Galaxy catalogs and the follow-up of GW event

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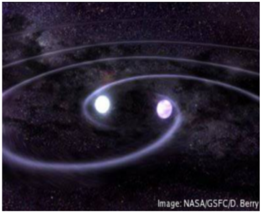
Sources

Search for electromagnetic counterparts related to GW



Merger : NS-NS

Kilonova
Short GRBs afterglow

Merger : NS-BH

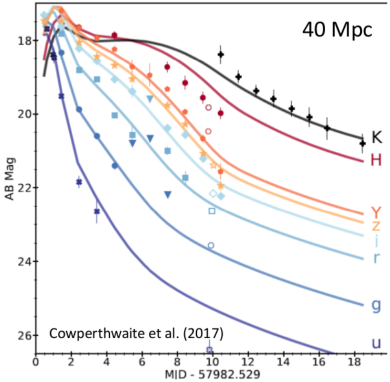
Possible EM counterpart

Other sources

Core collapse supernovae
Binary black hole merger

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

LIGO - Virgo alerts

Starting point : public alerts



LIGO Lab/Virgo

Released GW candidates

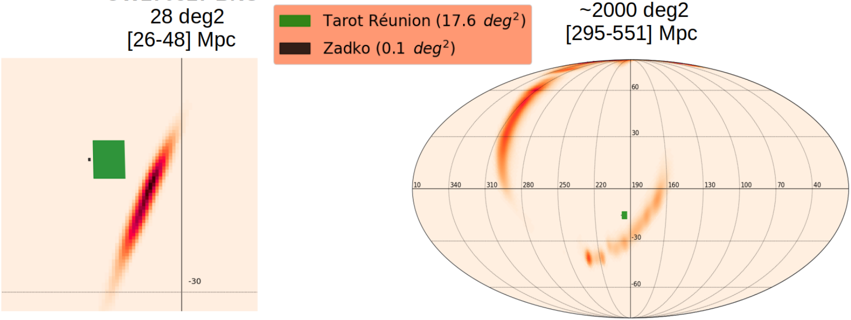
- skymap available after few minutes
- source classification
- Information of estimated distance in case of compact binaries merger

GW events localisation

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

GW170817 BNS
28 deg2
[26-48] Mpc

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



67 galaxies (GLADE)

~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 (stellar mass)
   - 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 catalog 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

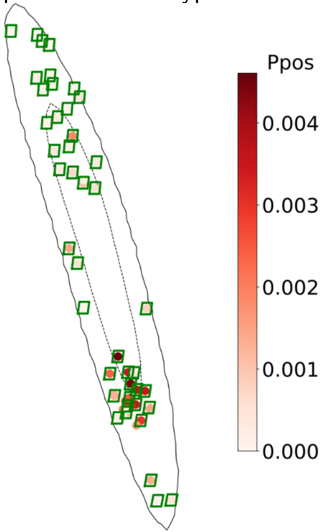
We use the 3D probability :

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

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

GW170817 example : tiles for a typical telescope FOV $= 20' \times 20'$

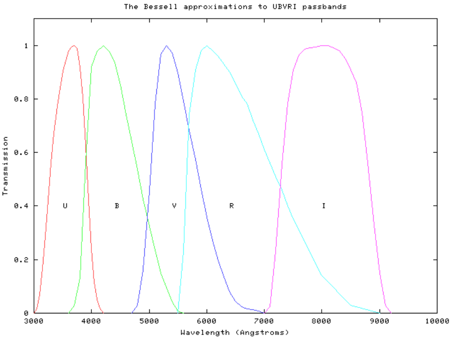


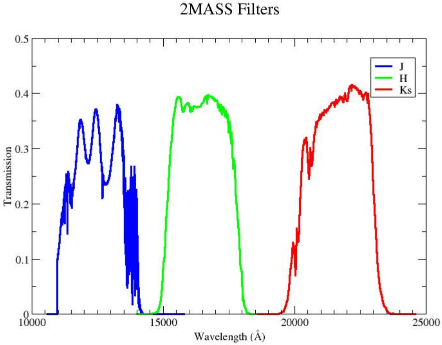
Upgrading the grade : available information

Adding galaxy properties to the grade

Only information available on GLADE

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



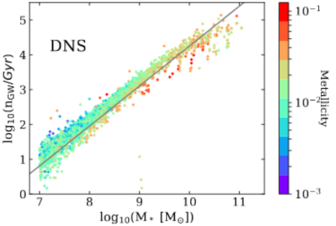


Upgrading the grade : focus on stellar mass

Why the stellar mass ?

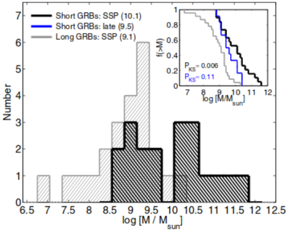
Both BNS merger population simulations and short GRB host population point out the stellar mass as an important indicator.

BNS population simulations



(Artale et al. 2019)

Short GRB host population



(Leibler & Berger 2010)

LCOGT grade ⇒ stellar mass

Use the B luminosity (from GLADE) as an "indicator of mass" (Arcavi et al. 2017)

The B band is highly sensitive to the galaxy dust attenuation

⇒ We should use near infrared band

⇒ K (2.2 μm) band is provided by GLADE but :

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

⟹ Utilization of the WISE1 band (3.4 μm)

Mangrove

A new catalog dedicated to the follow-up of GW event !

MANGROVE: Mass AssociatioN for GRavitational waves ObserVations Efficiency

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)

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

In good agreement with more robust stellar estimation using SED fitting algorithm

Reformulation

Adding a factor to the grade

We can now change the grade adding a mass factor :

$$\mathrm{P}_{mass} = \frac{M_{*,galaxy}}{\sum M_{*,galaxy}}$$

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

We chose to reformulate the grade :

$$\cancel{P_{tot} = P_{pos} \times P_{mass}} \quad \Rightarrow \quad P_{tot} = P_{pos}\,(1 + \alpha P_{mass})$$

Reformulation

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

whit α ensuring that the two factors in the addition are, in mean, contributing as much :

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

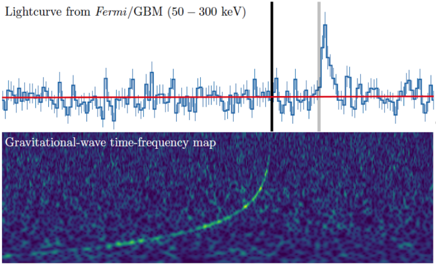
$$\Rightarrow \alpha = \frac{\sum P_{pos}}{\sum P_{pos}\,P_{mass}}$$

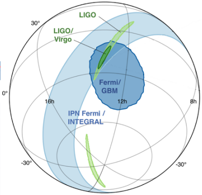
$\Rightarrow$ Set $P_{mass} = 0$ to fall back on P_{pos}

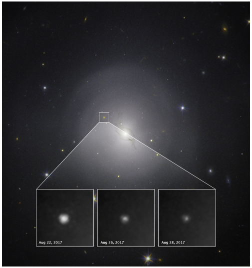
Results

GW170817

Only EM counterpart detected for a GW so far



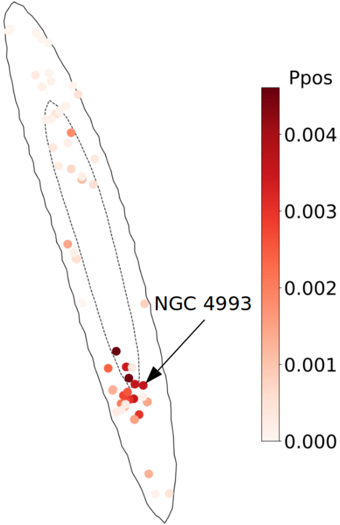




⇒ Mandatory to test our grade on it

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 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

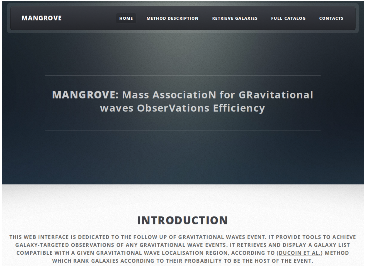
Conclusion

A brand new galaxy selection !

- This method is already used by GRANDMA, SVOM and Kilonova-Catcher
- Paper accepted in MNRAS describing the method available : (Ducoin et al. 2019)
  https ://ui.adsabs.harvard.edu/abs/2020MNRAS.tmp..110D/abstract

Conclusion

Catalog and tools publicly available !



Dedicated website : https ://mangrove.lal.in2p3.fr/

- The full Mangrove galaxy catalog
- The list of galaxies, ranked by our new grade, compatible for each CBC event below 400Mpc
- Possibility to add your observational configuration and limitation (latitude, longitude, elevation, horizon, distance to the moon, maximum airmass)

MERCI !

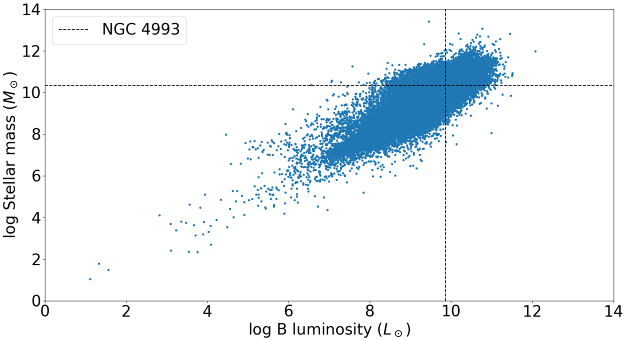
Backup slide 1

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

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

Backup slide 2

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)

Backup slide 3

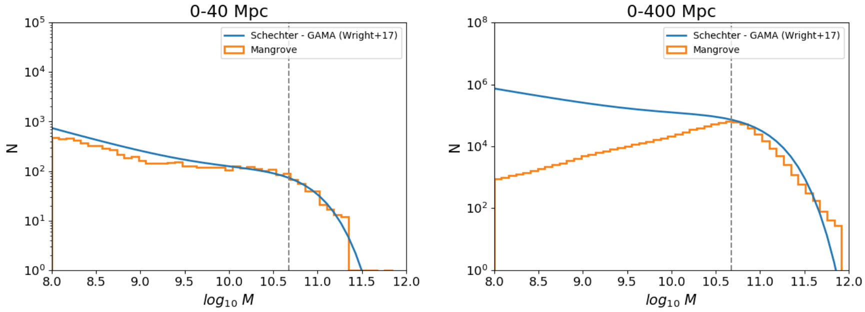
With the B luminosity ⇒ NGC 4993 ranked 2

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

Backup slide 4

Completeness definition

Completeness in terms of mass : ~100% up to 40Mpc, ~50% up to 400Mpc

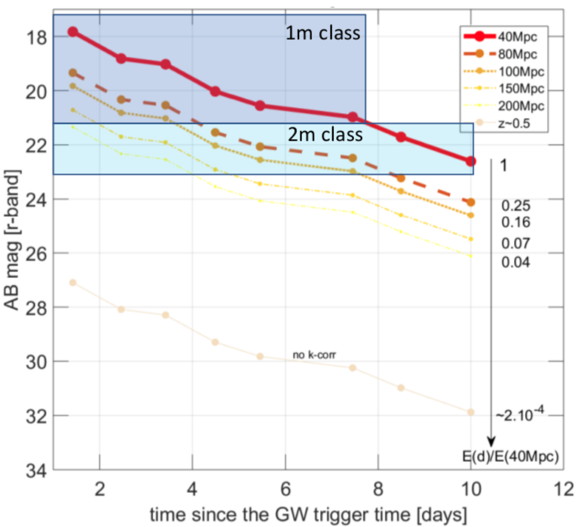


$$C_{m1,m2}^{d1,d2} = \frac{\int_{m1}^{m2} M_* \ catalog(M_*) \ dM_*}{\int_{m1}^{m2} M_* \ f_{Schechter}(M_*) \ dM_*} \quad (1)$$

$m_1 = 8, \ m_1 = 12$

Backup slide 5

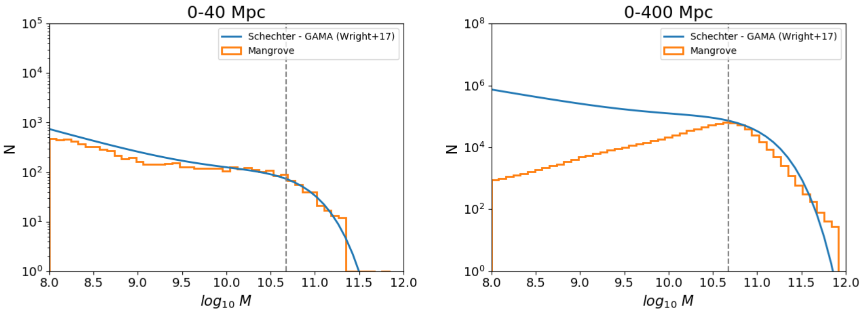
For a more distant event



Backup slide 6

Completeness

Completeness in terms of mass : ~100% up to 40Mpc, ~50% up to 400Mpc



AGN flag

Identification of AGN from mid-infrared color criterion : $W1 - W2 \geq 0.8$ mag