Optimisation of the optical follow up of gravitational waves events

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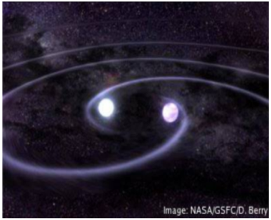
JRJC 2019

Sources

Search for electromagnetic counterparts related to GW



Merger : NS-NS

Kilonova
Short GRBs afterglow

Merger : NS-BH

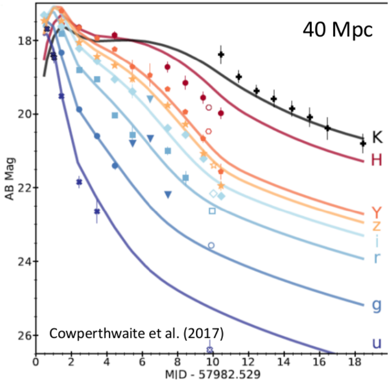
Possible EM counterpart

Other sources

Core collapse supernovae
Binary black hole merger
Kouign-amann

Kilonova - A faint and fast decreasing transient

Example of GW170817

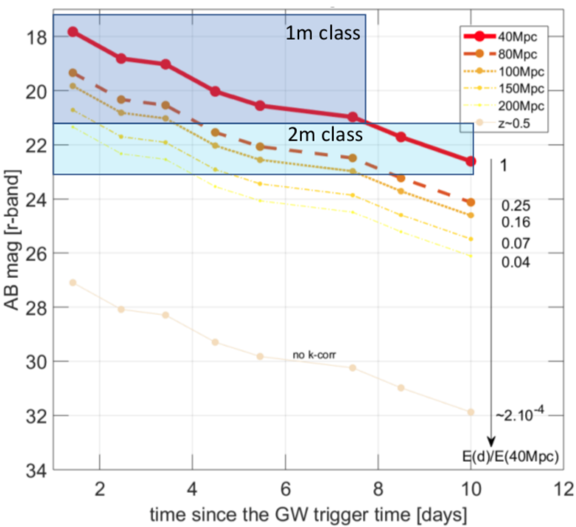


- mag peak at 17 after 1/2 days
- fast decrease, observable for few days

⇒ require a fast response

Kilonova - A faint and fast decreasing transient

For a more distant event



LIGO - Virgo alerts

Starting point : public alerts



LIGO Lab/Virgo

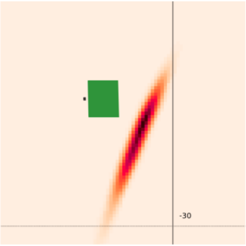
Released GW candidates

- skymap available after few minutes
- source classification
- Information of estimated distance in case of compact binaries merger

GW events localisation

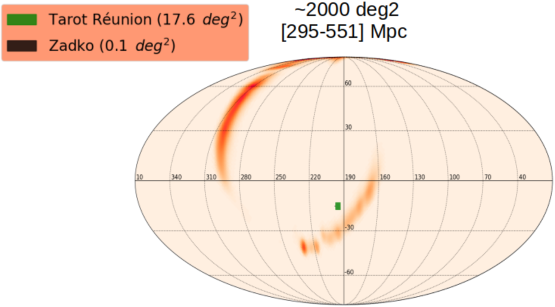
Vary from a few tens of square degrees to more than 1000 !

GW170817 BNS
28 deg2
[26-48] Mpc



67 galaxies (GLADE)

S190426c NS-BH
~2000 deg2
[295-551] Mpc



~50 000 galaxies (GLADE)

search of optical counterpart

- Poor 2D localization (up to some 1000 deg^2)
- Imprecise distance information (~20% error)

1. follow up of gravitational waves events : a disappearing needle in a haystack
2. Galaxies targeting
    - Standard approach
    - Adding galaxies properties
    - Results
3. Conclusion

Galaxies targeting - Standard approach

Galaxies targeting

Hypothesis : the source is located within a galaxy

- Choice of the catalog, what we need :
  - all sky
  - provide distance
  - completeness compatible with LIGO-Virgo range

  ⇒ GLADE (http ://aquarius.elte.hu/glade/)
  Constructed (combined and matched) from four existing galaxy catalogs : GWGC, 2MPZ, 2MASS XSC and HyperLEDA. GLADE contains 3,262,883 objects.

- Selection in the catalogue of compatible galaxies for a certain 3D volume : RA, Dec, distance

Galaxies targeting - Standard approach

How do we use the galaxies ?

We need to define a grade (weight) to put on each galaxy

Standard definition of the grade

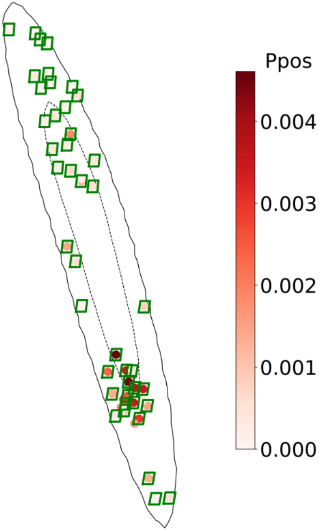
We use the 3D probability :

$$P_{pos} = P_{dV} = \frac{P_{pixel}}{Pixel\ area} N_{pixel}\, e^{-\frac{1}{2}\left(\frac{D_{galaxy} - \mu_{pixel}}{\sigma_{pixel}}\right)^2}$$

Where μ_{pixel} , σ_{pixel} and N_{pixel} are respectively the mean distance, the standard deviation and the normalization factor of the Gaussian distribution at the given pixel. D_{galaxy} is the galaxy distance fetch from the catalog.

Results

Example of tiles obtained, GW170817, FOV $= 20' \times 20'$

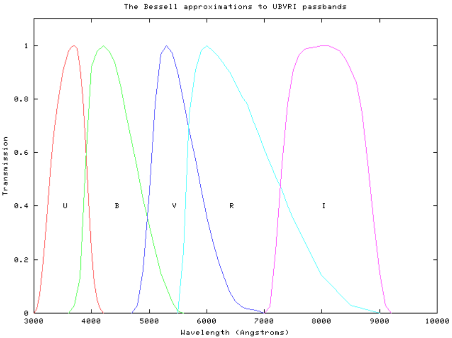


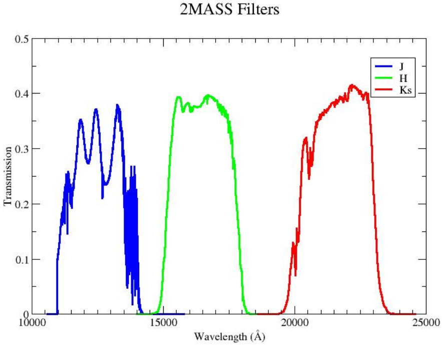
Upgrading the grade

More complete definition of the grade

Only information available on GLADE

- B,J,H,K Luminosity (not for all galaxies)
  ⇒ sufficient to deduce interesting properties from it ?





Upgrading the grade

LCOGT grade ⇒ stellar mass

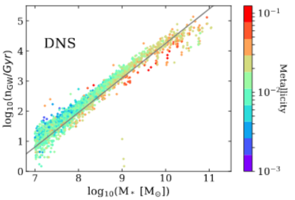
Use the B luminosity as an "indicator of mass"

We then calculate the B-band luminosity of the galaxy, L_B (based on the B-band magnitude and distance provided in the GLADE catalog), and assign it a score

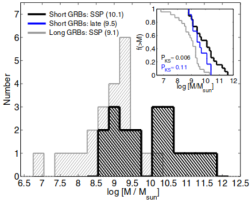
$$S_{\mathrm{lum}} = \frac{L_B}{\sum L_B}, \qquad (3)$$

(Arcavi et al. 2017)

BNS popullation simulations



Short GRB host popullation



⚠ The B band is highly sensitive to the galaxy dust attenuation

$\Rightarrow$ We should use near infrared band

$\Rightarrow$ K band is provided by GLADE but :

- K band is still a bit affected by the dust extinction
- only ∼67% of the galaxies in the catalog (up to 400Mpc) have K band information

$\Longrightarrow$ Utilization of the WISE1 band (3.4 μm)

Our works

Cross-match AllWISE and GLADE (400Mpc) :

After all treatment we have ~93% of the galaxies with WISE1 band

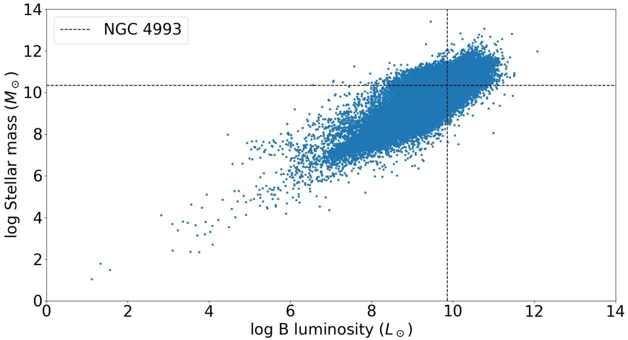
Determination of the stellar mass

From WISE1 band we can determine the stellar mass using a constant mass to light ratio : (Kettlety et al. 2017)

$$\Upsilon_{*}^{3.4\mu m} \sim 0.60 M_{\odot}/L_{\odot,3.4\mu m}$$

Results

Comparison with LCOGT method :



A NGC4993 like galaxy ($\sim 7.2 \times 10^9 L_\odot$ B band luminosity) can have a stellar mass which can span from $\sim 3.8 \times 10^7 M_\odot$ to $\sim 1.0 \times 10^{12} M_\odot$

$\Rightarrow$ Our grade is going to behave very differently from one using B band luminosity

$\Rightarrow$ B band luminosity is a very poor indicator of the stellar mass (assuming our determination of stellar mass is ok)

Reformulation

Adding a factor to the grade

As done previously we can now change the grade adding :

$$\mathrm{P}_{mass} = \frac{M_{*,galaxy}}{\sum M_{*,galaxy}} \Rightarrow P_{tot} = P_{pos} \times P_{mass}$$

Huge drawback of the product expression

Can't define P_{mass} when you don't have the stellar mass info (= the W1 mag)

$\Rightarrow$ forced to throw away $\sim 7\%$ of the catalog

<u>We chose to reformulate the grade :</u>

$$P_{tot} = P_{pos}\,(1 + \alpha P_{mass})$$

Reformulation

$$P_{tot} = P_{pos}\,(1 + \alpha P_{mass})$$

whit α that ensure the two factor in the addition are, in mean, contributing as much :

$$\frac{\sum P_{pos}}{N} = \frac{\sum P_{pos}\,\alpha\,P_{mass}}{N}$$

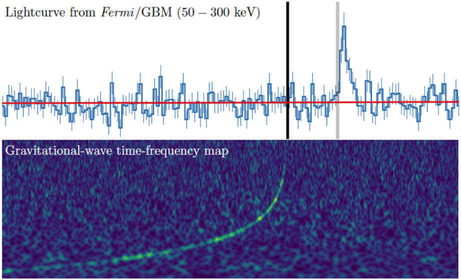
$$\Rightarrow \alpha = \frac{\sum P_{pos}}{\sum P_{pos}\,P_{mass}}$$

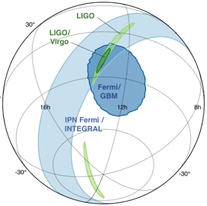
$\Rightarrow$ Put $P_{mass} = 0$ to fall back on P_{pos}

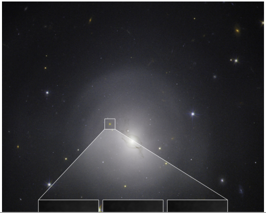
Results

GW170817

Only counterpart for a GW found at the moment

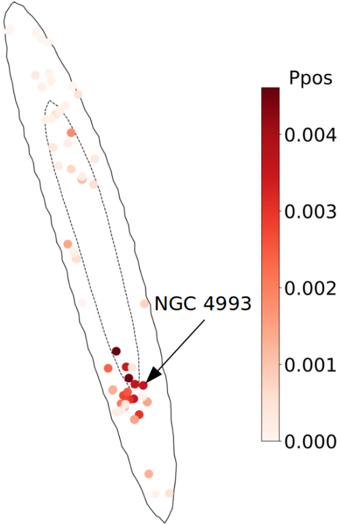






Results

GW170817



- 90% skymap $\sim 30deg^2$
- distance 40 ± 8 Mpc
- 65 galaxies compatibles

Results

With the standard 3D localization ⇒ NGC 4993 ranked 5

Rank	RA	Dec	P_{loc}	Distance	Galaxy name
1	196.27	-22.38	0.0604	33.71	ESO575-053
2	196.88	-23.17	0.0588	38.04	PGC803966
3	194.26	-17.39	0.0588	25.94	WINGSJ125701.38-172325.2
4	197.13	-23.35	0.047	43.15	ESO508-014
5	197.45	-23.38	0.0465	39.35	NGC4993
6	197.18	-23.78	0.0464	36.55	PGC797164
7	196.72	-22.84	0.0452	30.51	ESO508-004
8	197.02	-23.8	0.0403	41.06	IC4197
9	197.47	-24.24	0.0397	39.47	ESO508-019
10	197.69	-23.87	0.0385	38.73	2MASS 13104593-2351566
11	196.89	-23.82	0.0369	41.12	796755
12	196.77	-23.68	0.0364	40.49	NGC4968
13	197.32	-24.38	0.0338	35.5	6dFJ1309178-242256
14	196.91	-23.58	0.0334	45.19	ESO508-010
15	196.06	-22.88	0.0314	36.56	PGC169663
16	196.74	-23.92	0.027	40.67	IC4180
17	193.71	-16.05	0.024	47.39	PGC043966
18	196.35	-23.52	0.0208	37.17	PGC799951
19	194.26	-17.39	0.0206	20.21	WINGSJ125701.40-172325.3
20	197.33	-24.38	0.0196	28.99	ESO508-015
21	197.69	-23.87	0.0191	29.06	ESO508-024
22	194.0	-19.27	0.019	39.95	ESO575-029
23	196.35	-23.5	0.0172	42.35	PGC169670
24	198.19	-25.99	0.017	39.19	PGC772879
25	196.89	-24.01	0.0169	47.07	NGC4970
26	194.26	-17.39	0.015	18.87	WINGSJ125701.40-172325.3
27	194.37	-19.69	0.0108	48.87	NGC4830
28	193.11	-15.52	0.0105	50.9	PGC043664
29	197.06	-21.0	0.0104	31.45	ESO575-061
30	193.84	-17.1	0.0092	53.88	PGC044023

Results

With the B luminosity ⇒ NGC 4993 ranked 2

Rank	RA	Dec	P_{tot}	Distance	Galaxy name
1	197.02	-23.8	0.1371	41.06	IC4197
2	197.45	-23.38	0.1112	39.35	NGC4993
3	196.89	-24.01	0.0807	47.07	NGC4970
4	196.77	-23.68	0.0717	40.49	NGC4968
5	197.47	-24.24	0.0638	39.47	ESO508-019
6	196.74	-23.92	0.0634	40.67	IC4180
7	194.37	-19.69	0.0481	48.87	NGC4830
8	196.27	-22.38	0.0432	33.71	ESO575-053
9	194.0	-19.27	0.0423	39.95	ESO575-029
10	197.69	-23.87	0.0403	29.06	ESO508-024
11	196.91	-23.58	0.0398	45.19	ESO508-010
12	192.25	-14.4	0.0283	51.89	IC3799
13	197.69	-23.87	0.0269	38.73	2MASS 13104593-2351566
14	196.72	-22.84	0.0162	30.51	ESO508-004
15	193.71	-16.05	0.016	47.39	PGC043966
16	193.11	-15.52	0.0154	50.9	PGC043664
17	193.36	-17.01	0.0152	56.57	NGC4763
18	197.18	-23.78	0.0144	36.55	PGC797164
19	197.33	-24.38	0.0135	28.99	ESO508-015
20	197.13	-23.35	0.0129	43.15	ESO508-014
21	193.22	-15.41	0.0088	57.42	NGC4756
22	192.52	-14.73	0.0082	55.63	PGC043424
23	196.6	-24.16	0.0074	53.47	ESO508-003
24	199.1	-26.56	0.007	47.93	ESO508-033
25	194.69	-17.54	0.0066	53.76	PGC044500
26	193.83	-14.95	0.0064	43.14	PGC044021
27	194.25	-17.32	0.005	57.9	PGC044234
28	192.83	-14.57	0.0042	55.44	IC3831
29	194.64	-16.8	0.004	52.46	PGC044478
30	193.62	-16.35	0.0037	57.36	PGC043908

Results

With the stellar mass addition ⇒ NGC 4993 ranked 1

Rank	RA	Dec	P_{tot}	Distance	Galaxy name	Stellar mass
1	197.45	-23.38	0.119	39.35	NGC4993	10.56
2	197.02	-23.8	0.1055	41.06	IC4197	10.57
3	196.77	-23.68	0.0811	40.49	NGC4968	10.48
4	196.89	-24.01	0.0694	47.07	NGC4970	10.8
5	196.74	-23.92	0.0592	40.67	IC4180	10.47
6	194.37	-19.69	0.0535	48.87	NGC4830	10.89
7	196.27	-22.38	0.0467	33.71	ESO575-053	9.68
8	196.91	-23.58	0.0326	45.19	ESO508-010	9.92
9	196.88	-23.17	0.0296	38.04	PGC803966	7.84
10	194.26	-17.39	0.0294	25.94	WINGSJ125701.38-172325.2	–
11	197.18	-23.78	0.0251	36.55	PGC797164	8.87
12	197.13	-23.35	0.0246	43.15	ESO508-014	8.61
13	196.72	-22.84	0.0233	30.51	ESO508-004	8.42
14	197.47	-24.24	0.0222	39.47	ESO508-019	9.01
15	197.69	-23.87	0.0192	38.73	2MASS 13104593-2351566	–
16	196.89	-23.82	0.0187	41.12	796755.0	7.97
17	197.32	-24.38	0.0171	35.5	6dFJ1309178-242256	8.08
18	196.06	-22.88	0.0159	36.56	PGC169663	8.18
19	194.0	-19.27	0.0129	39.95	ESO575-029	9.5
20	192.52	-14.73	0.0126	55.63	PGC043424	11.06
21	193.71	-16.05	0.0125	47.39	PGC043966	8.58
22	196.35	-23.52	0.0106	37.17	PGC799951	8.26
23	193.36	-17.01	0.0105	56.57	NGC4763	10.74
24	194.26	-17.39	0.0103	20.21	WINGSJ125701.40-172325.3	–
25	197.33	-24.38	0.0099	28.99	ESO508-015	7.78
26	193.11	-15.52	0.0098	50.9	PGC043664	9.89
27	197.69	-23.87	0.0095	29.06	ESO508-024	–
28	196.35	-23.5	0.0088	42.35	PGC169670	8.44
29	198.19	-25.99	0.0086	39.19	PGC772879	7.87
30	199.1	-26.56	0.0083	47.93	ESO508-033	10.16

Results

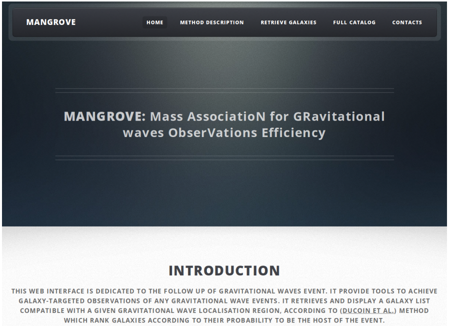
With the stellar mass addition ⇒ NGC 4993 ranked 1

Rank	RA	Dec	P_{tot}	Distance	Galaxy name	Stellar mass
1	197.45	-23.38	0.119	39.35	NGC4993	10.56
2	197.02	-23.8	0.1055	41.06	IC4197	10.57
3	196.77	-23.68	0.0811	40.49	NGC4968	10.48
4	196.89	-24.01	0.0694	47.07	NGC4970	10.8

26	193.11	-15.52	0.0098	50.9	PGC043664	9.89
27	197.69	-23.87	0.0095	29.06	ESO508-024	–
28	196.35	-23.5	0.0088	42.35	PGC169670	8.44
29	198.19	-25.99	0.0086	39.19	PGC772879	7.87
30	199.1	-26.56	0.0083	47.93	ESO508-033	10.16

Conclusion

A brand new galaxy selection !



- This method is already used by GRANDMA, SVOM and Kilonova-Catcher
- Paper describing the method available : (Ducoin et al.) https ://arxiv.org/abs/1911.05432
- All the tools are publicly available via dedicated web-site : https ://mangrove.lal.in2p3.fr/index.php

MERCI !

Backup slide

$$P_{tot} = P_{pos}(1 + \alpha\beta P_{mass})$$

$\Rightarrow$ β which will determine at which point the mass factor will count in the grade
$\Rightarrow$ β is skymap independent
$\Rightarrow$ β should be to fit with a statistically significant sample of gravitational wave host galaxies, but as we don't have such sample yet $\Rightarrow$ $\beta = 1$