# AGN and GW host, BBH mergers counterparts: follow the unexpected.

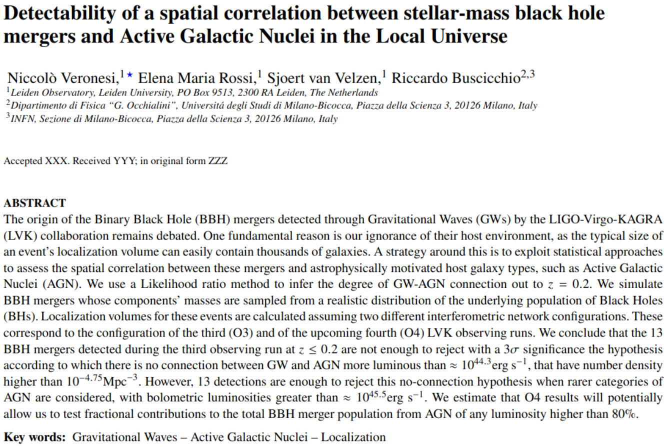
……

**IAP - High energy journal club April 2022**

**Ducoin Jean-Grégoire**

# Table of Contents

# AGN - GW connection



## Detectability of a spatial correlation between stellar-mass black hole mergers and Active Galactic Nuclei in the Local Universe

Niccolò Veronesi,[1]★ Elena Maria Rossi,[1] Sjoert van Velzen,[1] Riccardo Buscicchio[2,3]
[1]*Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands*
[2]*Dipartimento di Fisica "G. Occhialini", Universitá degli Studi di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[3]*INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*

Accepted XXX. Received YYY; in original form ZZZ

### ABSTRACT

The origin of the Binary Black Hole (BBH) mergers detected through Gravitational Waves (GWs) by the LIGO-Virgo-KAGRA (LVK) collaboration remains debated. One fundamental reason is our ignorance of their host environment, as the typical size of an event's localization volume can easily contain thousands of galaxies. A strategy around this is to exploit statistical approaches to assess the spatial correlation between these mergers and astrophysically motivated host galaxy types, such as Active Galactic Nuclei (AGN). We use a Likelihood ratio method to infer the degree of GW-AGN connection out to $z = 0.2$. We simulate BBH mergers whose components' masses are sampled from a realistic distribution of the underlying population of Black Holes (BHs). Localization volumes for these events are calculated assuming two different interferometric network configurations. These correspond to the configuration of the third (O3) and of the upcoming fourth (O4) LVK observing runs. We conclude that the 13 BBH mergers detected during the third observing run at $z \leq 0.2$ are not enough to reject with a $3\sigma$ significance the hypothesis according to which there is no connection between GW and AGN more luminous than $\approx 10^{44.3}$erg s$^{-1}$, that have number density higher than $10^{-4.75}$Mpc$^{-3}$. However, 13 detections are enough to reject this no-connection hypothesis when rarer categories of AGN are considered, with bolometric luminosities greater than $\approx 10^{45.5}$erg s$^{-1}$. We estimate that O4 results will potentially allow us to test fractional contributions to the total BBH merger population from AGN of any luminosity higher than 80%.

**Key words:** Gravitational Waves – Active Galactic Nuclei – Localization

# AGN - GW connection

## Where does the high mass BBH come from?

**Astrophysical Implications of the Binary Black-Hole Merger GW150914**

**Abstract:**

The discovery of the gravitational-wave source GW150914 with the Advanced LIGO detectors provides the first observational evidence for the existence of binary black-hole systems that inspiral and merge within the age of the Universe. Such black-hole mergers have been predicted in two main types of formation models, involving isolated binaries in galactic fields or dynamical interactions in young and old dense stellar environments. The measured masses robustly demonstrate that relatively heavy" black holes (>~25 Msun) can form in nature. This discovery implies relatively weak massive-star winds and thus the formation of GW150914 in an environment with metallicity lower than ~1/2 of the solar value. The rate of binary black-hole mergers inferred from the observation of GW150914 is consistent with the higher end of rate predictions (>~ 1 Gpc^(-3) yr^(-1)) from both types of formation models. The low measured redshift (z ~0.1) of GW150914 and the low inferred metallicity of the stellar progenitor imply either binary black-hole formation in a low-mass galaxy in the local Universe and a prompt merger, or formation at high redshift with a time delay between formation and merger of several Gyr. This discovery motivates further studies of binary-black-hole formation astrophysics. It also has implications for future detections and studies by Advanced LIGO and Advanced Virgo, and gravitational-wave detectors in space.

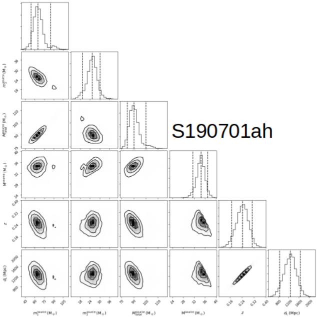
**Other Versions:**

ABSTRACTIONS BLOG

**Possible Detection of a Black Hole So Big It 'Should Not Exist'**

*At stake are fundamental ideas about how black holes form — and a six-way bet.*

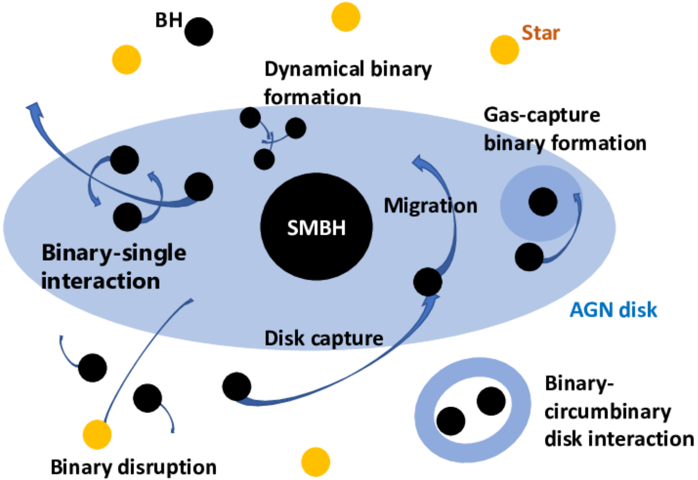
72



S190701ah

# AGN basics

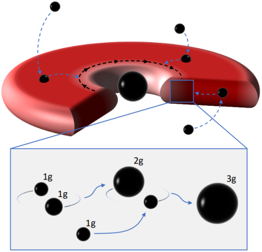
*AGN gravitational capture*



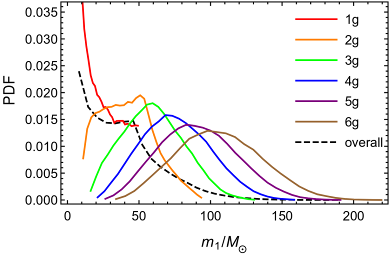
(Tagawa et al. 2020)

# AGN, one of the channel of BBH mergers?

Hierarchical Black Hole Mergers in AGN



(Gayathri et al. 2019)

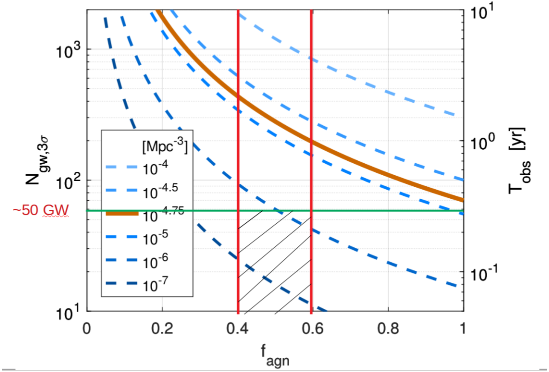


(Yang et al. 2019)

# Table of Contents

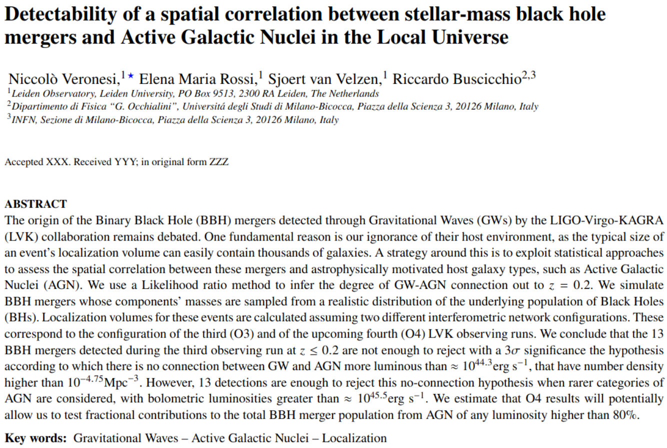
# Statistical approach

Gravitational-wave localization alone can probe origin of stellar-mass black hole mergers



(Bartos et al. 2017)

# (Veronesi et al. 2022)



## Detectability of a spatial correlation between stellar-mass black hole mergers and Active Galactic Nuclei in the Local Universe

Niccolò Veronesi,[1]★ Elena Maria Rossi,[1] Sjoert van Velzen,[1] Riccardo Buscicchio[2,3]
[1]*Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands*
[2]*Dipartimento di Fisica "G. Occhialini", Universitá degli Studi di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[3]*INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*

Accepted XXX. Received YYY; in original form ZZZ

### ABSTRACT

The origin of the Binary Black Hole (BBH) mergers detected through Gravitational Waves (GWs) by the LIGO-Virgo-KAGRA (LVK) collaboration remains debated. One fundamental reason is our ignorance of their host environment, as the typical size of an event's localization volume can easily contain thousands of galaxies. A strategy around this is to exploit statistical approaches to assess the spatial correlation between these mergers and astrophysically motivated host galaxy types, such as Active Galactic Nuclei (AGN). We use a Likelihood ratio method to infer the degree of GW-AGN connection out to $z = 0.2$. We simulate BBH mergers whose components' masses are sampled from a realistic distribution of the underlying population of Black Holes (BHs). Localization volumes for these events are calculated assuming two different interferometric network configurations. These correspond to the configuration of the third (O3) and of the upcoming fourth (O4) LVK observing runs. We conclude that the 13 BBH mergers detected during the third observing run at $z \leq 0.2$ are not enough to reject with a $3\sigma$ significance the hypothesis according to which there is no connection between GW and AGN more luminous than $\approx 10^{44.3}$erg s$^{-1}$, that have number density higher than $10^{-4.75}$Mpc$^{-3}$. However, 13 detections are enough to reject this no-connection hypothesis when rarer categories of AGN are considered, with bolometric luminosities greater than $\approx 10^{45.5}$erg s$^{-1}$. We estimate that O4 results will potentially allow us to test fractional contributions to the total BBH merger population from AGN of any luminosity higher than 80%.

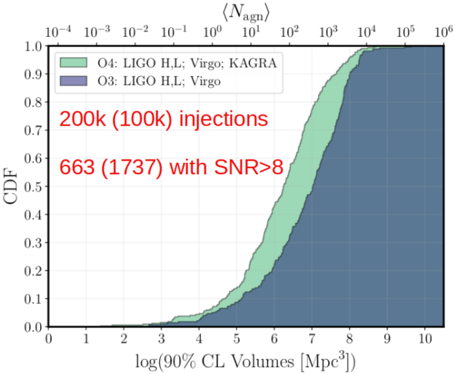
**Key words:** Gravitational Waves – Active Galactic Nuclei – Localization

# Statistical approach

Correlation between Gravitational Waves 90% credibility level localization volumes and the positions of AGN ($z \leq 0.2$)

- Two catalogues of simulated GW detection (O3 and O4)
  - Synthetic population of BBHs
    - Power Law + Peak analytical model (Abbott et al. 2021b)
      $\Rightarrow$ sample values of masses
      $\Rightarrow$ uniform spin magnitude distribution between 0 and 1
  - Simulate the response of the network (duty cycle, keep SNR$\geq 8$)
  - Evaluation of 90% localization volumes

# Statistical approach



200k (100k) injections

663 (1737) with SNR>8

**Figure 1.** Cumulative distributions of the 90% CL localization volumes of simulated GW events with SNR> 8 and $z \leq 0.2$. The blue and the green histograms are for O3 and O4 runs, respectively. The top axis shows the expected number of AGN within the corresponding localization volume, for a homogeneous distribution of AGN with a number density of $n_{\rm agn} = 10^{-4.75}\,{\rm Mpc}^{-3}$.

# Statistical approach

- Minimum number of GW detections to test the AGN origin $N_{GW}^{3\sigma}$

GW <u>not</u> originating from an AGN, number of AGN within $V_i$

$$\mathscr{B}_i(N_{AGN,i}) = Poiss(N_{AGN,i}, \rho_{AGN} V_i)$$

GW originating from an AGN, number of AGN within $V_i$

$$\mathscr{S}_i(N_{AGN,i}) = Poiss(N_{AGN,i} - 1, \rho_{AGN} V_i)$$

hypothesis that a fraction $f_{agn}$ of the detected GWs originated from AGN

$$\mathscr{L}(f_{agn}) = \prod_i [f_{agn} \mathscr{S}_i + (1 - f_{agn}) \mathscr{B}_i]$$

# Statistical approach

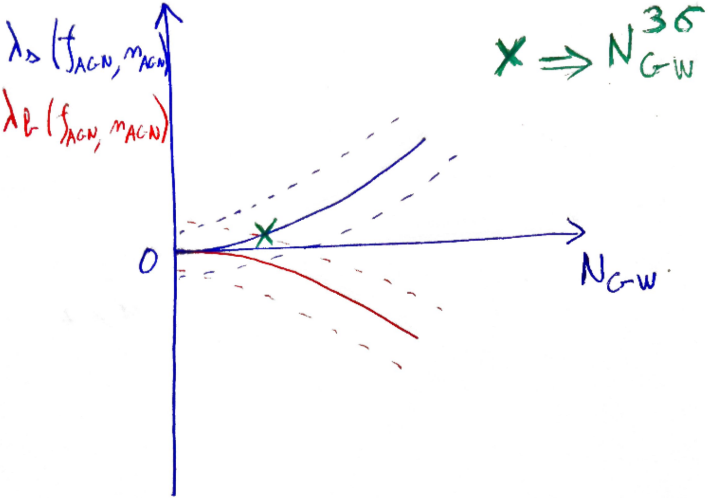
Test statistic of a set of detected GWs is the likelihood ratio

$$\lambda = 2log\left[\frac{\mathscr{L}(f_{agn})}{\mathscr{L}(f_0)}\right]$$

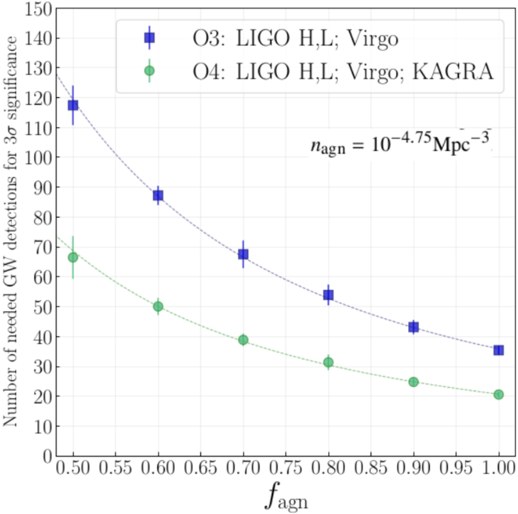
Every simulation is therefore associated to a value of $\lambda$ that depends on $\rho_{AGN}$ , $N_{gw}$ , $f_{agn}$ , error box of each simulated GW event, and the number $N_i$ of AGN within such volume.

3000 simulation centered in an AGN ($\lambda_s$), 3000 simulation randomly distributed ($\lambda_b$). no-connection hypothesis is reached when the median value of the distribution of $\lambda_s$ corresponds to a p-value lower than 0.00135 ($3\sigma$) when compared to the $\lambda_b$ distribution.

# Statistical approach

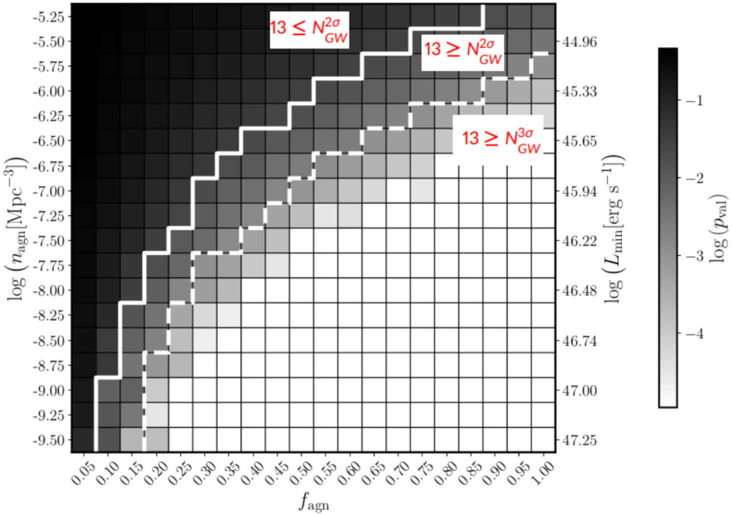


# Statistical approach



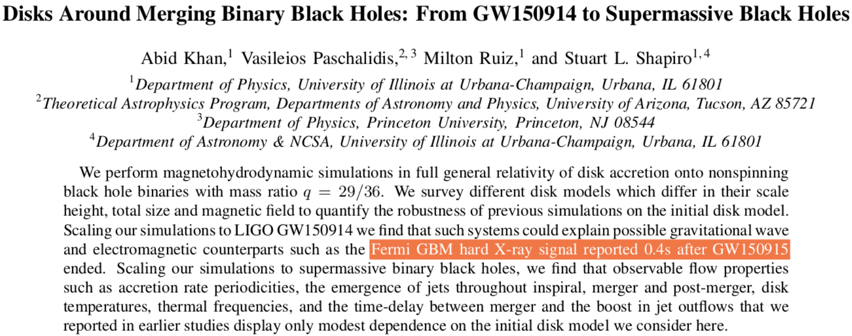
# Statistical approach

O3, 13 detected BBH mergers with $z \lesssim 0.2$. $N_{GW} = 13$ :



## Table of Contents

# BBH - EM counterpart



**Disks Around Merging Binary Black Holes: From GW150914 to Supermassive Black Holes**

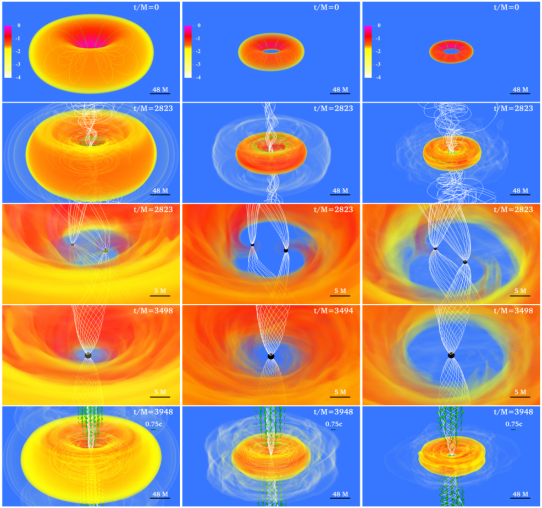
Abid Khan,[1] Vasileios Paschalidis,[2, 3] Milton Ruiz,[1] and Stuart L. Shapiro[1, 4]

[1]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801*
[2]*Theoretical Astrophysics Program, Departments of Astronomy and Physics, University of Arizona, Tucson, AZ 85721*
[3]*Department of Physics, Princeton University, Princeton, NJ 08544*
[4]*Department of Astronomy & NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801*

We perform magnetohydrodynamic simulations in full general relativity of disk accretion onto nonspinning black hole binaries with mass ratio $q = 29/36$. We survey different disk models which differ in their scale height, total size and magnetic field to quantify the robustness of previous simulations on the initial disk model. Scaling our simulations to LIGO GW150914 we find that such systems could explain possible gravitational wave and electromagnetic counterparts such as the Fermi GBM hard X-ray signal reported 0.4s after GW150915 ended. Scaling our simulations to supermassive binary black holes, we find that observable flow properties such as accretion rate periodicities, the emergence of jets throughout inspiral, merger and post-merger, disk temperatures, thermal frequencies, and the time-delay between merger and the boost in jet outflows that we reported in earlier studies display only modest dependence on the initial disk model we consider here.

(Khan et al. 2018)

# BBH - EM counterpart



(Khan et al. 2018)

# BBH - EM counterpart

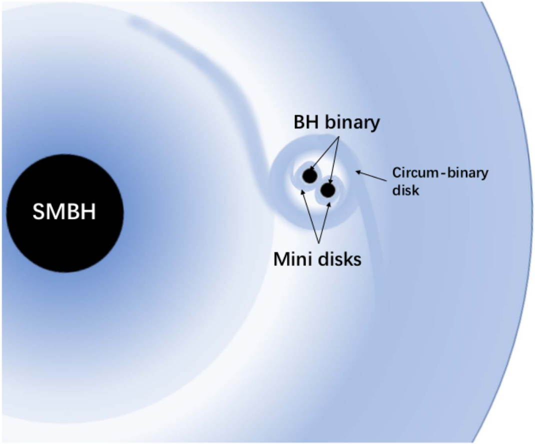
### Not very convincing

The models require:

- Large spins
- Large mass ratio
- Eccentricity
- Really high masses
- **Very high density of matter around the binary**

# BBH - EM counterpart

*AGN channel fulfilling the requirement*

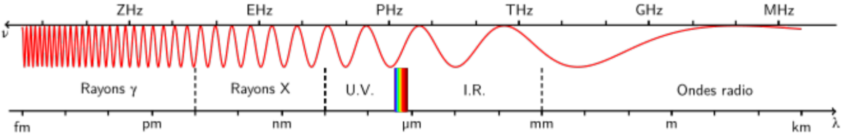


(Shu-Xu et al. 2019)

# BBH - Observation strategy

*expected emission?*

l’embarras du choix



(Loeb 2016)
Gamma ray

(Khan et al. 2018)
Hard X-ray

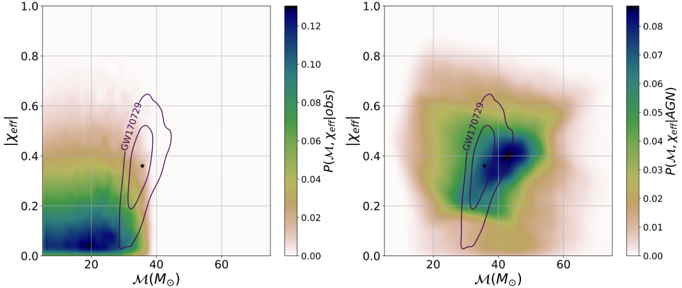
(Farris et al. 2011)
IR + optic

(Shu-Xu et al. 2019)
FRB

(De Mink et al. 2017)
X-ray to IR

# Offline analysis

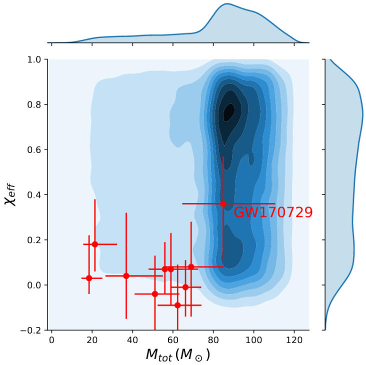
## *Is a given event compatible with AGN channel?*



(Yang et al. 2019)

# Offline analysis

*Is a given event compatible with AGN channel?*

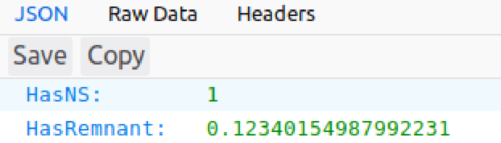


(Shu-Xu et al. 2019)

# Low-latency analysis

*AGN flag*

## An analogue of em_bright



```
HasNS:          1
HasRemnant:     0.12340154987992231
```

Useful for EM follow

Is there any reliable calculation?

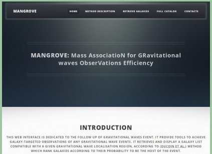
# BBH - Observation strategy

*AGN channel fulfilling the requirement*

~~Galaxy targeting~~ ⇒ AGN targeting

## Which catalog?

mangrove catalog



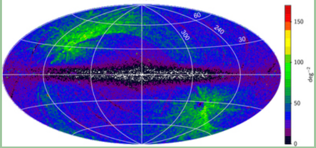
**MANGROVE:** Mass AssociatioN for GRavitational waves ObserVations Efficiency

INTRODUCTION

THIS WEB INTERFACE IS DEDICATED TO THE FOLLOW UP OF GRAVITATIONAL WAVES EVENT. IT PROVIDE TOOLS TO ACHIEVE GALAXY-TARGETED OBSERVATIONS OF ANY GRAVITATIONAL WAVE EVENTS. IT RETRIEVES AND DISPLAY A GALAXY LIST COMPATIBLE WITH A GIVEN GRAVITATIONAL WAVE LOCALISATION REGION, ACCORDING TO (DUCOIN ET AL.) METHOD WHICH RANK GALAXIES ACCORDING TO THEIR PROBABILITY TO BE THE HOST OF THE EVENT.

(Ducoin et al. 2019)

Identification of 1.4 Million Active Galactic Nuclei in the Mid-Infrared using WISE Data



(Secrest et al. 2015)

# THANKS!