

# An Extended List of Galaxies for Gravitational-Wave Searches in the Advanced Detector Era

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# Motivation

Main motivation: to support EM follow-up efforts. Most important parameters are *B mag*, *z* and possibly IR magnitudes (they correlate with the stellar mass of the galaxy [1]).

Recently more galaxy catalogs became available for the same purpose such as CLU [2], our project is independent from them.

Catalog used in the initial detector era: GWGC [3]

- ▶ Contains 53,255 galaxies
- ▶ Complete out to 40 Mpc

Higher completeness (even out to  $\sim 300$  Mpc) is needed in the advanced detector era. [4]

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[1] Wen, X-Q., Wu, H., Zhu, Y.-N. et al., 2013, MNRAS, doi:10.1093/mnras/stt939

[2] Gehrels, N., Cannizzo, J. K., Kanner, J. et al., 2015, submitted to ApJ  
<http://arxiv.org/abs/1508.03608>

[3] White, D. J., Daw, E. J. & Dhillon, V. S., 2011, Class. Quantum Grav., **28** 085016

[4] Evans, P. A., Osborne, J. P., Kennea, J. A. et al., 2015, astro-ph/1506.01624

# Catalogs used

## 2MASS XSC [1]

- ▶ 1,646,844 galaxies
- ▶ contains no distances or B-band magnitude

## 2MPZ (value added, 2MASS + WISE + SuperCOSMOS) [2]

- ▶ 928,353 galaxies
- ▶ photometric redshift and B-band magnitude for every galaxy

## HyperLEDA [3]

- ▶ 836,388 galaxies
- ▶ we improved galaxy-quasar separation and left out quasars

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[1] <http://www.ipac.caltech.edu/2mass/>

[2] Bilicki, M., Jarrett, T. H., Peacock, J. A. et al., 2014, ApJS, **210** 16 pp.

[3] <http://leda.univ-lyon1.fr/>

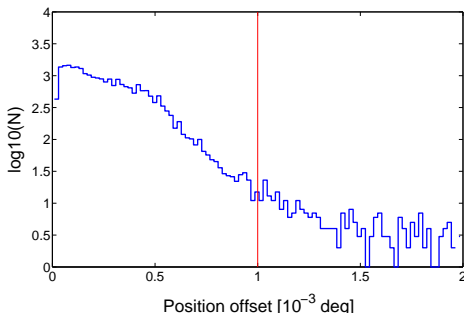
# Filtering out duplicate galaxies

We have used a k-d tree algorithm. It quickly eliminates large portions of the search space, have  $\mathcal{O}(\log n)$  time complexity for nearest neighbour search.

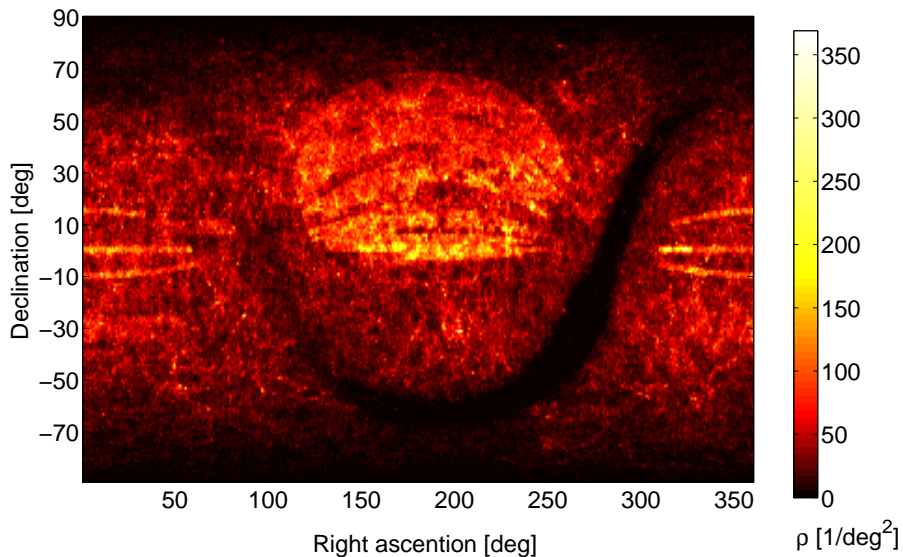
Criterion: position offset  $< 0.001^\circ$

*B mag* or *z* based filters were not used since they only had a very minor effect.

$\Rightarrow$  The final catalog contains 2,068,841 galaxies.



# Density of galaxies



2MASS galaxies do not have  $B$  mag and  $z \rightarrow$  2MPZ

We have a non-LIGO member machine learning-expert in our group (R. S. de Souza).

Random forest algorithm: a robust methodology, requires little fine tuning. [1]

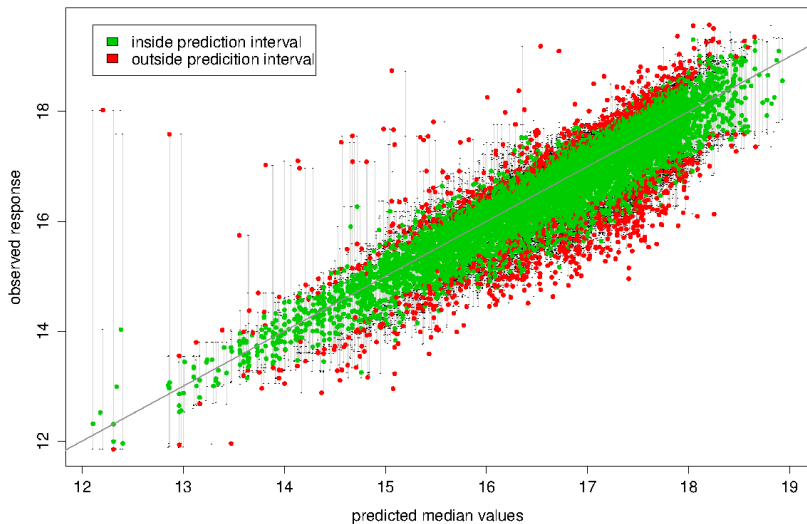
Enlarging the teaching sample: the precision enhances slowly and it becomes computationally costly

Teaching sample: 10,000 2MPZ galaxies, learning based on  $J$ ,  $H$ ,  $K$  magnitudes

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[1] Meinshausen, N., 2006, *Journal of Machine Learning Research*, 7 983

## 90 % prediction intervals on out-of-bag data

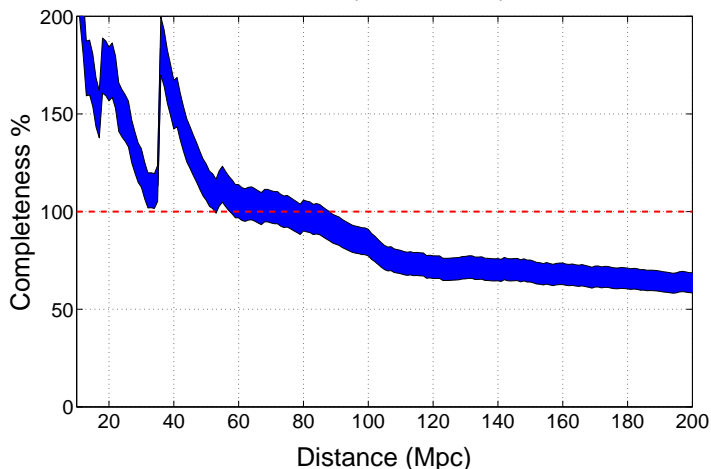




# Completeness

Using the same method as in the GWGC paper. [1]

Blue luminosity density:  $(1.98 \pm 0.16) \cdot 10^{-2} L_{10} \text{ Mpc}^{-3}$ . [2]



At 300 Mpc:  
53%

[1] White, D. J., Daw, E. J. & Dhillon, V. S., 2011, *Class. Quantum Grav.*, **28** 085016

[2] Kopparapu, R. K., Hanna, C., Kalogera, V. et al., 2008, *ApJ*, **675**, 1495

# Summary and comparison with other catalogs

	GWGC [1]	CLU [2]	GLADE
No. of galaxies	53,255	?	2,068,841
Completeness % at 60 Mpc	60	100	$104 \pm 7$
Completeness % at 120 Mpc		80	$71 \pm 5$
Completeness % at 180 Mpc		40	$65 \pm 5$

Other advantages:

- ▶ Value-added with  $B$  mag and  $z$  data
- ▶ We are working on associating stellar masses to each galaxy
- ▶ We have a working pipeline to associate any other parameters relevant for the Collaboration

[1] White, D. J., Daw, E. J. & Dhillon, V. S., 2011, *Class. Quantum Grav.*, **28** 085016

[2] Gehrels, N., Cannizzo, J. K., Kanner, J. et al., 2015, submitted to *ApJ*  
<http://arxiv.org/abs/1508.03608>

You can download the catalog and read its documentation using this website:

`aquarius.elte.hu/glade`



The screenshot shows a web page for the GLADE project. At the top left is the EGRG logo (Eötvös Gravity Research Group) and at the top right is the seal of Eötvös Loránd University. The main content area has a left sidebar with navigation links: 'Description', 'Download the catalog', and 'Documentation'. The main text area features the title 'GLADE (Galaxy List for the Advanced Detector Era)' followed by a 'Description' section. The description text states: 'We are introducing a value-added full-sky galaxy catalog with high completeness for identifying gravitational wave (GW) sources in order to support future electromagnetic (EM) follow-up projects of the LIGO/Virgo Collaboration. The catalog has been constructed (combined and matched) from four existing galaxy catalogs: GWGC, 2MPZ, 2MASS XSC and HyperLEDA. It contains 2,068,841 galaxies, which is two orders of magnitude greater than the number of galaxies in the GWGC catalog alone (53,312), which is currently in use by the collaboration. Furthermore, we have associated B-band magnitudes and photometric redshifts for 548,876 2MASS galaxies which lacked these properties with a regression algorithm trained on a subsample of the 2MPZ catalog. Our catalog is complete to 73 Mpc and even at 300 Mpc has a relatively high completeness (53%). Naturally, our catalog could be used in a broad range of various astrophysical projects besides EM follow-up efforts.'