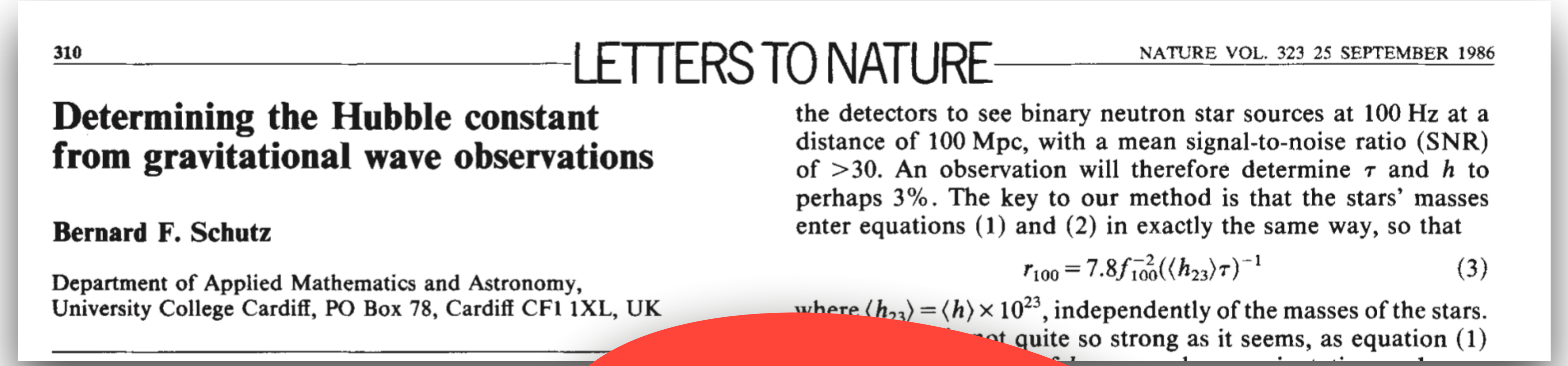
STATISTICAL APPROACH BY B. F. SCHUTZ

- **Standard siren**'s method: the d_L is obtained from a signal coming from a merger of compact objects while the redshift is from the electromagnetic counterpart [4]

→ **GW170817 + NGC 4993** [5-7]

- Statistical approach with **dark standard siren** based on galaxies clustering and with the use of **galaxies' catalogues** [4]

→ **CATALOGUES' INCOMPLETENESS**


310 LETTERS TO NATURE NATURE VOL. 323 25 SEPTEMBER 1986

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

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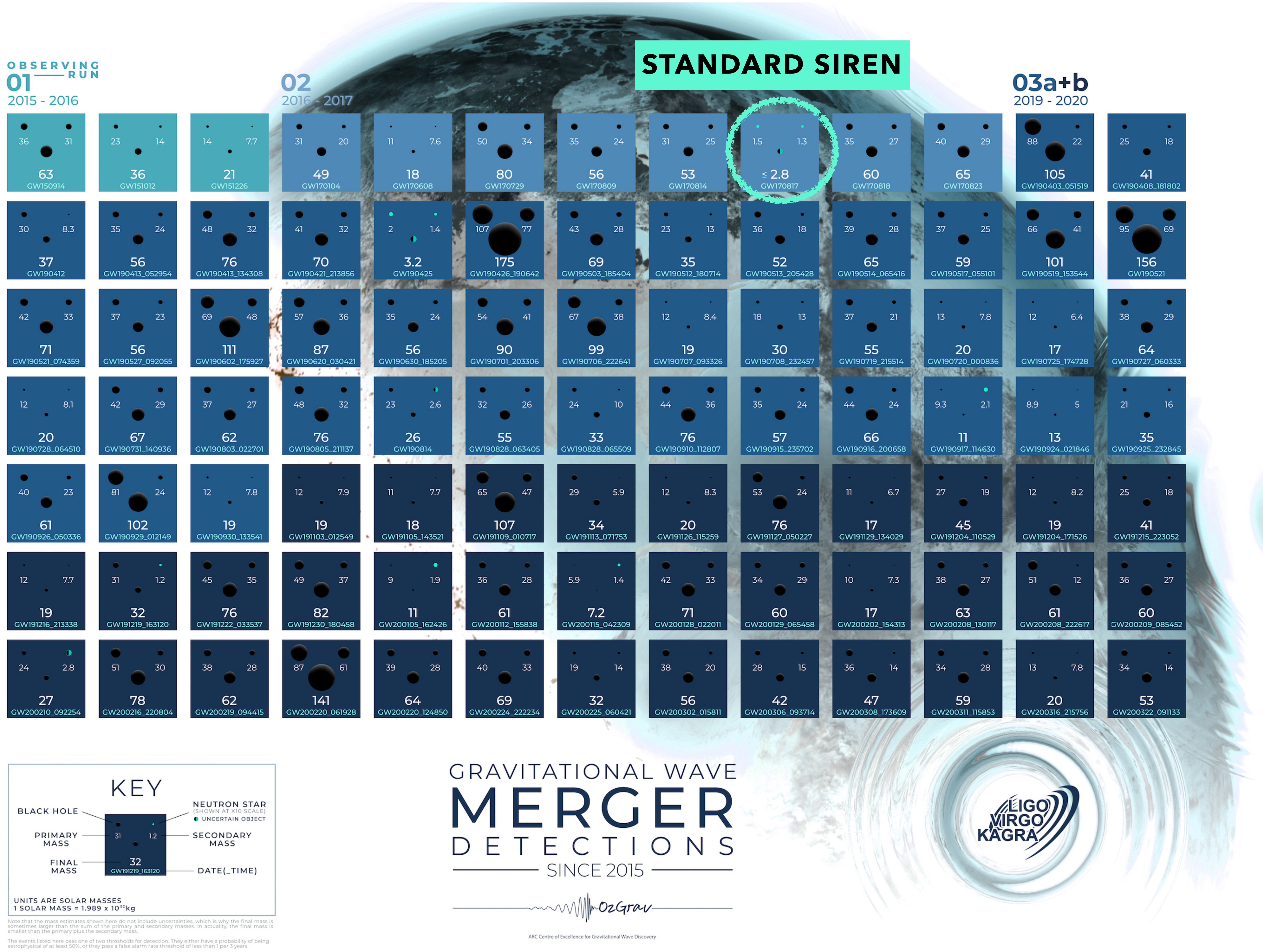
the detectors to see binary neutron star sources at 100 Hz at a distance of 100 Mpc, with a mean signal-to-noise ratio (SNR) of >30. An observation will therefore determine τ and h to perhaps 3%. The key to our method is that the stars' masses enter equations (1) and (2) in exactly the same way, so that

$$r_{100} = 7.8 f_{100}^{-2}(\langle h_{23}\rangle \tau)^{-1} \quad (3)$$

where $\langle h_{23}\rangle = \langle h\rangle \times 10^{23}$, independently of the masses of the stars. ... not quite so strong as it seems, as equation (1)

INDEPENDENT FROM COSMOLOGICAL DISTANCE LADDER



DARK STANDARD SIRENS

- Gravitational Wave events detected without electromagnetic counterpart[8].

THE BAYESIAN APPROACH

$$p(H_0 | \{x_{GW}\}, \{D_{GW}\}) \propto p(H_0)\, p(N_{det} | H_0) \prod_{i}^{N_{det}} p(x_{GW_i} | D_{GW_i}, H_0)$$

- $\{x_{GW}\}$ is a set of GW data,
- $\{D_{GW}\}$ denotes that a GW signal was detected,
- N_{det} detections;
- $p(H_0)$ is the flat prior on H_0;
- $p(N_{det} | H_0)$ is the probability of detecting N_{det} events;

THE BAYESIAN APPROACH

$$p(H_0 | \{x_{GW}\}, \{D_{GW}\}) \propto p(H_0)\, p(N_{det} | H_0) \prod_i^{N_{det}} p(x_{GW_i} | D_{GW_i}, H_0)$$

THE GALAXIES CATALOGUE METHOD

The likelihood for a single GW event is marginalised over the case where the host galaxy is, and is not, in the catalogue (denoted by G and $\bar{G}$ respectively):

$$p(x_{GW} | D_{GW}, H_0) = p(x_{GW} | G, D_{GW}, H_0) p(G | D_{GW}, H_0) + p(x_{GW} | \bar{G}, D_{GW}, H_0) p(\bar{G} | D_{GW}, H_0)$$

THE BAYESIAN APPROACH

$$p(H_0 \,|\, \{x_{GW}\}, \{D_{GW}\}) \propto p(H_0)\, p(N_{det} \,|\, H_0) \prod_i^{N_{det}} p(x_{GW_i} \,|\, D_{GW_i}, H_0)$$

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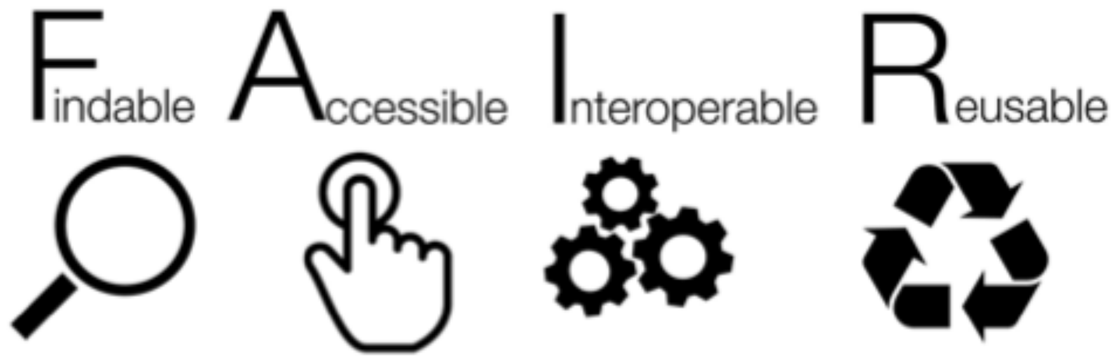
1° COMPLETENESS COEFFICIENT

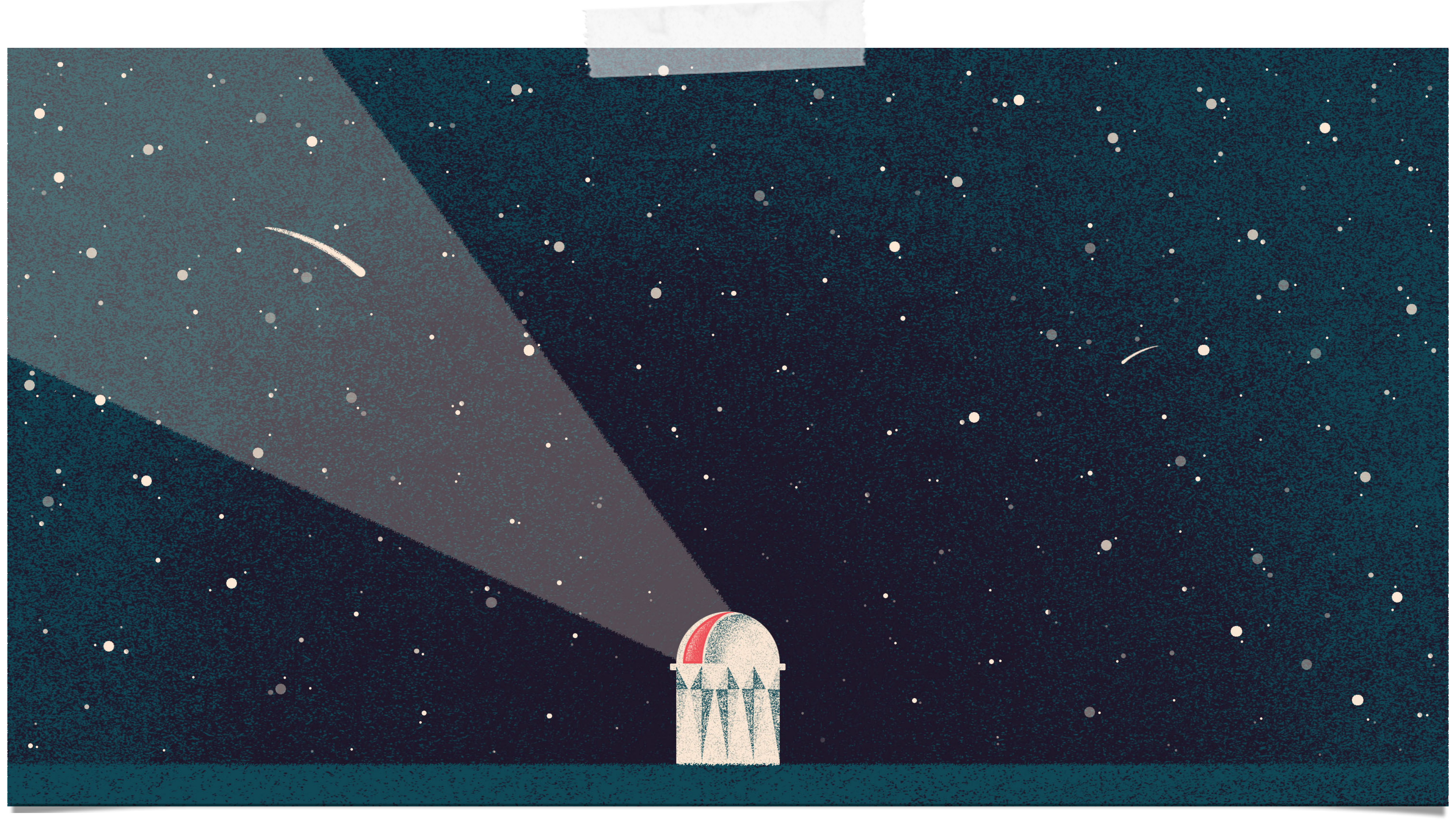
VIRTUAL OBSERVATORY

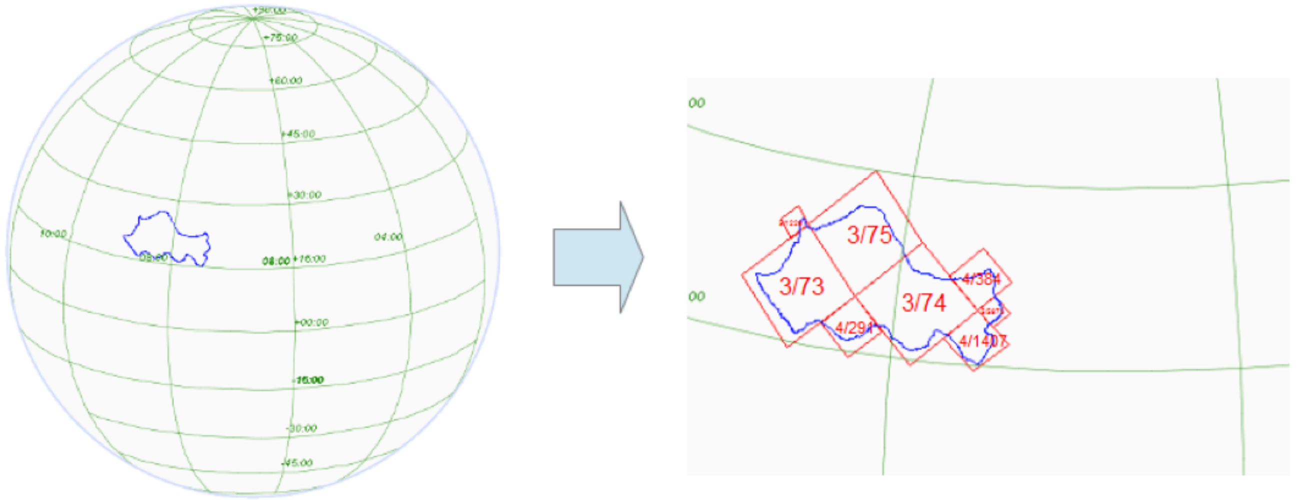
- The International **Virtual Observatory Alliance** (IVOA) was born in June 2002 [15].

- It is composed of 22 international members to "facilitate the international coordination and collaboration necessary for the *development and deployment of the* ***tools, systems and organisational structures*** *necessary to enable the international utilisation of astronomical archives* as an integrated and interoperating Virtual Observatory (VO)"

➡ **standards** that are complaint with



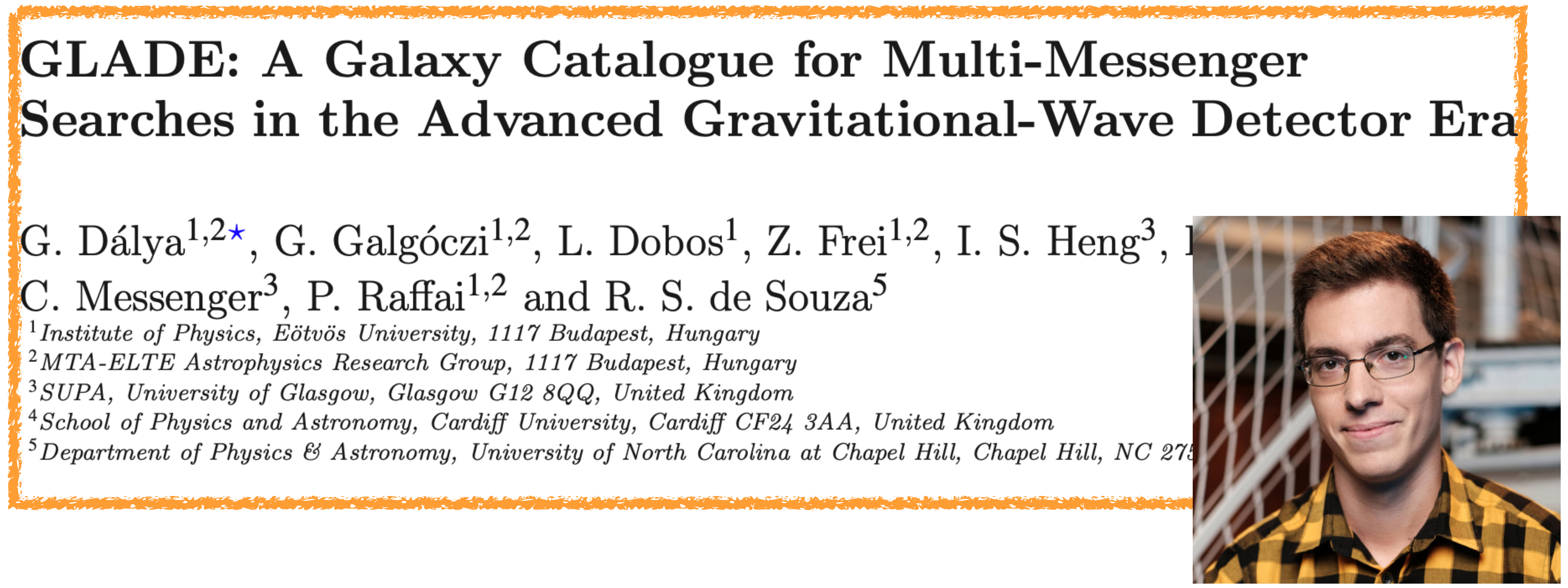




VIRTUAL OBSERVATORY: GLADE

The **Galaxy List for the Advanced Detector Era** is a value-added full-sky catalogue of inactive and active galaxies that can be potential host of GW+EM sources [16].

- complete up to $d_L = 37^{+3}_{-4}$ Mpc in B-band;
- GWGC , 2MASS XSC, 2MPZ, HyperLEDA, SDSS-DR12Q


GLADE: A Galaxy Catalogue for Multi-Messenger Searches in the Advanced Gravitational-Wave Detector Era

G. Dálya[1,2⋆], G. Galgóczi[1,2], L. Dobos[1], Z. Frei[1,2], I. S. Heng[3], I
C. Messenger[3], P. Raffai[1,2] and R. S. de Souza[5]
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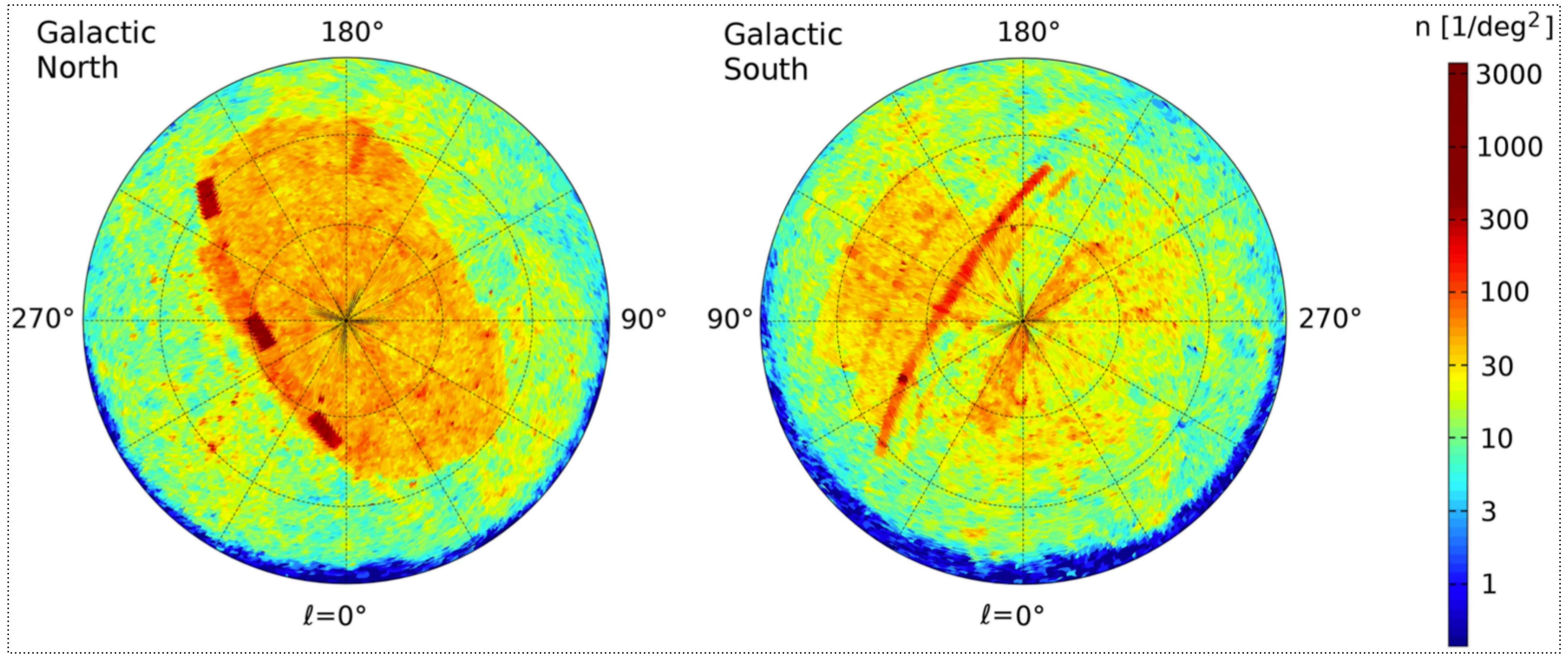
[4]School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, United Kingdom
[5]Department of Physics & Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27



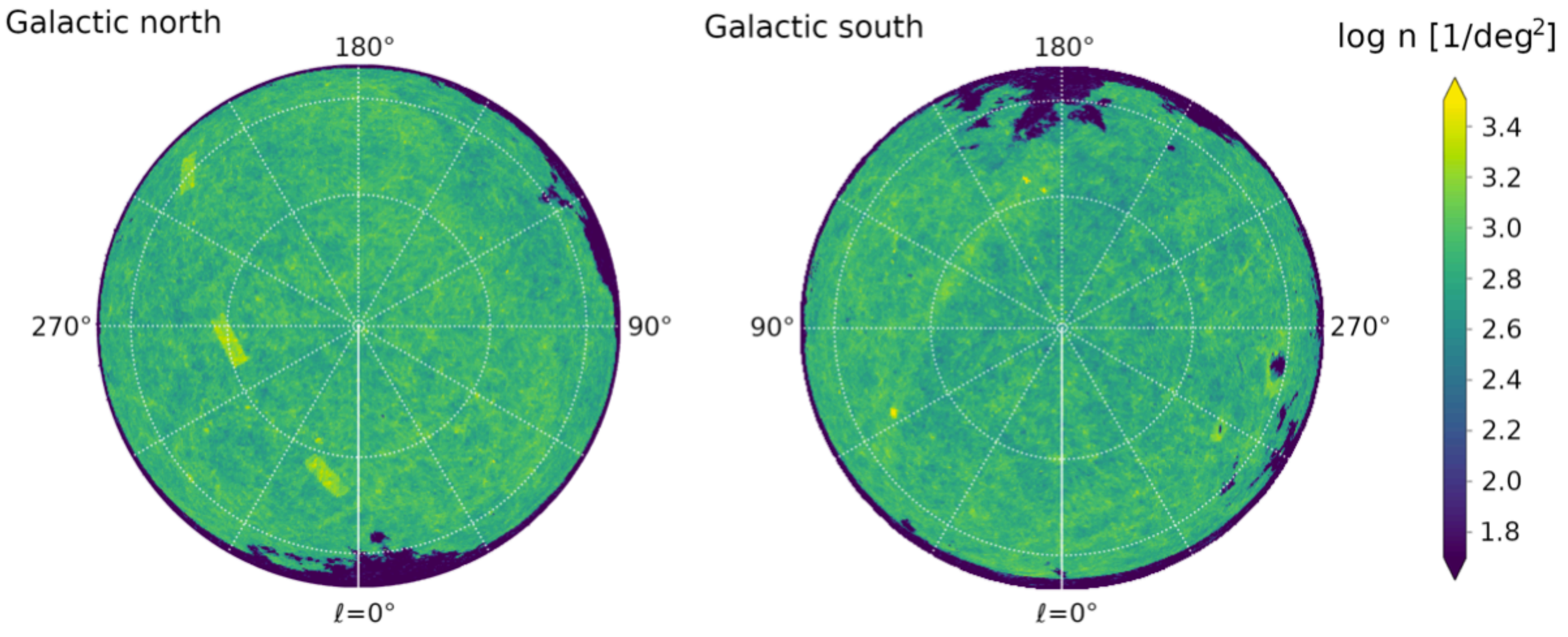
Number density (n) of objects in GLADE [16].

VIRTUAL OBSERVATORY: GLADE+

The last version **GLADE+** includes $\sim 22{,}5$ million galaxies and ~ 750 thousand quasars

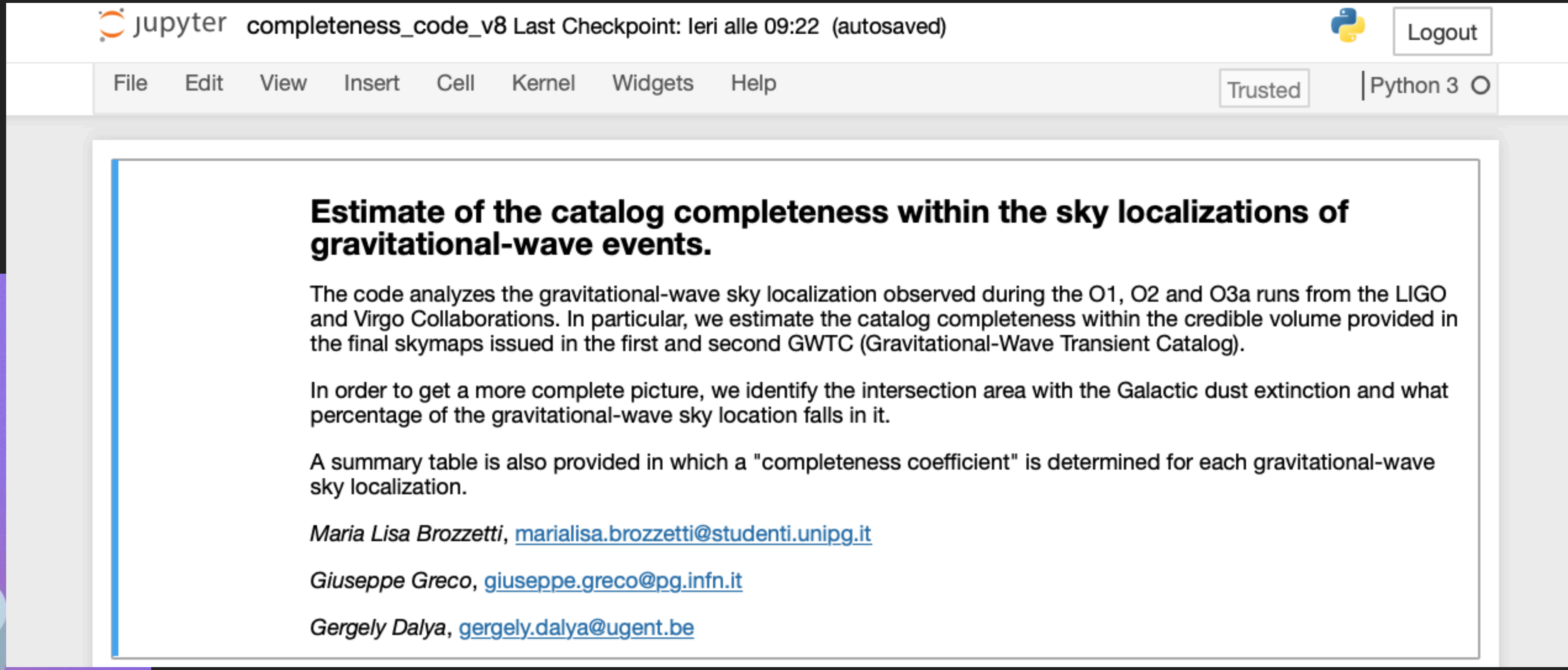
It contains all the brightest galaxies that give half the total brightness of the B-band up to ~ 250 Mpc.

* GWGC , 2MASS XSC, 2MPZ, HyperLEDA, SDSS-DR12Q + * WISExSCOSPZ



Number density (n) of objects in GLADE+ [21].

THE ALGORITHM & RESULTS



Estimate of the catalog completeness within the sky localizations of gravitational-wave events.

The code analyzes the gravitational-wave sky localization observed during the O1, O2 and O3a runs from the LIGO and Virgo Collaborations. In particular, we estimate the catalog completeness within the credible volume provided in the final skymaps issued in the first and second GWTC (Gravitational-Wave Transient Catalog).

In order to get a more complete picture, we identify the intersection area with the Galactic dust extinction and what percentage of the gravitational-wave sky location falls in it.

A summary table is also provided in which a "completeness coefficient" is determined for each gravitational-wave sky localization.

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Giuseppe Greco, giuseppe.greco@pg.infn.it

Gergely Dalya, gergely.dalya@ugent.be

https://github.com/MLisaBrozz

THE ALGORITHM & RESULTS

We describe the techniques used to evaluate completeness in term of the **Luminosity function** for galaxies.

In 1976 **Schechter** proposed a model for a galaxy number density in a given comoving volume with a given luminosity [17].

- $\rho_{gal}\, dx \;=\; \phi^*\, x^{\alpha}\, e^{-x}\, dx$
- $\phi^* \;=\; (1.6 \pm 0.3) \times 10^{-2} h^3 Mpc^{-3};$
- $x = L/L_B^* \quad with \;\; L_B^* \;=\; (1.2 \pm 0.1) \times 10^{10} h^{-2} L_{B,\odot};$
- $\alpha \;= -\, 1.07 \;\pm\; 0.07.$

```python
def Schechter(lum, volume, h=0.7, phi=(1.6e-2)*(0.7**3) , a=-1.07, alfa=-0.07):
    """
    The Schechter function with fixed parameters.
    """

    sigma = phi * np.power(lum, alfa) * np.power(np.e,-lum) * volume * (0.7*0.7*0.7)

    return sigma
```

THE ALGORITHM & RESULTS

We describe the techniques used to evaluate completeness in term of the **Luminosity function** for galaxies.

In 1976 **Schechter** proposed a model for a galaxy number density in a given comoving volume with a given luminosity [17].

- $\rho_{gal}\, dx \; = \; \phi^* \, x^{\alpha} \, e^{-x} \, dx$
- $\phi^* \; = \; (1.6 \pm 0.3) \times 10$
- $x = L/L^*_B \quad with \quad L^*_B \; =$
- $\alpha \; = -\, 1.07 \; \pm \; 0.07.$

```
def Schechter(lum, volume, h=0.7, phi=(1.6e-2)*(0.7**3) , a=-1.07, alfa=-0.07):
    """
    The Schechter function with fixed parameters.
    """
wer(np.e,-lum) * volume * (0.7*0.7*0.7)
```

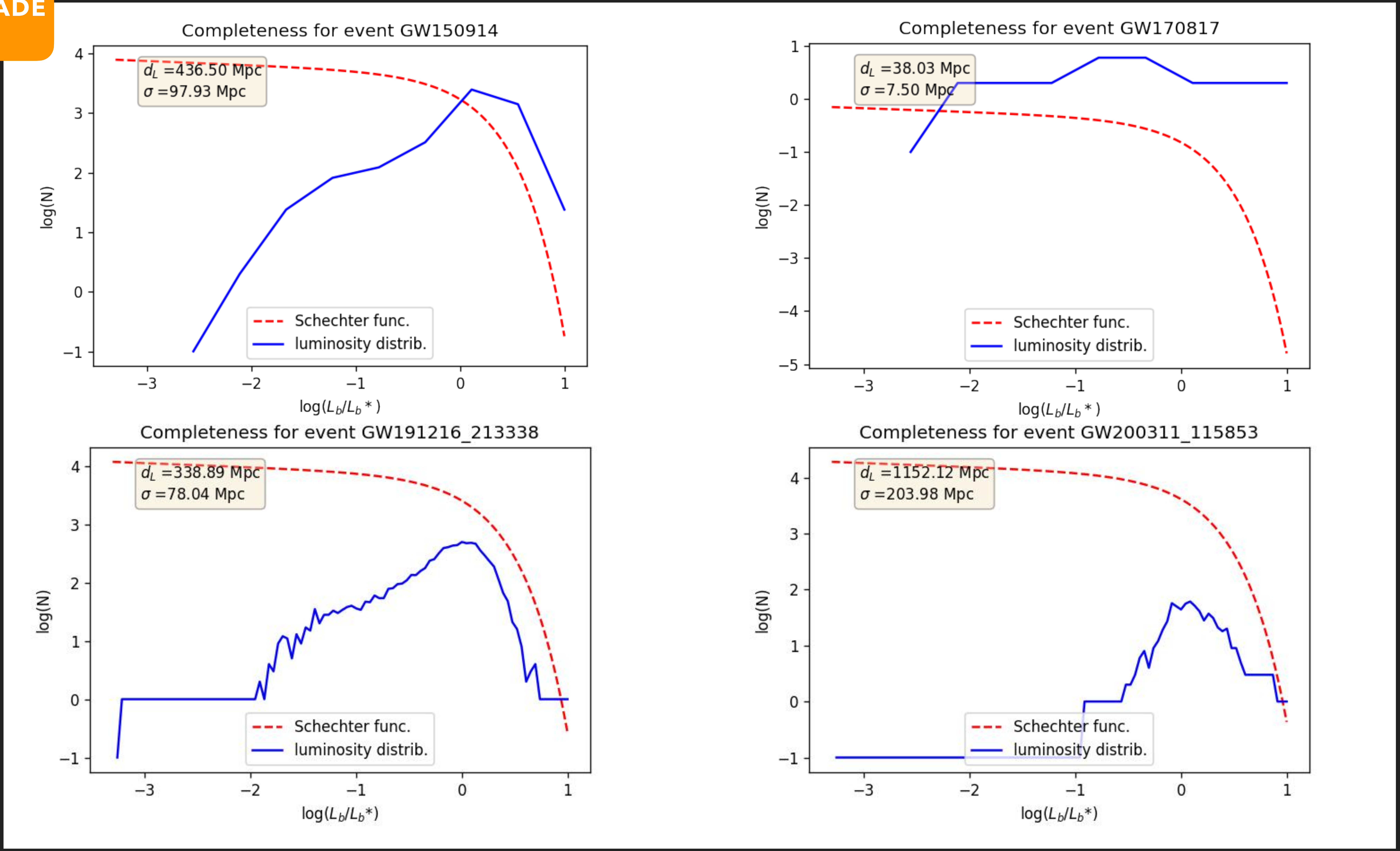
The completeness of the catalogues will be evaluated integrating the Schechter functions over the n-th luminosity distance-shells that cover the galaxies collected

$$\int_{x_1}^{\infty} \phi^* \, L^* \, x^{(\alpha+1)} exp(-x) \, dx = \phi^* \, L^* \, \Gamma(\alpha \, + 2, x_1)$$

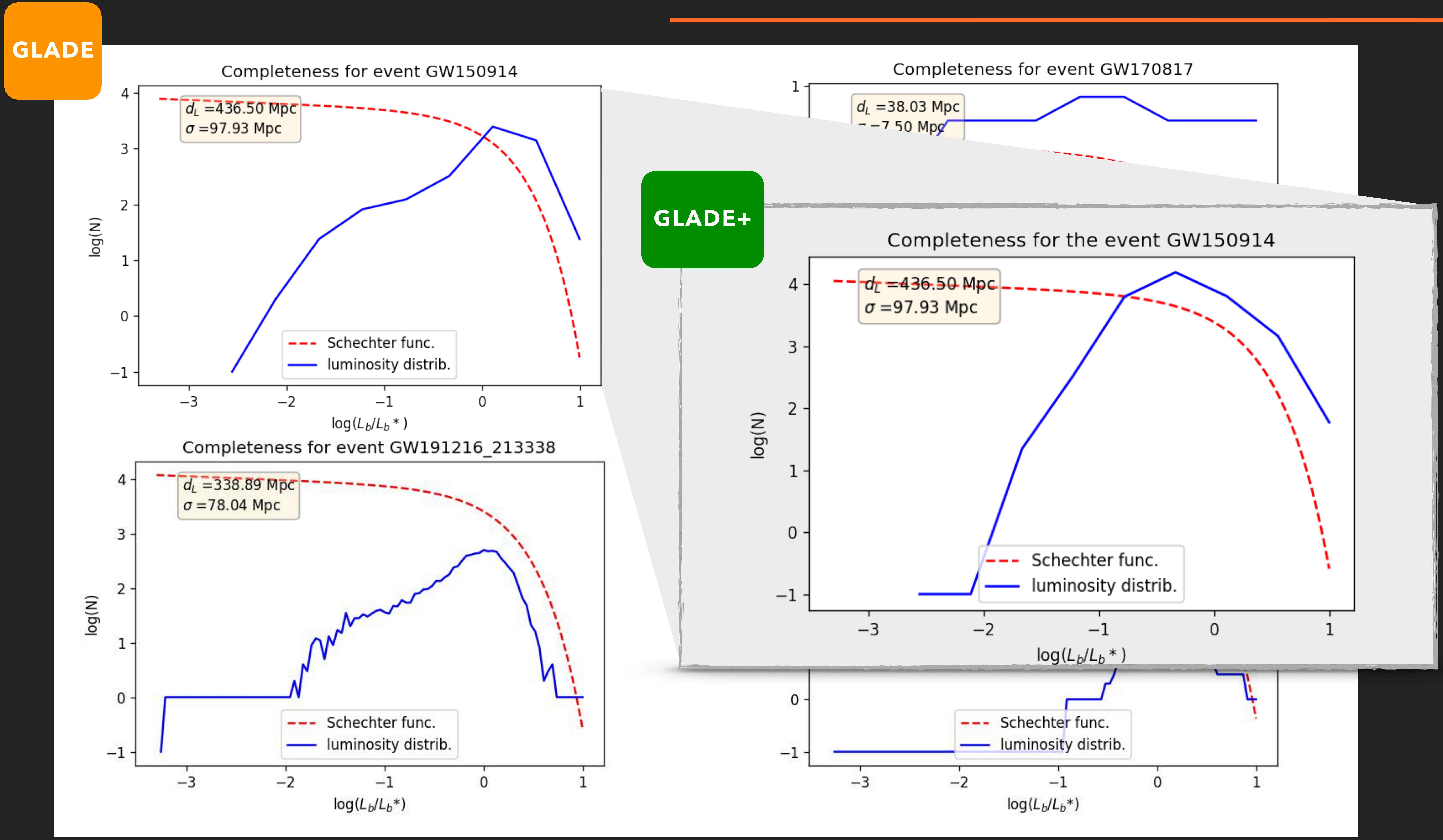
```
def luminosity_from_schechter_function(volume):
    '''
    Luminosity estimation with the Schechter Function.
    '''

    h = 0.7 # H_0/100
    Lb0 = 2.16e33 # solar luminosity in B-band
    l_csill = 1.2*10**10 * h**(-2) * Lb0
    fi_csill = 1.6*pow(10,-2)*pow(h,3)

    lum =  gammaincc(0.93,0.0)*gamma(0.93) * 0.7 * fi_csill * l_csill * volume

    return lum
```

LUMINOSITY FUNCTIONS

GLADE



LUMINOSITY FUNCTIONS

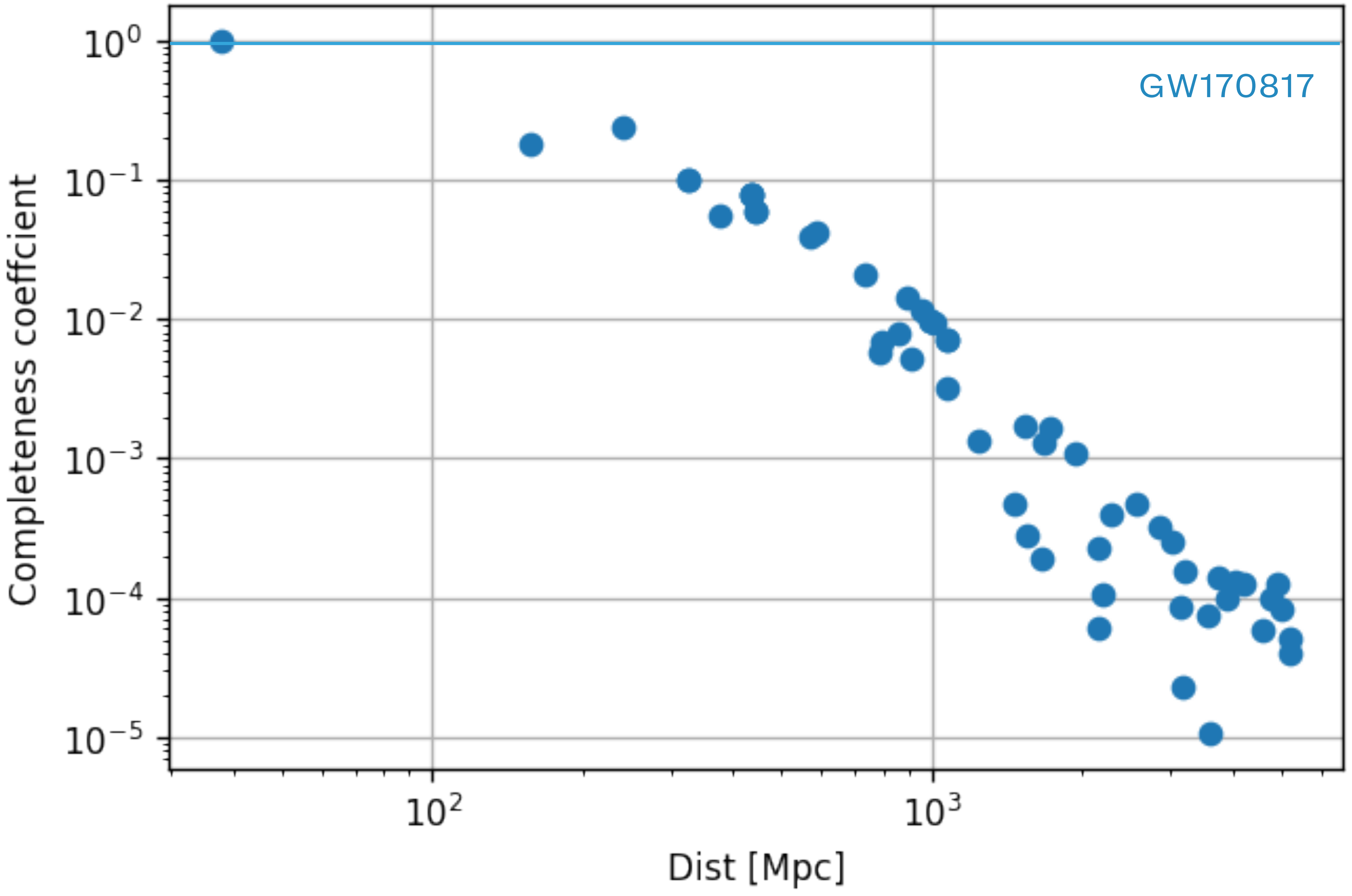


```python
def coeff_completeness(lum_tot, volume):
    '''
    Coefficient to evaluate the completeness of the catalogue in the gravitational-
    '''

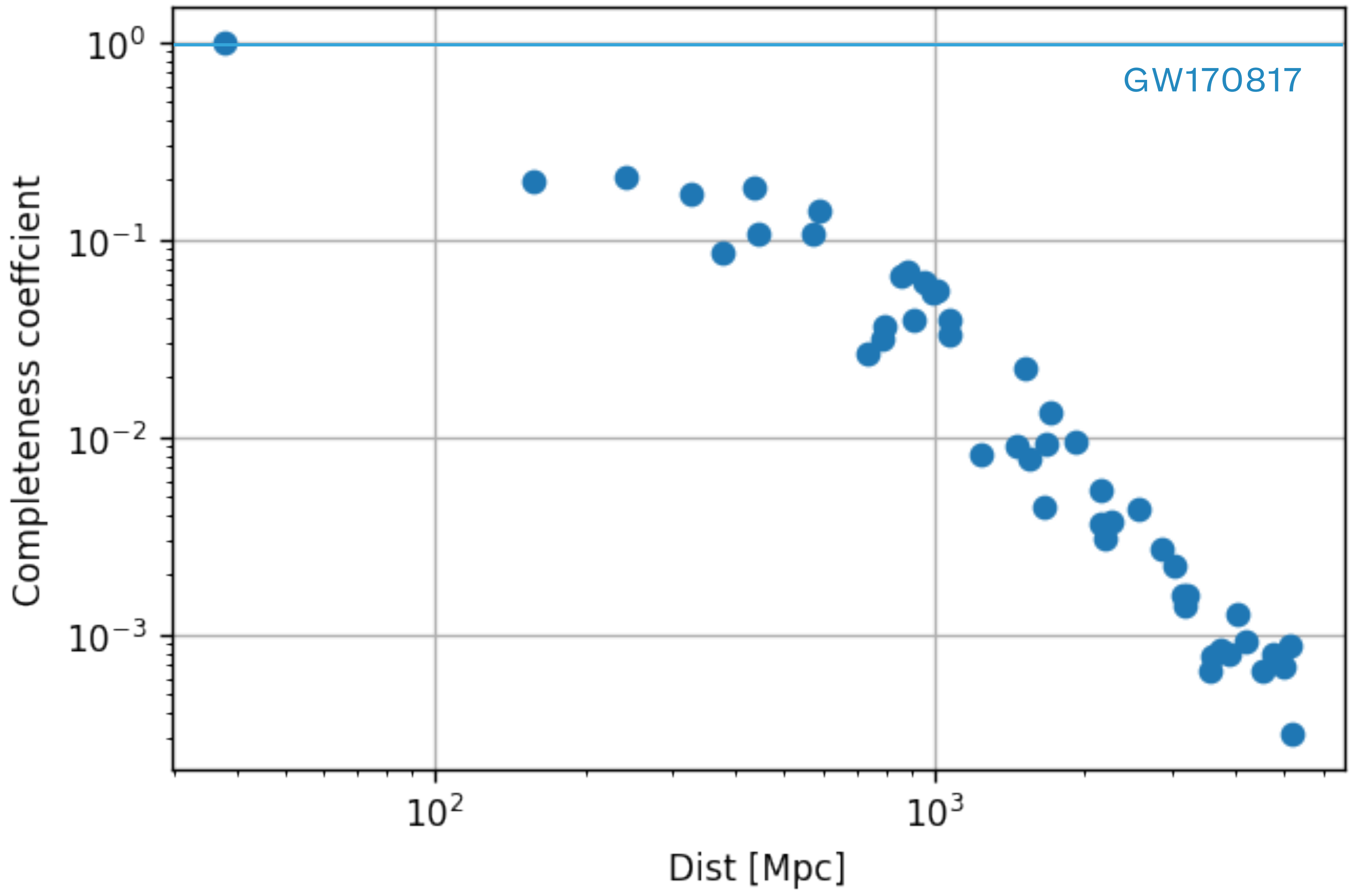
    coeff=lum_tot*100/luminosity_from_schechter_function(volume)

    return coeff
```

THE COEFFICIENT C



GLADE



GLADE+

THE COEFFICIENT C

```
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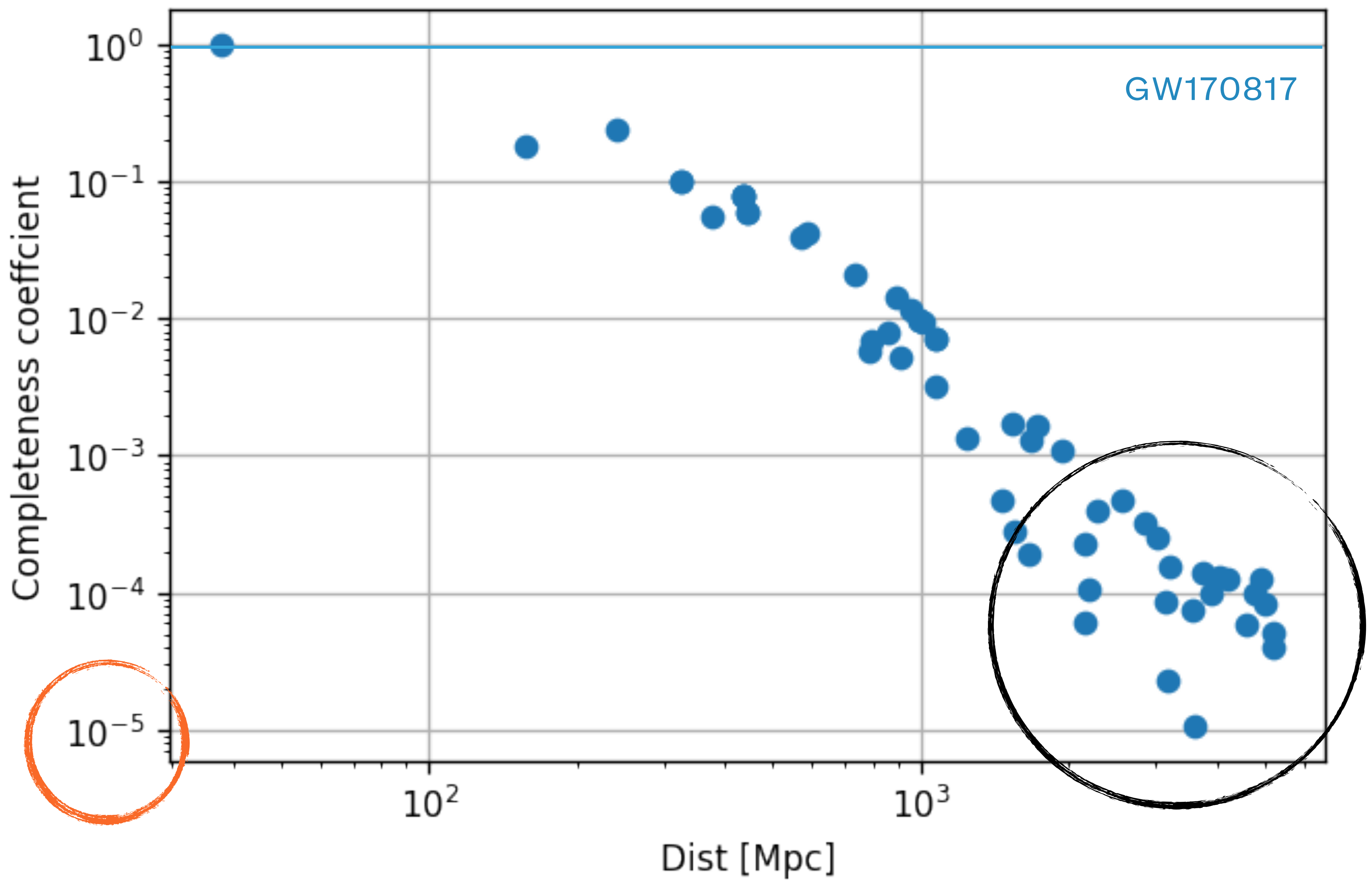
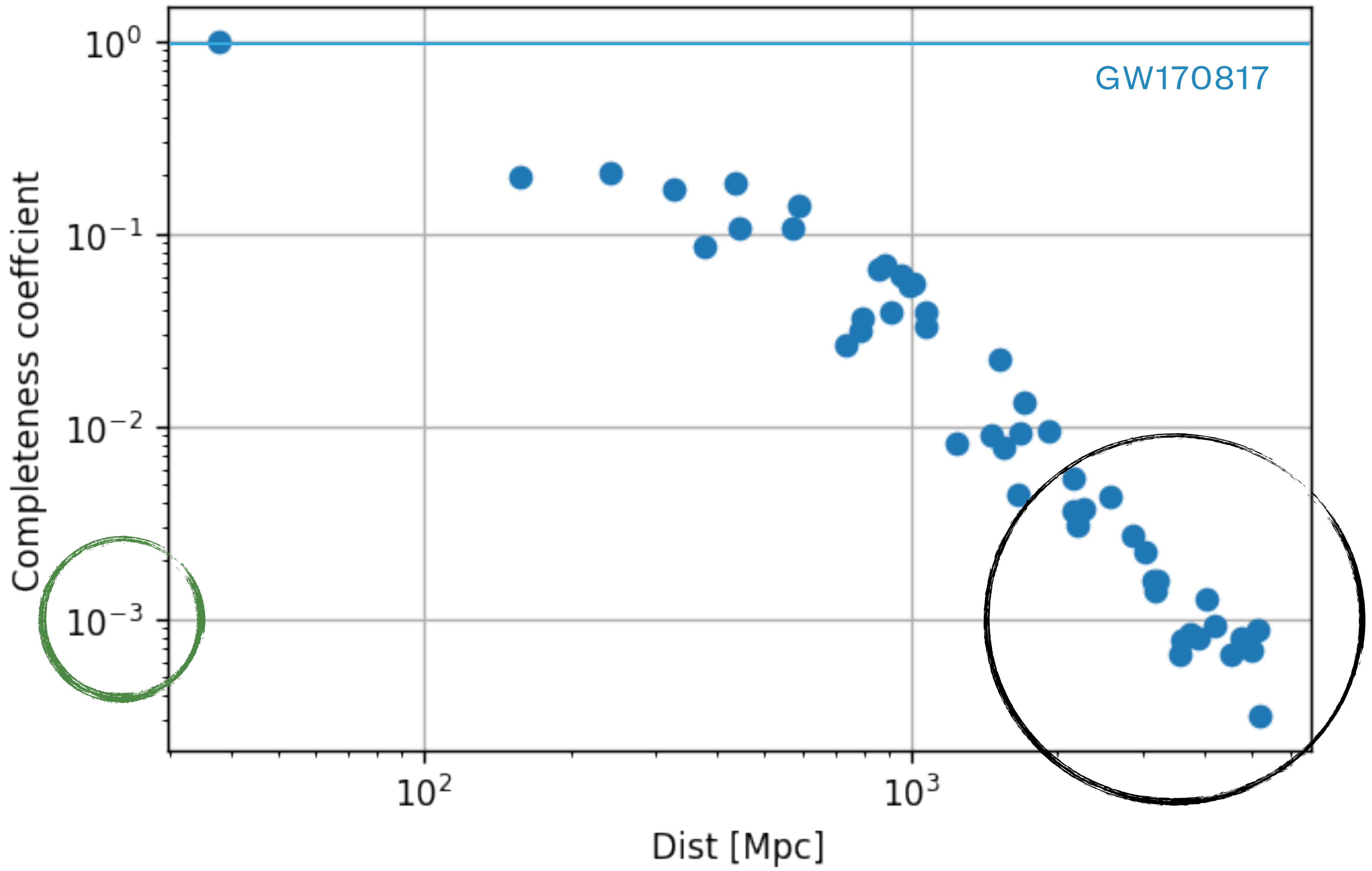
    coeff=lum_tot*100/luminosity_from_schechter_function(volume)

    return coeff
```

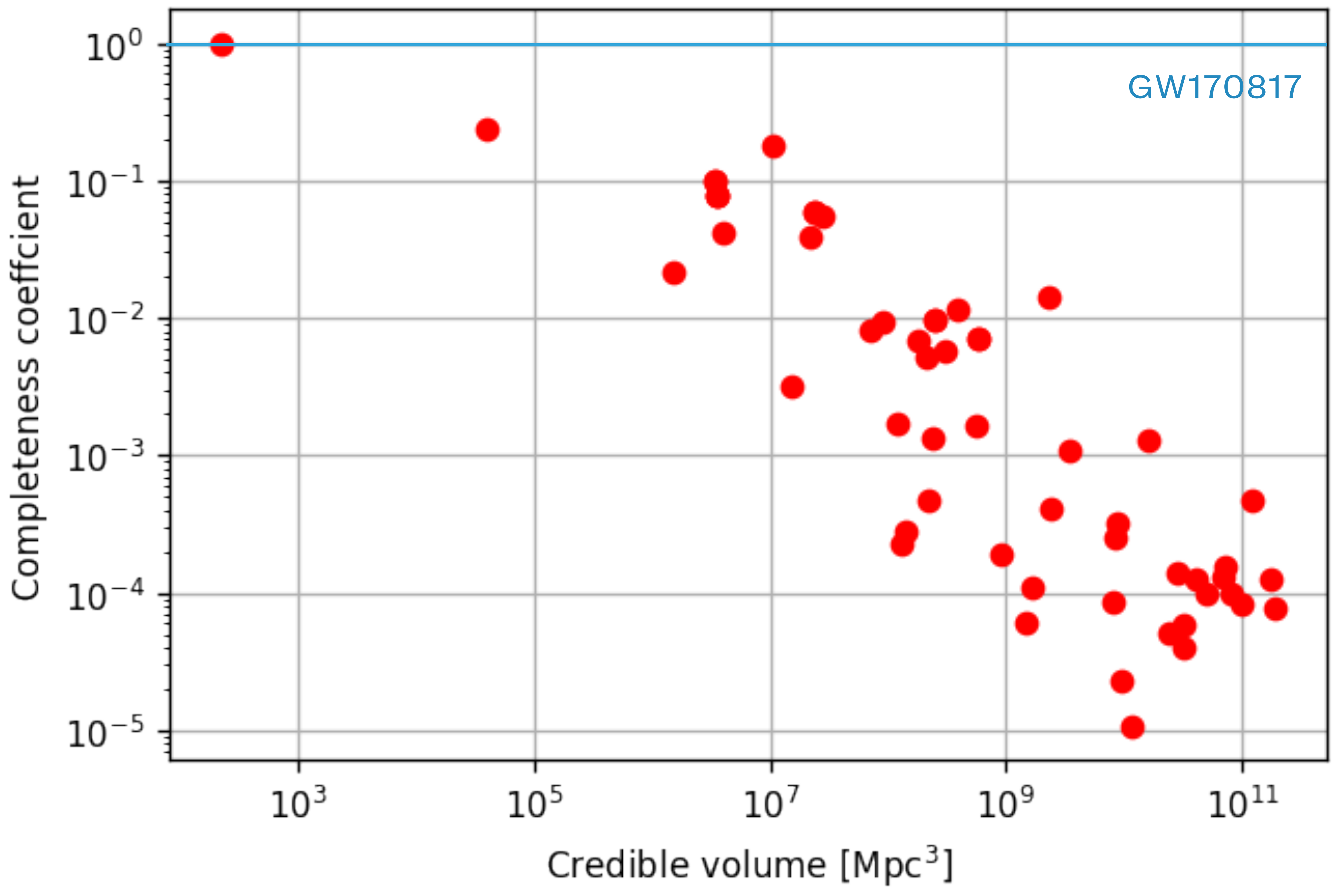


GLADE



GLADE+

THE COEFFICIENT C



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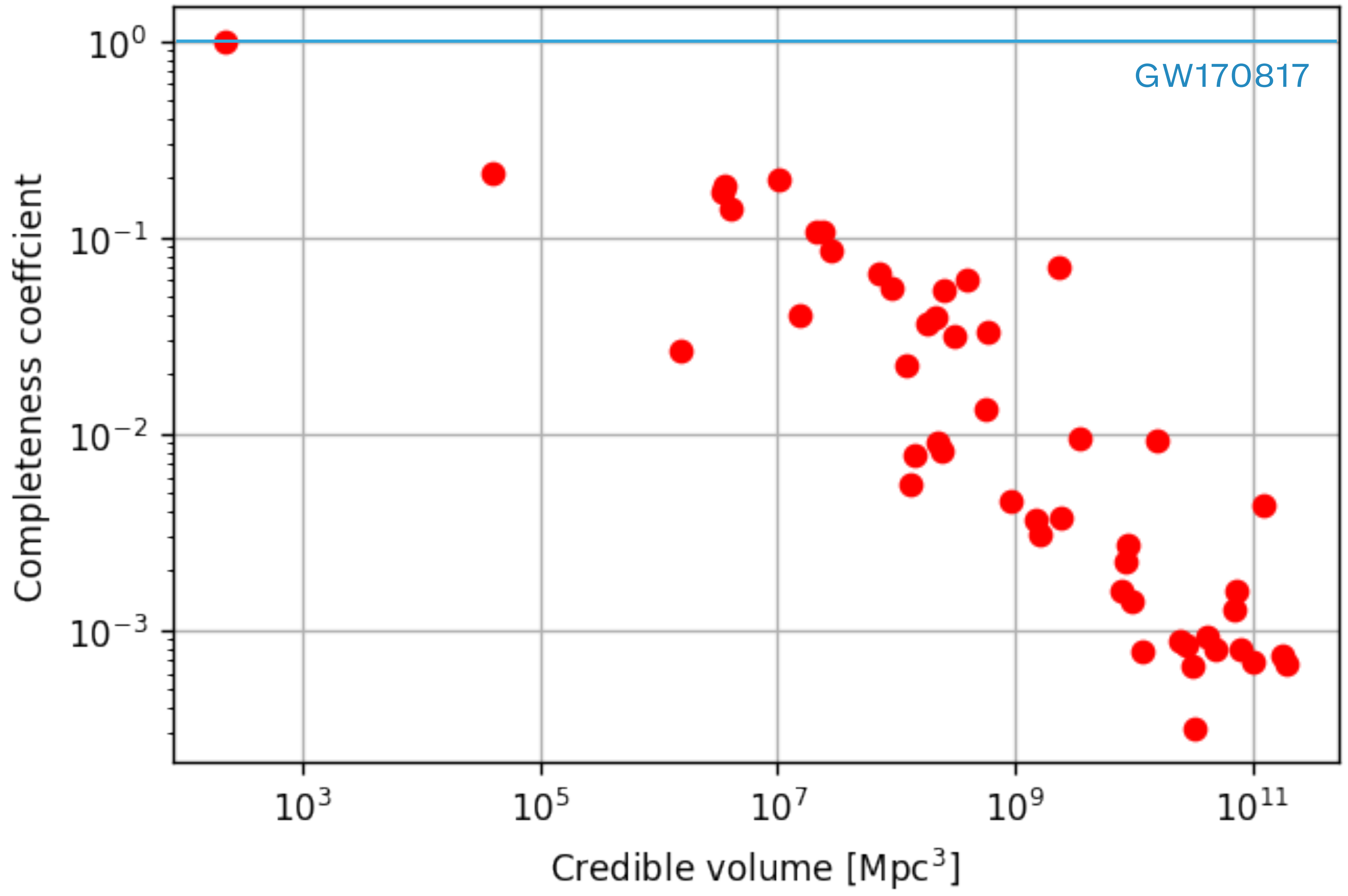


GLADE+

THE GALACTIC DUST REDDENING AND EXTINCTION

The Milky Way contains **gas and dust** that can **absorb the EM** radiation of some bands of the spectrum. It is therefore essential to assess whether the event has a region of credibility that falls within the Milky Way and which leads to effects on the Luminosity distribution.

- ☑ We create a MOC **exp_map.fits** from Galactic Dust Reddening map with **.from_fits** MOCpy function, given a certain **resolution** and an **extinction value** >= 0.5 in each pixels.

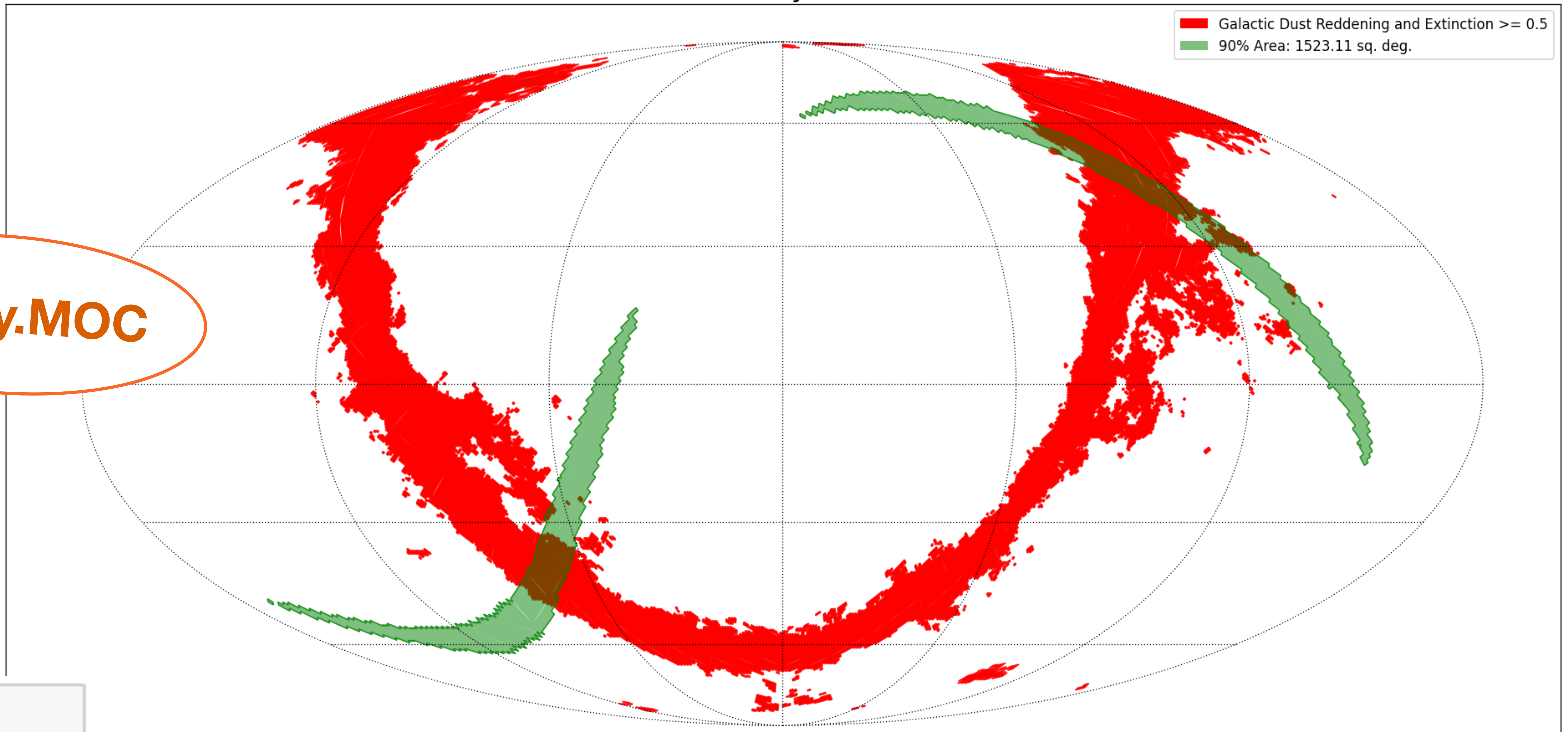
mocpy.MOC

- ☑ We evaluate and plot the intersection with the **intersection_credible_region_galactic_dust function**, passing it the GW event skymap and the exp_map.fits

```
def intersection_credible_region_galactic_dust(skymap_url, ext_map, path):
    '''
    Calculation and plot of the intersection region between the gravitational-wave
    and the Galactic Dust Reddening and Extinction (>= 0.5).
    '''

    skymap = download_file('file:'+skymap_url)
```

GW151012: Sky Localization



The intersection area with the Galactic Dust Reddening is 285.54 sq. deg. - 18.75% of the plotted credible region area

THE GALACTIC DUST REDDENING AND EXTINCTION

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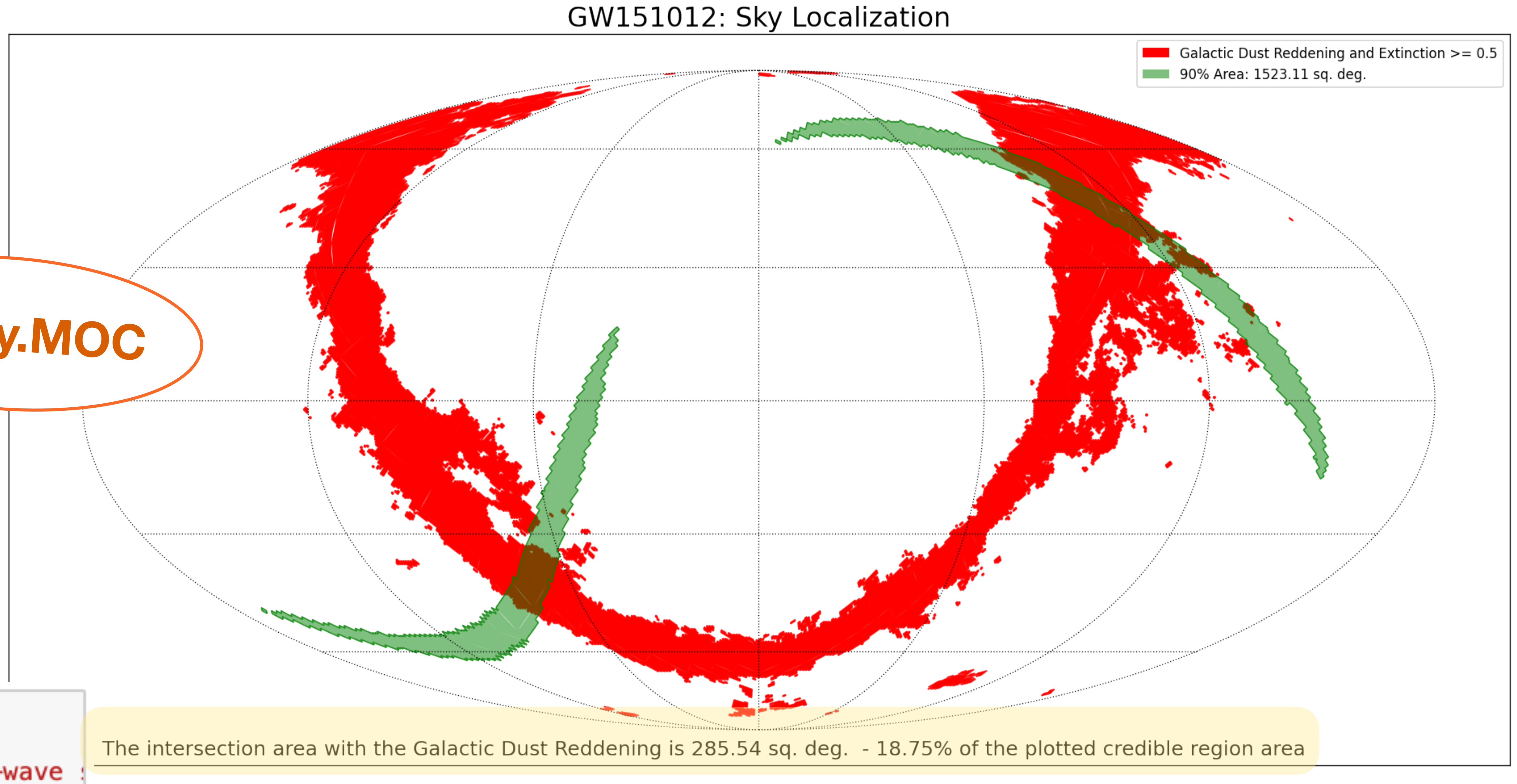


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```

FUTURE GOALS

- Implementation of low latency notifications of the Gamma-ray Coordinates Network **GCN** with **C** , apparent magnitude $\mathbf{m_{th}}$ and links of **intersection maps** with the Milky Way.

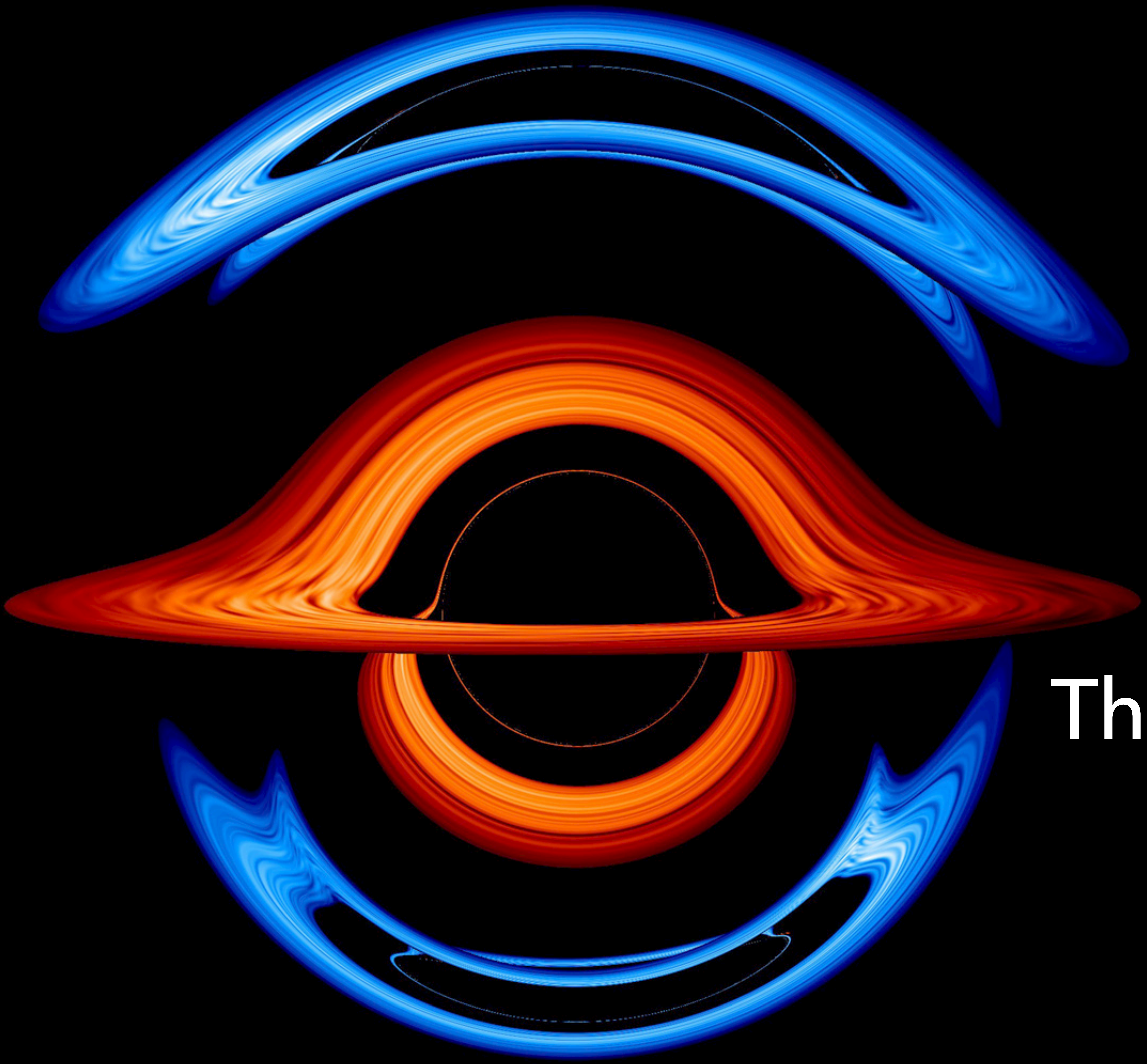
- Astronomers will investigate **incomplete sky regions** and subsequently upload new data through the VizieR channel.

- Working with **gwcosmo** package with the **parameters** obtained in the thesis work so as **to estimate the Hubble constant** and see the **effects** of the use of increasingly complete catalogues.

- Combine the H_0 's posterior probability distribution of each revealed event in a **real time** flow.

➡ **Einstein Telescope**

BBH ~ $\mathbf{10^5}$-$\mathbf{10^6}$/years[10]



NASA Visualization Probes the Light-bending Dance of Binary Black Holes

Thank you.

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