Università degli Studi di Perugia

Master Thesis in Physics

# "Evaluating catalogues completeness extending the Virtual Observatory framework to estimate the $H_0$ Hubble constant with dark standard sirens"

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4 Maggio 2022 - AHEAD 2020

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

## Measuring the Hubble constant

The universe in which we live is not static but is expanding at a rate described by the Hubble constant, $H_0$ , in support of the Friedmann-Lemaître-Robertson-Walker metric (FLRW) [1,2] , the exact solution of Einstein’s field equation of general relativity.

$\sim$ 50 Mpc the Hubble law is well approximated by the note expression:

$$v = H_0 d$$

where *v* is an object's recession velocity and *d* is the proper distance between the observer and the object [4].

z << 1, the 'redshift-distance relation' is written as

$$d_L(z) = c\, z / H_0$$

➡ $H_0$ is independent of the other cosmological parameters from the $\Lambda$-cold-dark matter model, $\Lambda$CDM.

# The Hubble tension

- *Cosmic Microwave Background* (*CMB*) , early universe:

the latest Planck results give a Hubble constant value of $H_0 = 67.36 \pm 0.54\, km\, s^{-1}\, Mpc^{-1}$ [5].

- Related to local expansion , late universe, the intrinsic luminosity from light curves of *Type Ia Supernovae* (SN Ia), making them usable as **standard candles** :

SHOES, Supernovae-H0-for the equation of State of Dark energy, led to $H_0 = 73.24 \pm 1.44 km\, s^{-1}\, Mpc^{-1}$ [6].

The disagreement is of $\sim 4 - 6\sigma$ and it's statistically significant [7]

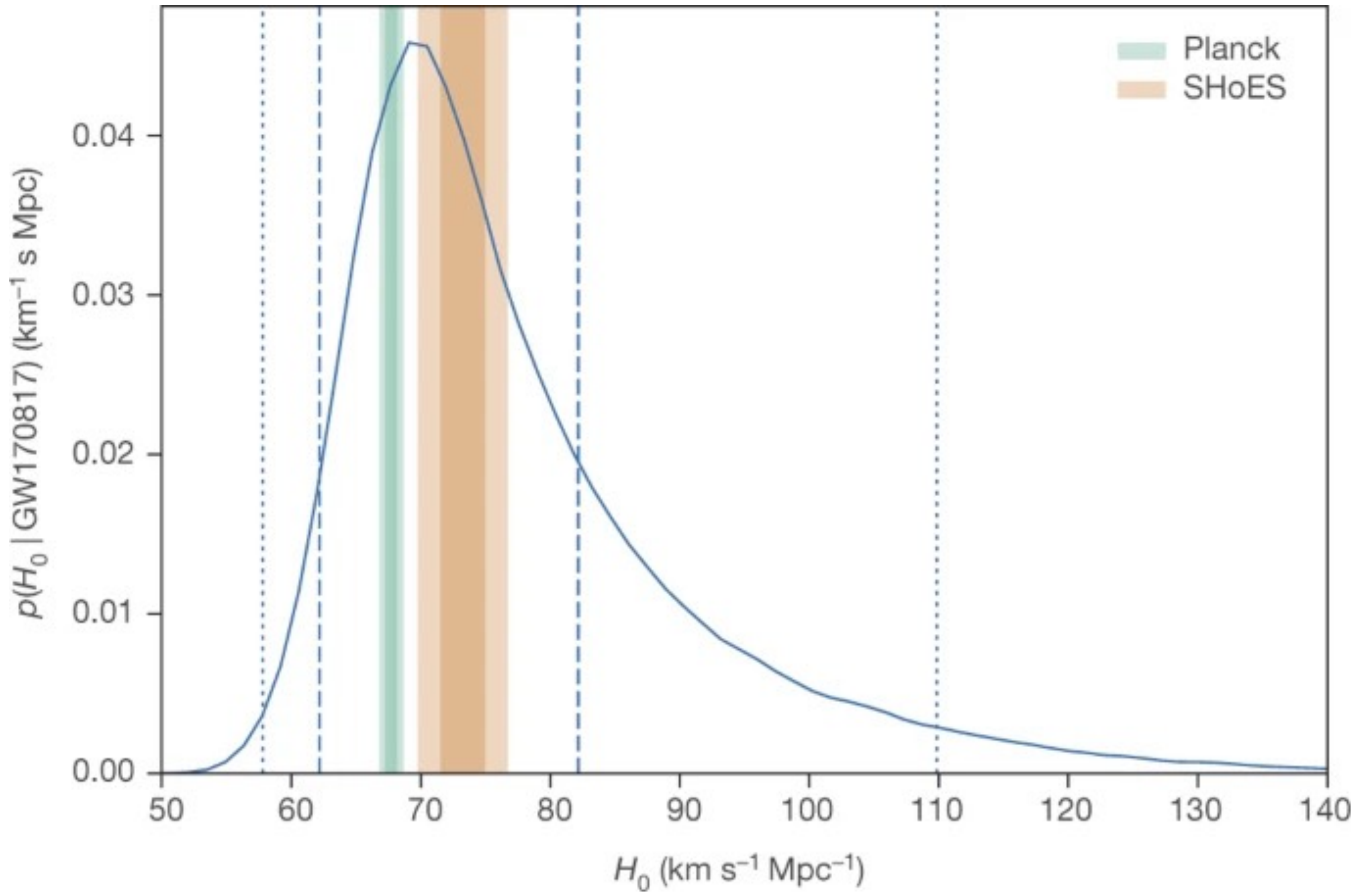


Fig. From reference [8]: Posterior distribution of H_0 based on the GW170817 data event

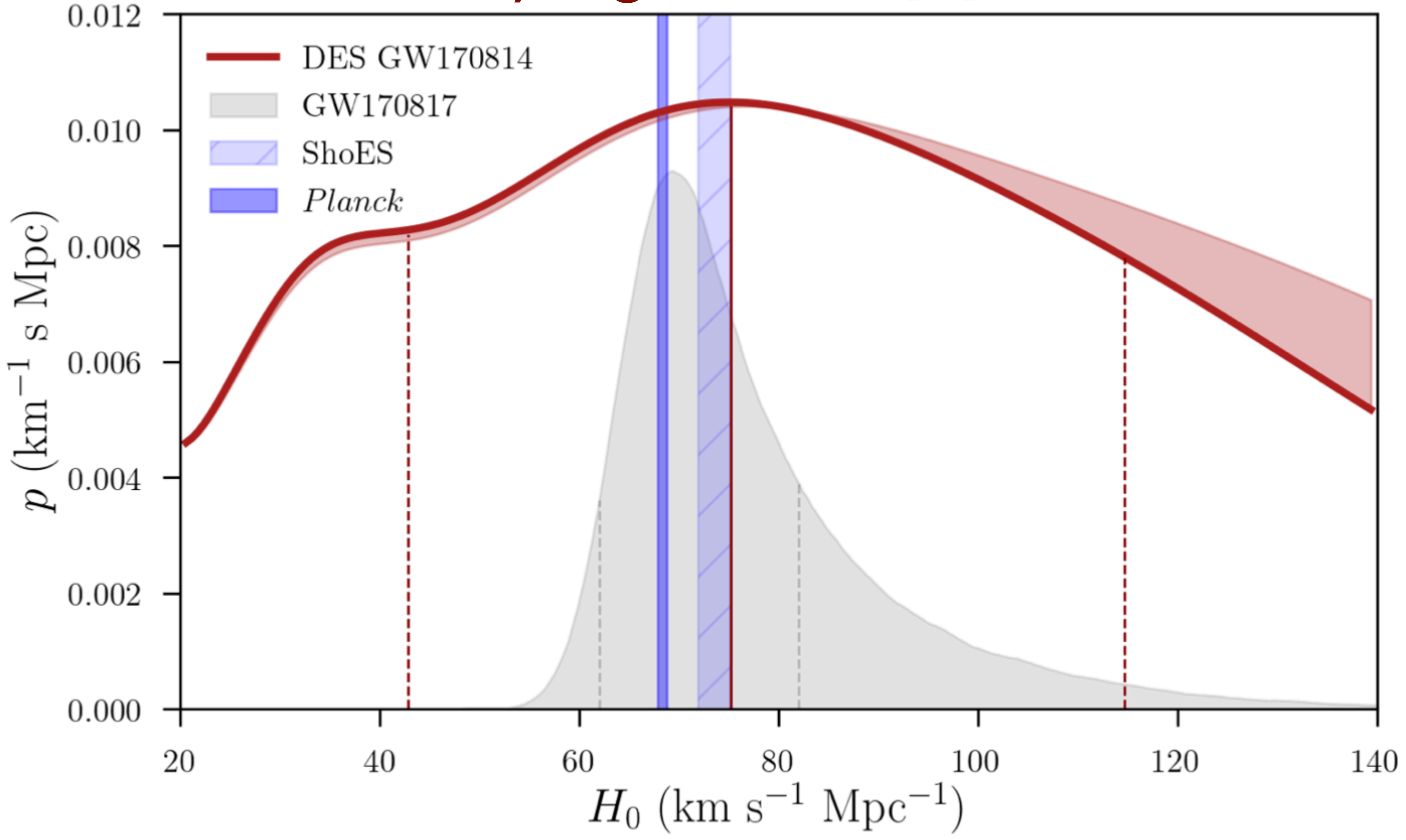


Fig. From reference [9]: Posterior distribution of H_0 based on the GW170814 data event

# Dark standard sirens

- 1986 *Schutz* developed a statistical method based on *galaxy clustering*, given a sufficient event rate [10] and other authors (Del Pozzo, Chen et al [11-14]) shows how *Bayesian* method works including all assumptions and prior information about a GW origin.



**Determining the Hubble constant from gravitational wave observations**

**Bernard F. Schutz**

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

the detectors to see binary neutron star sources at 100 Hz at a

**Inference of the cosmological parameters from gravitational waves: application to second generation interferometers**

Walter Del Pozzo[1,2]

[1] *Nikhef, National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, The Netherlands* and

[2] *School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*

(Dated: today)

The advanced world-wide network of gravitational waves (GW) observator begin operations within the current decade. Thanks to their improved sensit to yield a number of detections and thus to open a new observational wind

from a network of advanced interferometers will constrain the Hubble constant of $\sim 4-5\%$ at 95% confidence.

PACS numbers: 95.85.Sz,98.80.-k,04.30.-w

**A 2 per cent Hubble constant measurement from standard sirens within 5 years**

Hsin-Yu Chen[1,2,*], Maya Fishbach[2] and Daniel E. Holz[2,3,4]

THE ASTROPHYSICAL JOURNAL, 820:136 (9pp), 2016 April 1 doi:10.3847/0004-637X/820/2/136



CrossMark

**GALAXY STRATEGY FOR LIGO-VIRGO GRAVITATIONAL WAVE COUNTERPART SEARCHES**

NEIL GEHRELS[1], JOHN K. CANNIZZO[2,3], JONAH KANNER[4], MANSI M. KASLIWAL[5], SAMAYA NISSANKE[6], AND LEO P. SINGER[1,7]

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ABSTRACT

In this work we continue a line of inquiry begun in Kanner et al. which detailed a strategy for utilizing telescopes

*Key words:* galaxies: statistics – gamma-ray burst: general – gravitational waves – X-rays: general

**Cosmological Inference using Gravitational Wave Standard Sirens: A Mock Data Analysis**

Rachel Gray,[1,*] Ignacio Magaña Hernandez,[2,†] Hong Qi,[3,‡] Ankan Sur,[4,5,§] Patrick R. Brady,[6] Hsin-Yu Chen,[7] Will M. Farr,[8,9] Maya Fishbach,[10] Jonathan R. Gair,[11,12] Archisman Ghosh,[4,13,14,15] Daniel E. Holz,[16] Simone Mastrogiovanni,[17] Christopher Messenger,[1] Danièle A. Steer,[17] and John Veitch[1]

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[3] *Cardiff University, Cardiff CF24 3AA, United Kingdom*

# Dark standard sirens

- 1986 *Schutz* developed a statistical method based on *galaxy clustering*, given a sufficient event rate [10] and other authors (Del Pozzo, Chen et al [11-14]) shows how *Bayesian* method works including all assumptions and prior information about a GW origin.

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

- $\{x_{GW}\}$ 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;

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$x_{GW}$ passes some detection threshold

$$p(x_{GW} \,|\, D_{GW}, H_0) = \frac{p(D_{GW} \,|\, x_{GW}, H_0) p(x_{GW} \,|\, H_0)}{p(D_{GW} \,|\, H_0)} = \frac{p(x_{GW} \,|\, H_0)}{p(D_{GW} \,|\, H_0)}$$

**The galaxy 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):

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

# 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 FAIR:

Findable, Accessible, Interoperable and Reusable.

VOEvents, Flexible Image Transport System (FITS) astronomical file format

Multi-Order Coverage maps (MOC)

# 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;

**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], R. Macas[4], C. Messenger[3], P. Raffai[1,2] and R. S. de Souza[5]
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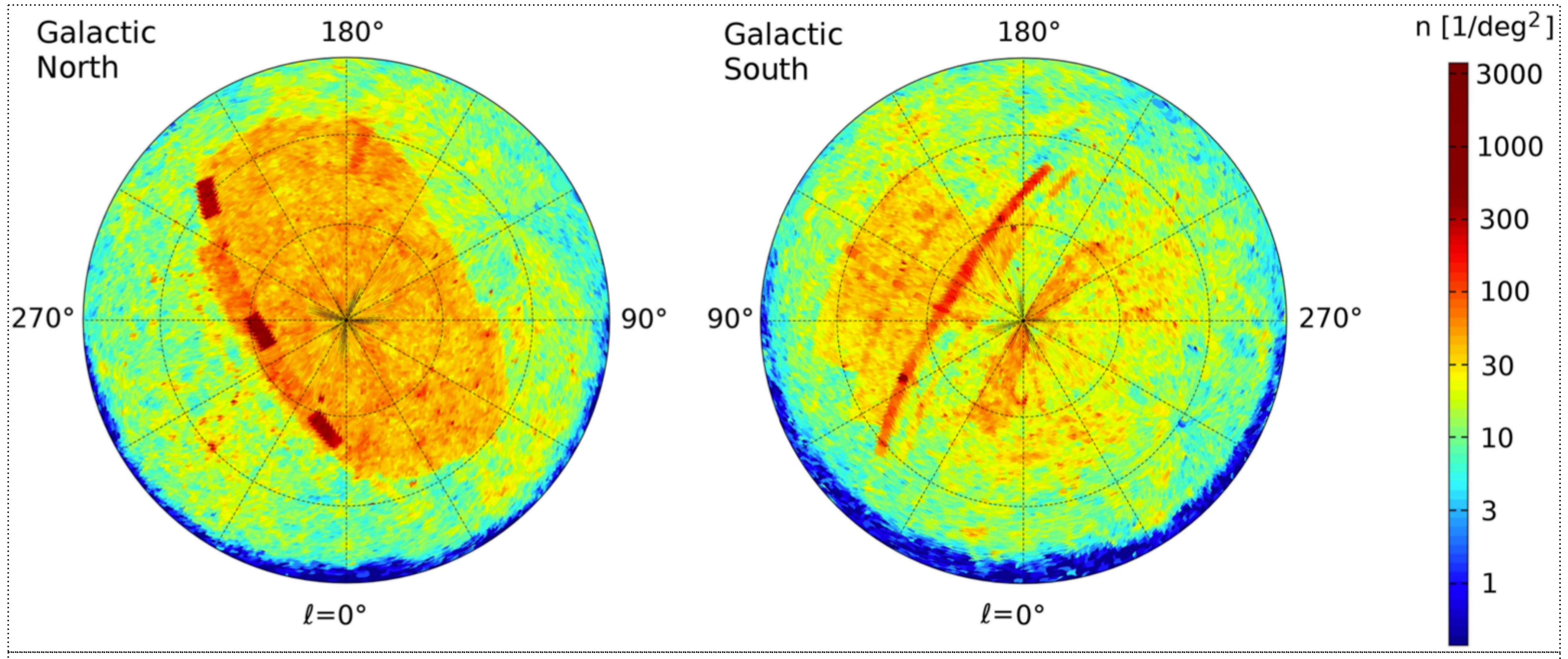
[5] *Department of Physics & Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255, USA*

1. The Gravitational Wave Galaxy Catalogue, GWGC
2. the 2Micron All-Sky Survey Extendeed Source Catalog 2MASS XSC,
3. the 2MASS Photometric Redshift Catalog 2MPZ,
4. the HyperLEDA
5. the Sloan Digital Sky Survey quasar catalogue from the 12th data release, SDSS-DR12Q




Number density (n) of objects in GLADE, using azimuthal projection with galactic coordinates. The plane of the Milky Way obscures the visibility of background galaxies near the edges of the two plots. Overdense (red) patches and stripes, originating from the HyperLEDA catalogue, show up as a result of deeper, more sensitive surveys, that have been made towards the corresponding sky directions.

# GLADE

The use of complete catalogues is necessary

1. to maximise the performance of the electromagnetic follow-ups

↓

Reducing the required number of pointings, the total integration time and the number of false positives found [18-19].

2. to include all the possible host galaxies of a GW event

↓

Improving the estimation of the $H_0$

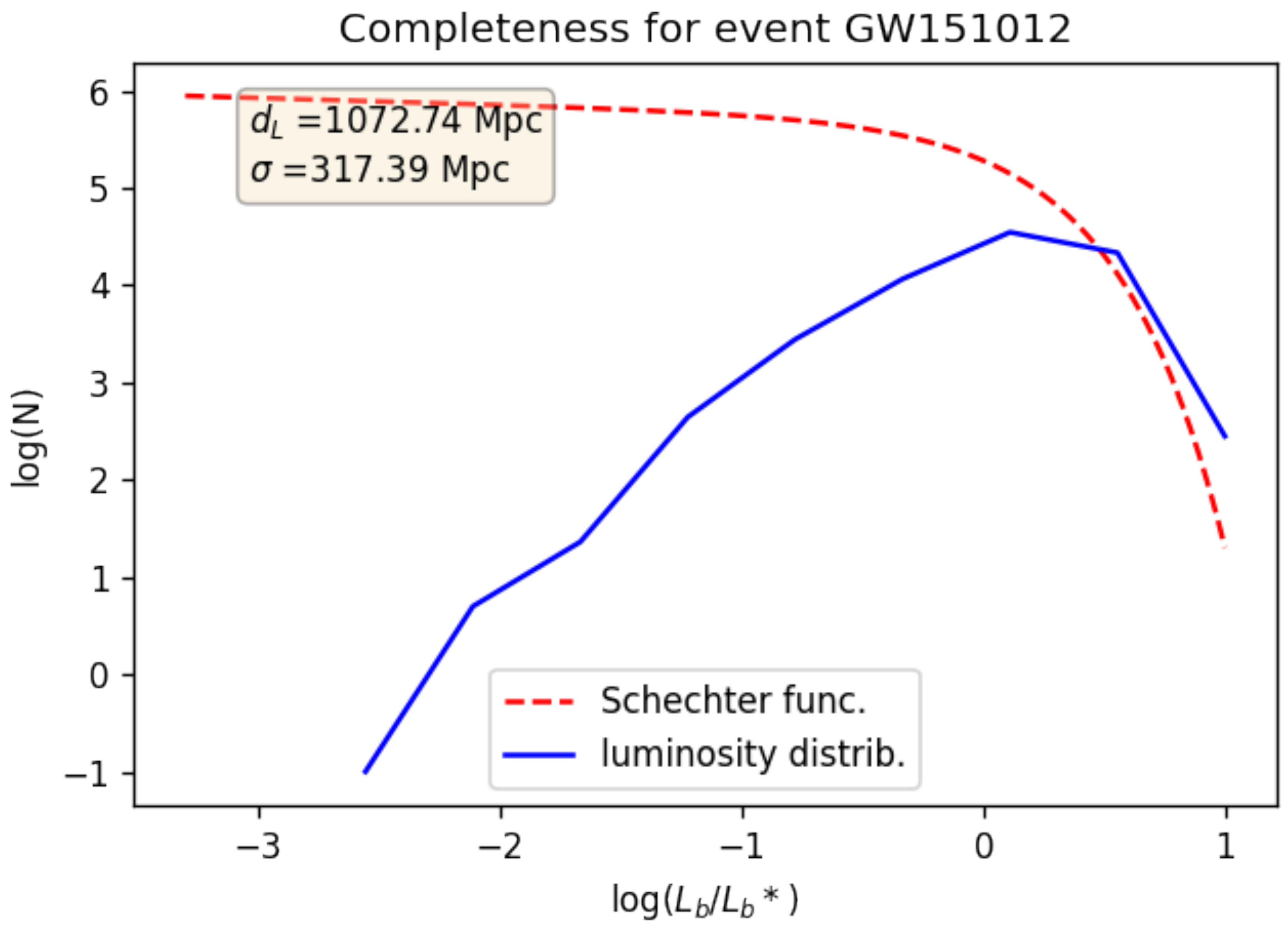
# Catalogue Completeness

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

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

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

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



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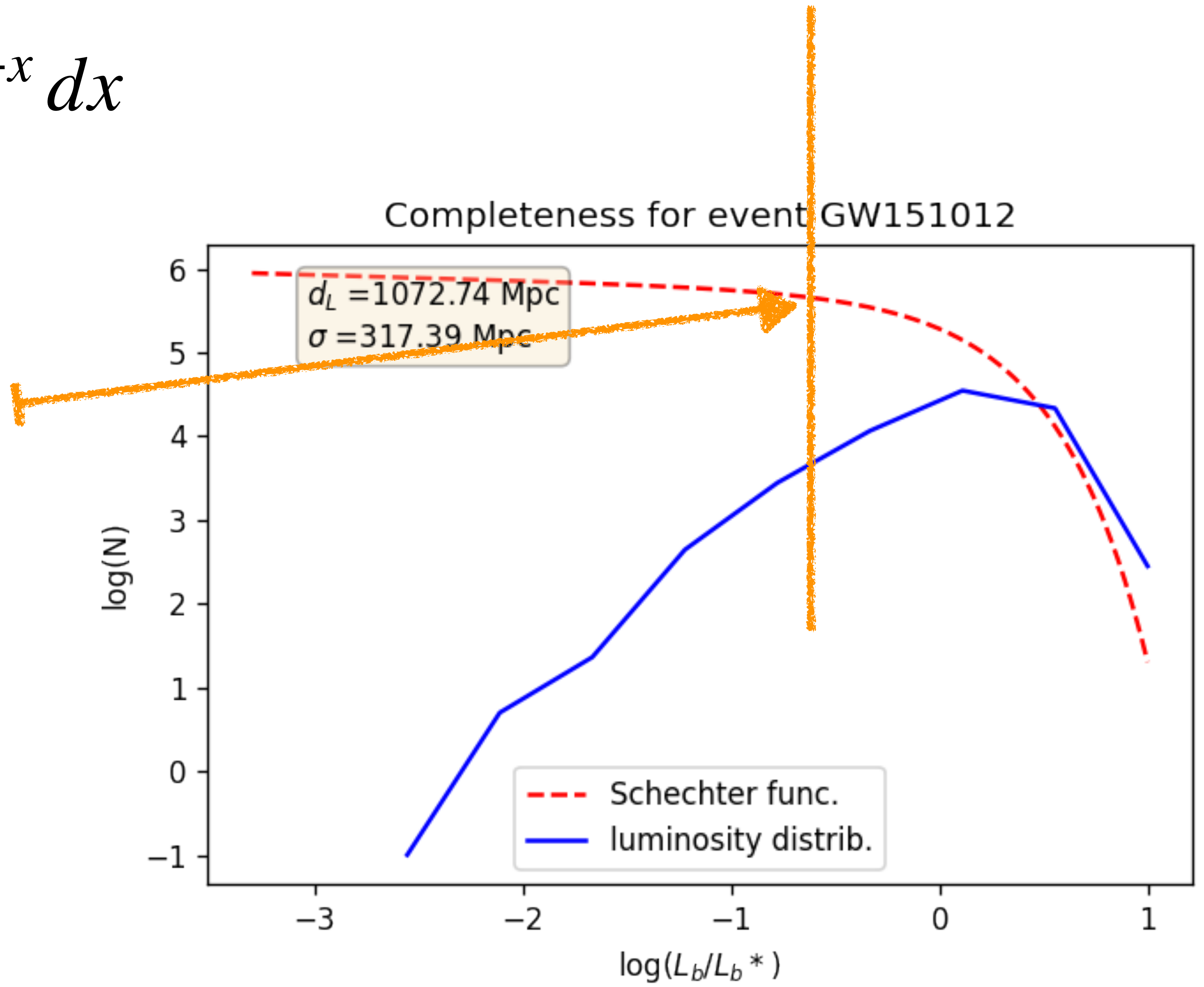
- $\alpha \;=\!-\,1.07 \;\pm\; 0.07.$



## Catalogue Completeness

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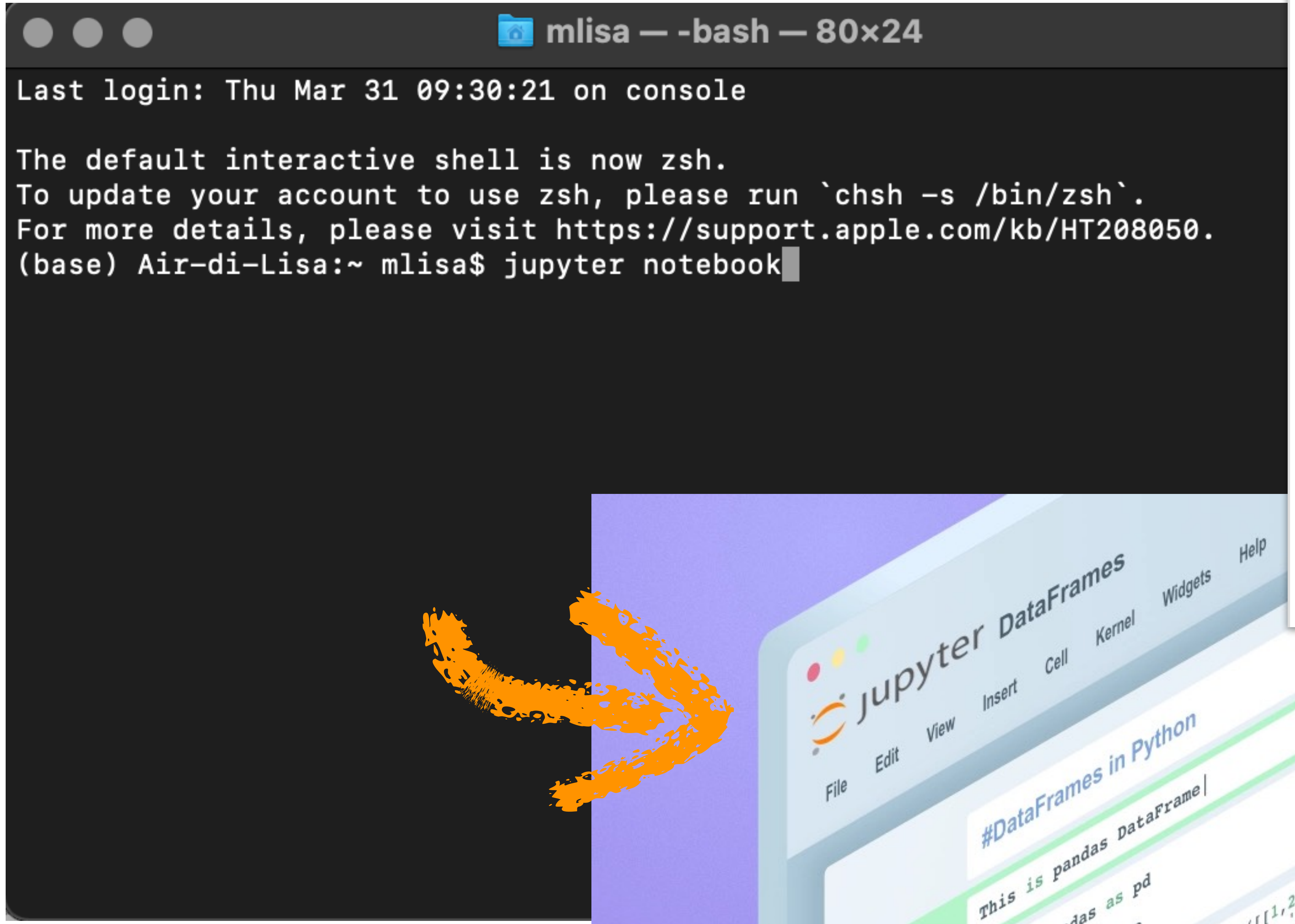
- 1976 *Schechter* proposed a model for a galaxy number density in a given comoving volume with a given luminosity [17].

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

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

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

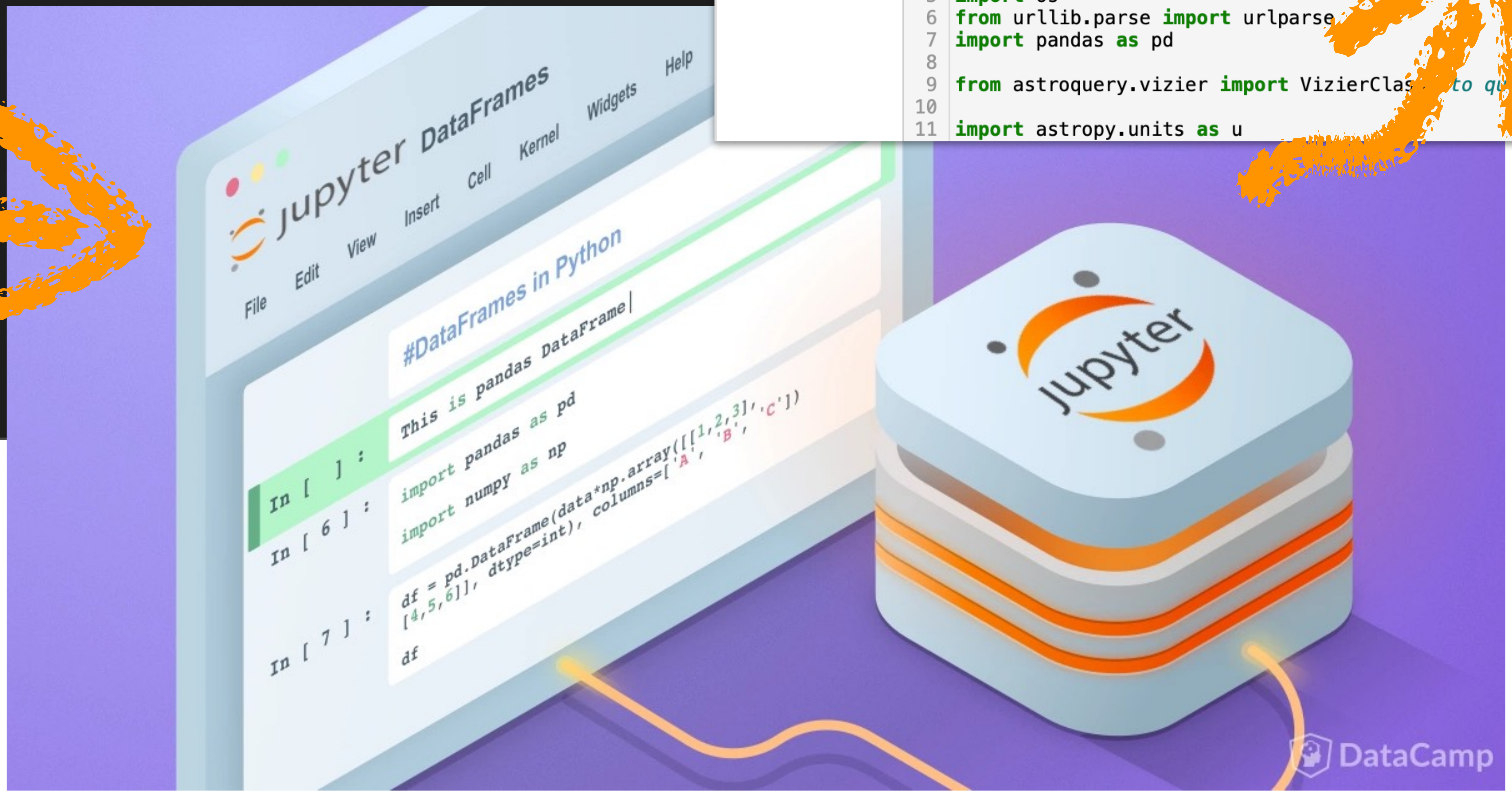
# Code and plots



```
Last login: Thu Mar 31 09:30:21 on console

The default interactive shell is now zsh.
To update your account to use zsh, please run `chsh -s /bin/zsh`.
For more details, please visit https://support.apple.com/kb/HT208050.
(base) Air-di-Lisa:~ mlisa$ jupyter notebook
```







## Estimate of the Completeness of the Glade catalog in the region of localization for the O1-O2-O3a-O3b observing run events

The code analyzes the skymaps of the observed events in the O1-O2-O3a-O3b runs and using the *Crossmatch* method with the **GLADE** catalog in Vizier, it estimates the distance of the source, **distmean**, the apparent average magnitude, $m_{th}$, the Luminosity distribution of Galaxies in shells with a radius equal to $\pm 3\sigma$ distmean. The distribution is compared with the *Schechter function* in order to evaluate completeness in the detected volume, expressed by the *coefficient of completeness* **c**. In addition, the number of missed galaxies from Schehcter's semiempirical function is estimated.

In order to get a more complete picture, we used the gas and dust skymap of the Milky Way from **CADE** to find out what percentage of the location of the event under study falls in it. This way you can estimate the efficiency of any future survey to complete the catalog.

In the concluding part of the code it is possible to visualize a summary table of all the analyzed events along with the useful parameters in this analysis.

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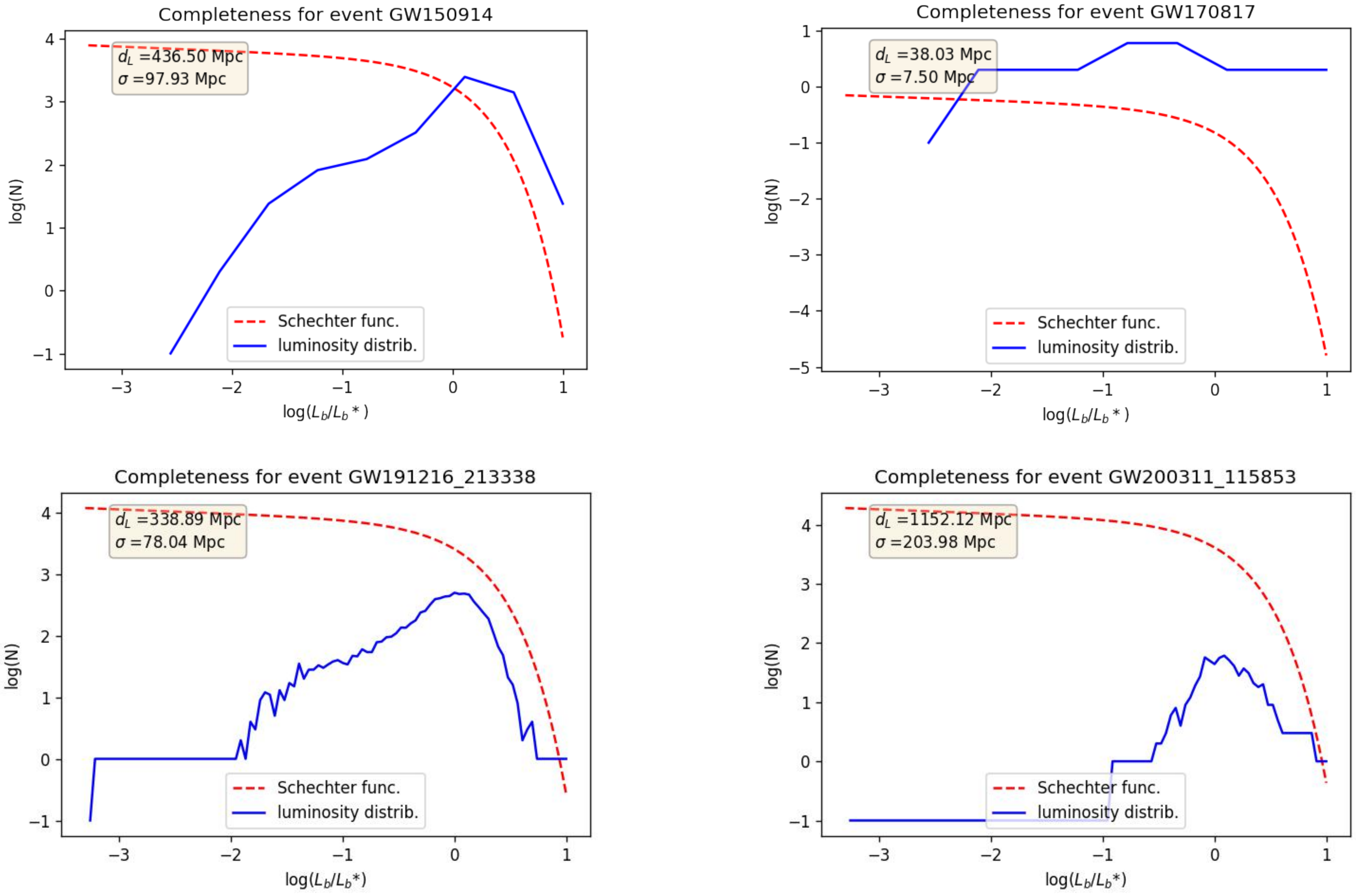
*Giuseppe Greco*, giuseppe.greco@pg.infn.it

*Gergely Dàlya*, gergely.dalya@ugent.be

In [5]:

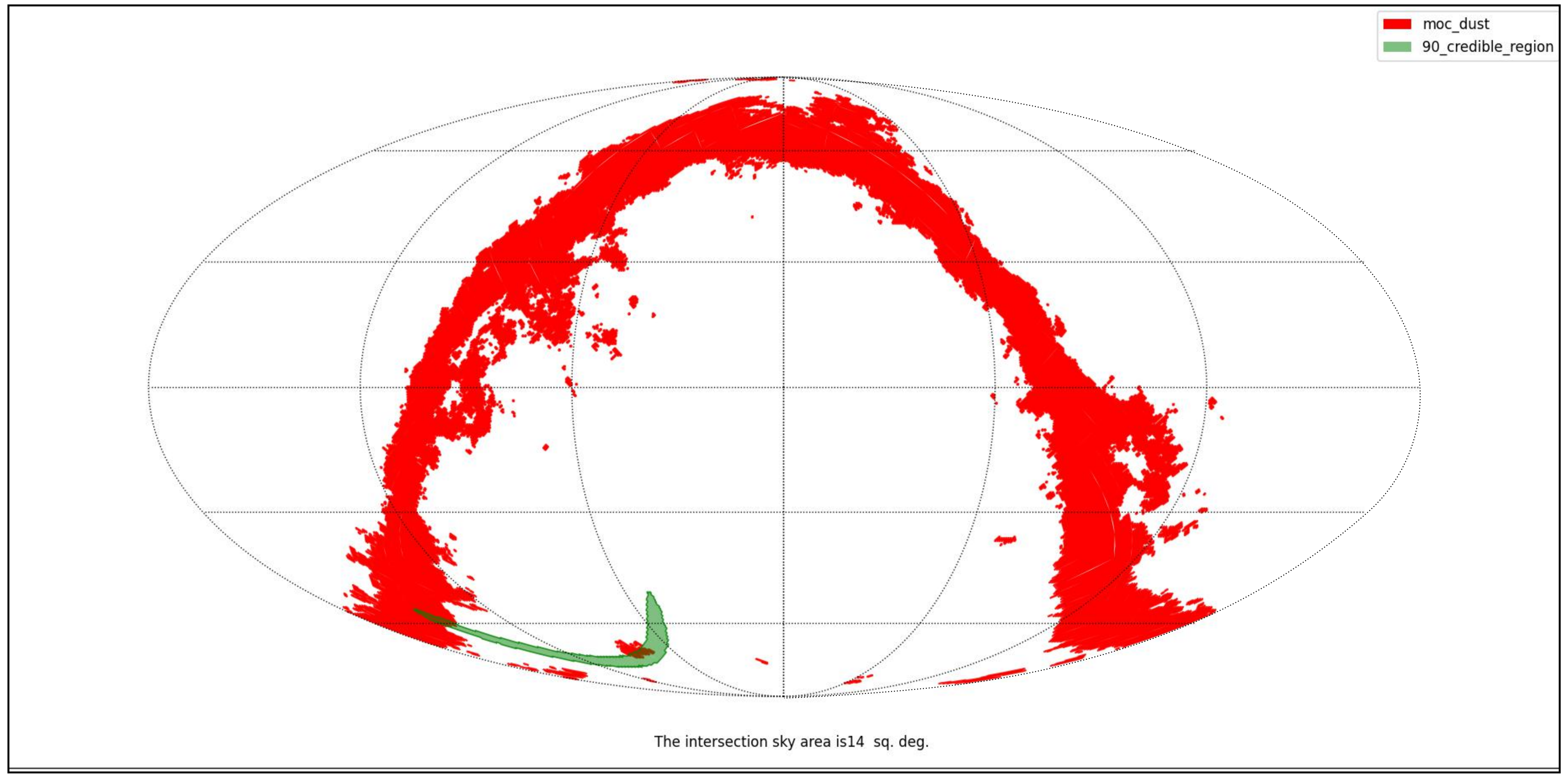
```
import numpy as np
import matplotlib.pyplot as plt
from tabulate import tabulate

import os
from urllib.parse import urlparse
import pandas as pd

from astroquery.vizier import VizierClas  to qu y astronomical web forms and databases

import astropy.units as u
```

# Luminosity functions

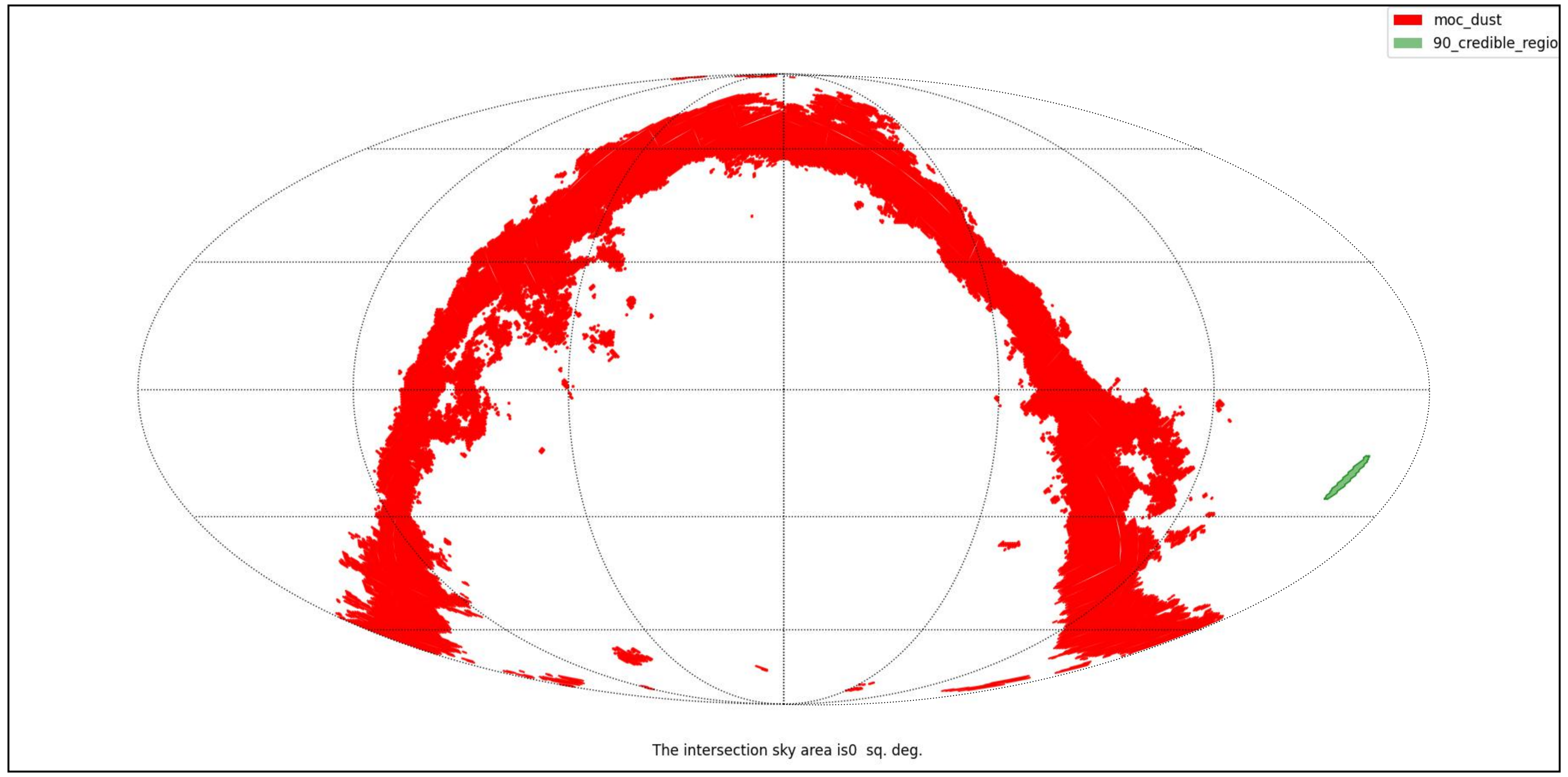


# Intersection with dust

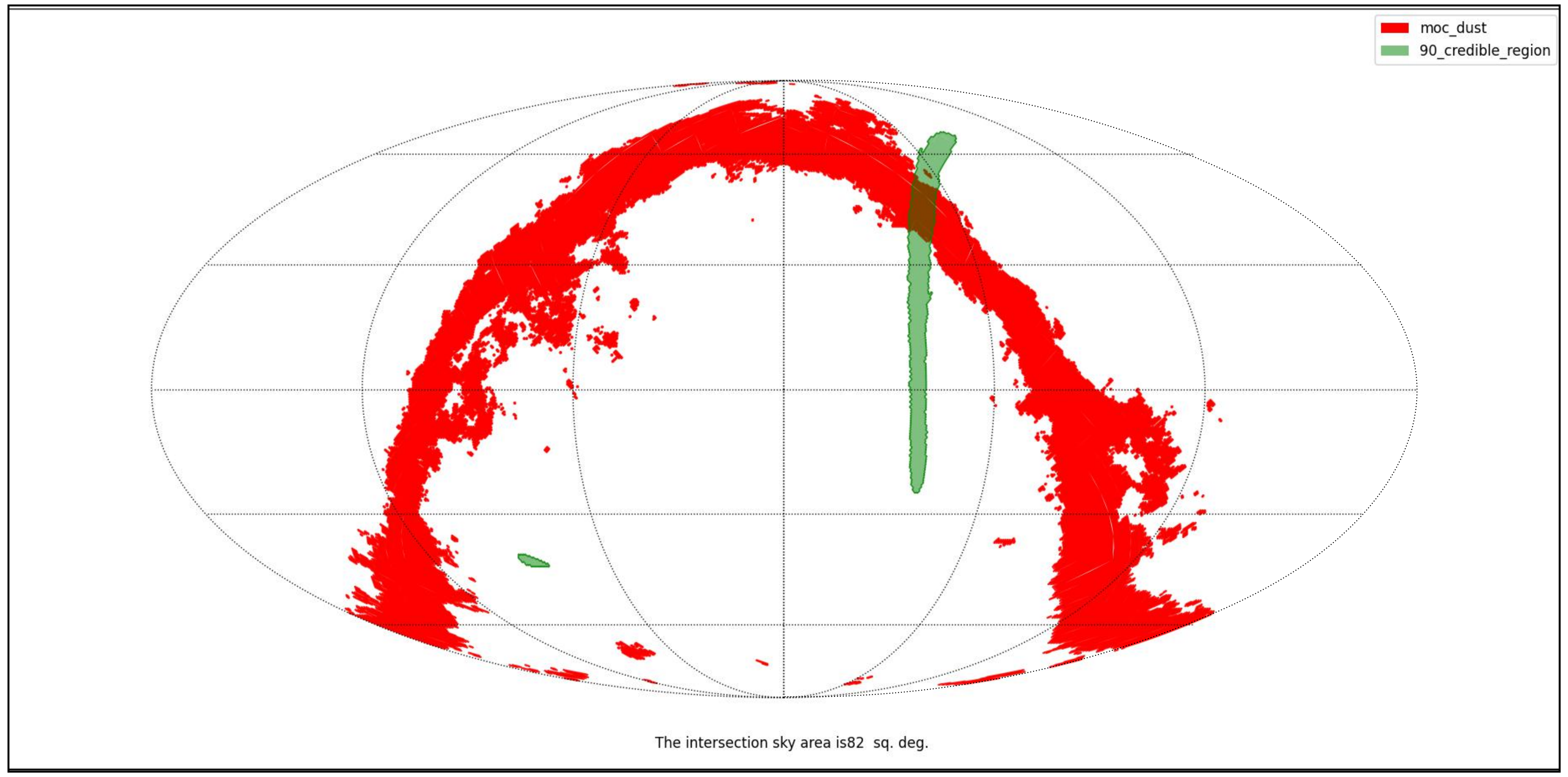
GW150914



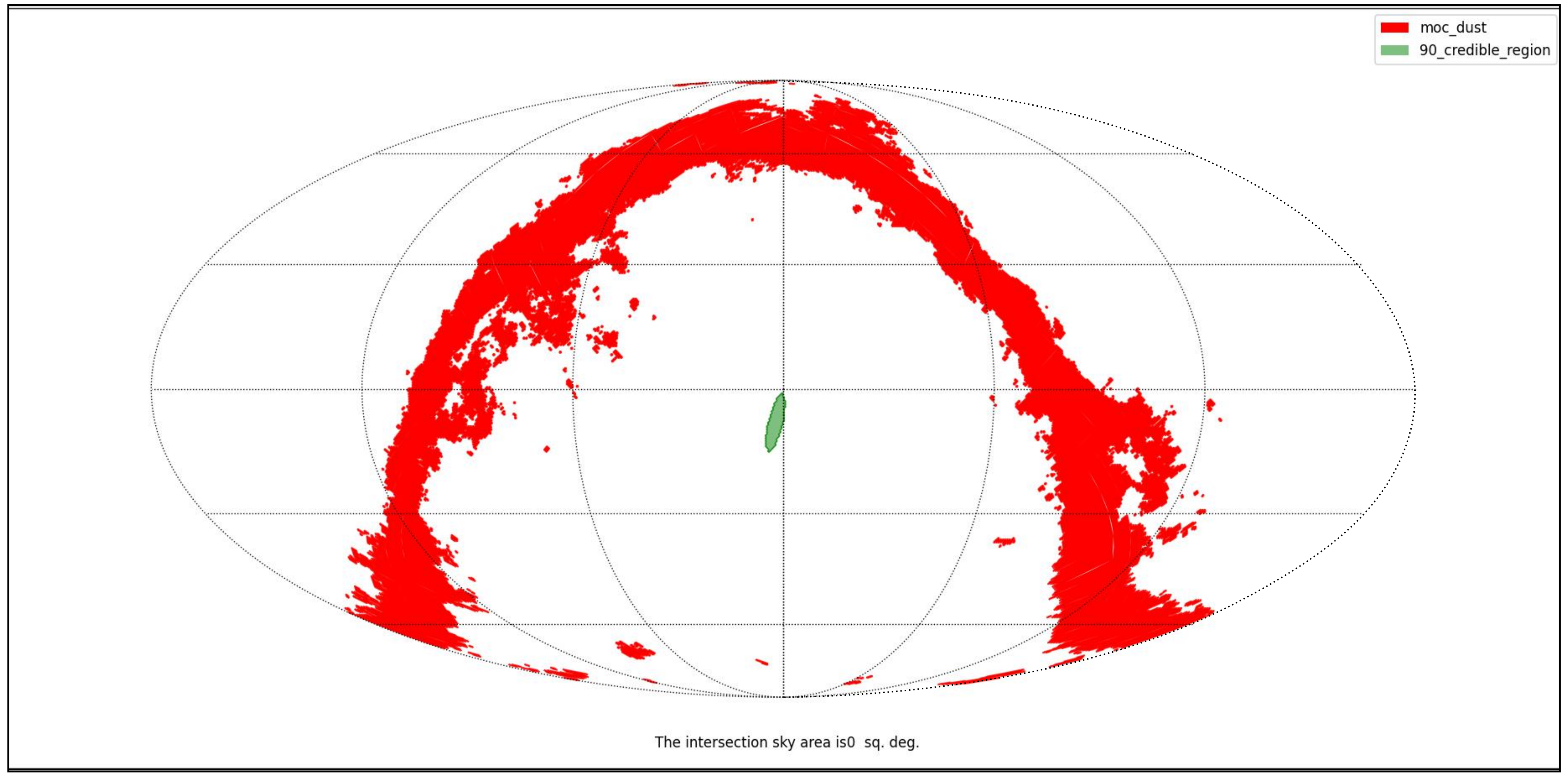

GW170817




GW191216_213338




GW200311_115853



# Next steps

➡ We will implemented **GCN notifications** for low latency analysis with information on the galaxies completeness of the volume as a function of the B-band Luminosity, in term of the percentage coefficient **c** and with the mean apparent magnitude **m_th** of the 90% credible regions

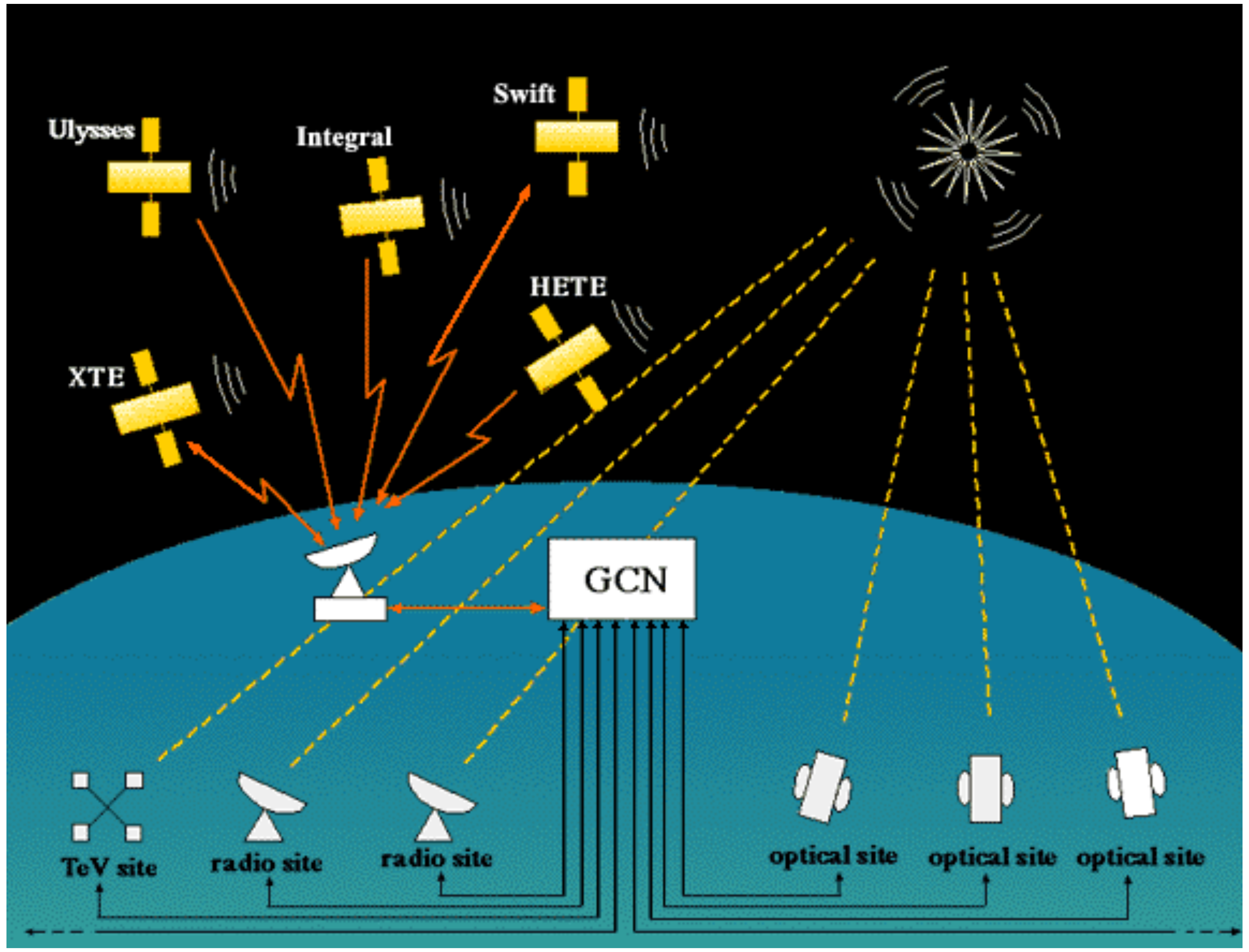



**Table B.1:** The following table represents the total observations of the three runs (O1-O2-O3a-O3b) of Ligo and Virgo Network with the probability distance of events (Dist [Mpc]) , the mean magnitude ($m_{th}$[magn]) of the Galaxies with 90% of probability, crossmatched with GLADE v2, and $c$, the Completeness Coefficient of the region.

| N° | GW event | Dist [Mpc] | $m_{th}$ [magn] | Intersection area [%] | V [$Mpc^3$] | c [%] |
|---|---|---|---|---|---|---|
| 1 | GW150914 | 436 | 17.11 | 7.55 | 3.5e+06 | 0.08 |
| 2 | GW151012 | 1073 | 17.78 | 18.75 | 5.8e+08 | 0.01 |
| 3 | GW151226 | 445 | 17.32 | 14.63 | 2.4e+07 | 0.06 |
| 4 | GW170104 | 989 | 18.02 | 3.5 | 2.5e+08 | 0.01 |
| 5 | GW170608 | 325 | 17.4 | 0.69 | 3.4e+06 | 0.1 |
| 6 | GW170729 | 2859 | 18.02 | 10.78 | 8.7e+09 | 0 |
| 7 | GW170809 | 1014 | 18.69 | 0 | 9.1e+07 | 0.01 |
| 8 | GW170814 | 586 | 17.54 | 0 | 4e+06 | 0.04 |
| 9 | GW170817 | 38 | 14.88 | 0 | 227 | 1 |
| 10 | GW170818 | 1068 | 17.8 | 0 | 1.5e+07 | 0 |
| 11 | GW170823 | 1926 | 18.34 | 18.69 | 3.5e+09 | 0 |

➡ We will learn to use the **gwcosmo** package to get the likelihood of the Hubble constant and to estimate its improvement depending on completeness;

https://github.com/simone-mastrogiovanni/gdr_gwcosmo_tutorial_2020/blob/master/notebooks/Tutorial.ipynb

# Thanks for your time

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# Missed Galaxies