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ASTRONOMICAL CATALOGS FOR LOCATING GRAVITATIONAL-WAVE EVENTS

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ABSTRACT

Gravitational wave transients are caused by some of the most energetic events in the Universe, and a precise location would allow deep examination of the counterpart by electromagnetic waves (telescopes collecting light), the combination of GW and EM resulting in very much improved science return (Multi-messenger Astronomy). Since the GW detectors do not provide good localization on the sky, the faint counterpart will be very difficult to find. One strategy to help the search is to look first where mass is concentrated, and thus the prior probability of GW events is highest. In the first part of this paper, we present methods used to estimate stellar masses and metallicities of galaxies and galaxy clusters in different catalogues. In the second part of the paper, we test our estimation accuracy by comparing our results with stellar masses given in Stripe 82 Massive Galaxy Catalogue (S82-MGC). Then we present how the stellar mass and metallicity are used to estimate the probability of a galaxy hosting different types of compact mergers (massive BBH, BBH, and BNS) in the last part of the paper. Our results are provided in an interactive web-based tool (Skymap Viewer) for astronomers to decide where to look first in EM follow-up observations of GW events in the future.

Subject headings: Catalogs, galaxies: clusters: general, X-rays: galaxies: clusters

1. INTRODUCTION

The first gravitational wave detection in September 2015 was a magnificent achievement, proving the existence of black holes of 30 solar masses, proving that such objects can inspiral and coalesce, and proving that Einstein's original conception of gravity is correct even in these strong, dynamic gravitational fields.

But great further understanding would be possible if conventional electromagnetic astronomy (optical, X-ray, etc, collectively "EM") could be brought to bear on the gravitational-wave (GW) source. As with the flowering of insight following optical identification of gamma-ray bursts in the 1990's, we hope that a program of rapid follow-up will be able to identify the EM counterpart of a future GW source, and for this multi-messenger astronomy to lead to greater insight.

The GW detection by the two LIGO instruments has not provided a tight localization in the sky, but rather a broad probability distribution (the "skymap") covering hundreds of square degrees on the sky. As more detectors come online in the next few years (Italy, Japan, India), we expect the localization to be much tighter, and the search area much smaller.

Presumably the GW source is located in a galaxy, where almost all the matter resides, and so the best place to look for the EM counterpart is among those galaxies that are in the skymap, with a priority given to more massive galaxies. Presumably the more matter that is there, the better chance of black-hole binaries being present. Earlier runs of LIGO from 2010 hoped to detect sources at a distance up to 100 Mpc, and a galaxy catalog was built (GWGC) listing about 60,000 galaxies out to that distance.

However, the LIGO detection was at a distance of 400 Mpc, four times further. Galaxy catalogs are incomplete out to this distance, and of course the numbers are much larger – if distance is four times further, then galaxy numbers multiply by 64, proportional to volume. However in the future, we expect there to be more GW detectors operating, with a much better localization of the source, so fewer galaxies in the observing list.

1.1. *Skymap Viewer*

Skymap Viewer [7] is an interactive, web-based tool to display a skymap along with a host of relevant information for follow-up observers. The skymap is shown as a contour plot, each color-coded line enclosing a given percentage of the total probability. The AladinLite platform [11] , on which Skymap Viewer is built, enables drill-down from whole-sky to arc-second resolution, including image surveys from radio to gamma-ray wavelengths. Also shown are the sun, moon, and milky way relative to the skymap, at any user-chosen time and location on the Earth.

This project adds a new capability: to visualize arbitrary astronomical catalogs in terms of ıobservation priority, which combines knowledge from the gravitational wave detection (the skymap), with known astrophysical objects. Skymap Viewer thus shows the product of these two terms:

observation priority=GW skymap∗astrophysical prior

where the astrophysical prior is based on stellar mass or blue luminosity, with future extensions to include, for example, metallicity. However, rather than building a single "expert" view of the astrophysical prior, we will provide the ability for a scientist to utilize many catalogs: of galaxies or of galaxy clusters or of X-ray sources, for example.

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1.2. *Astrophysical Prior*

The second focus of this paper is to compute astrophysical priors from attributes given in object catalogs. This in turn depends on theoretical ideas about environments that encourage binary neutron star systems (BNS), or binary black hole systems (BBH). Clearly mass is the most important thing: the more stars there are, the higher the chance of exotic systems that create GW. However, it is thought that BNS is a result of recent/current star-forming activity (Phinney 1991) [21] , and therefore that the mass of *blue* stars (starburst and young stars) should be a better proxy than the overall mass of stars. The BBH mergers detection range of aLIGO (advanced LIGO) reaches to 1000 Mpc, but the BNS mergers detection range is much smaller than 100 Mpc, due to the smaller masses of BNS mergers. So both stellar mass and blue luminosity contribute to the priors of galaxies and GCs (galaxy clusters) closer than $\sim$ 100 Mpc, but for more distant ones, only stellar masses are important.

The GLADE catalog (G. Dalya et al. 2016) [22] is a recent fusion of several existing catalogs, and covers the whole sky. Each source has a distance estimate as well as a blue magnitude (BMAG), so we could try to compute the mass of blue stars from it. However, blue light can under-emphasize mass as blue light is easily obscured by circumstellar material.

2. CROSSMATCHING THE GLADE CATALOG WITH S82-MGC

To compare these ways to compute priors, we have built a crossmatch of GLADE with a deeper catalog, built from the Stripe-82 Massive Galaxy Catalogue (S82-MGC) [3]. S82-MGC is a part of the SDSS survey [40] that was covered many times, and by stacking these images, is up to 2 magnitudes deeper than the SDSS survey, and has a wide range of colors, allowing excellent mass and distance estimation. The stripe-82 survey covers only a small area, $\sim$ 250 sq degrees, but it can be used to compare mass estimates in detail. Using this crossmatch, we have compared the stellar mass precisely estimated by SED fitting in S82-MGC with that derived from the blue luminosity in GLADE.

To precisely estimate the stellar mass of a galaxy, stellar population synthesis (SPS) modelling and SED fitting are needed. S82-MGC provides relatively precise stellar mass estimated by Bayesian SED fitting between Y JHK photometry from the UKIDSS Large Area Survey (LAS) [4] and FSPS models (FSPS: Flexible Stellar Population Synthesis Conroy et al. 2009 [17] , 2010 [18]). for galaxies up to z $\sim$ 0.7 but only within a small stripe of sky, while GLADE provides B band magnitude and distances for galaxies up to z $\sim$ 0.07 within a large sky coverage. Therefore, we performed a cross matching between GLADE and S82-MGC to test how well the blue luminosity describes the stellar mass of a galaxy in GLADE.

To find the best search radius of this cross-matching, we looped through GLADE galaxies inside the sky coverage of S82-MGC using a range of search radius (rs) from 0.0005 to 0.05 degrees. Each time, for each galaxy in GLADE, the number of S82-MGC galaxies that fall into a rectangle centered at the GLADE galaxy with length rs is counted, and the total numbers of GLADE galaxies that have 0, 1, and 2 S82-MGC galaxies in the searching rectangle are stored into lists Nrs0, Nrs1, and Nrs2, which are of the same length of the search radius list. In the end, rs is plotted against Nrs0, Nrs1, and Nrs2. The best search radius is the point where Nrs1 curve peaks, and Nrs2 curve starts to raise from zero. The plot is shown in Figure 1.

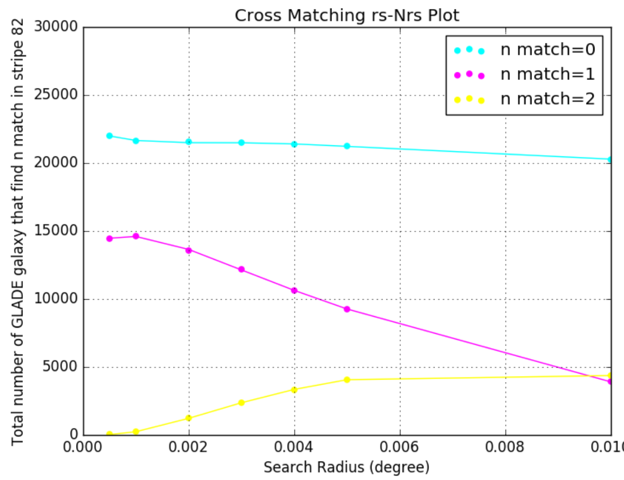

Fig. 1.— rs-Nrs Plot for Number of Galaxies in Search Rectangle= 0, 1, 2

As shown in Figure. 1, the best searching radius is 0.001 degree. So we performed the GLADE- S82-MGC cross-matching using rs= 0.001 deg for 14878 galaxies. We plotted the stellar mass from S82-MGC and the "blue" mass from GLADE, as shown in Figure 2.

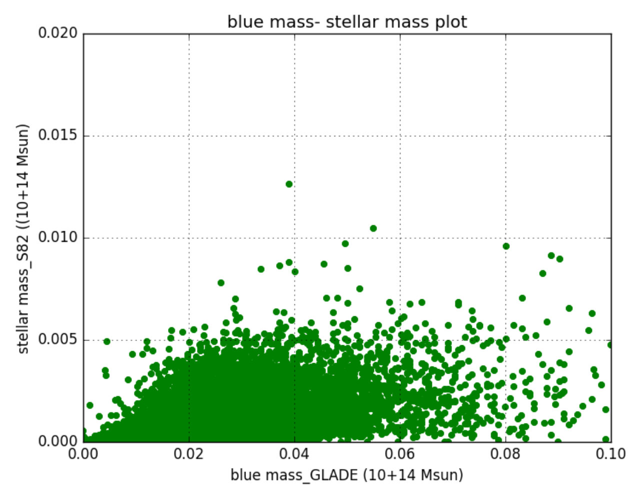

Fig. 2.— Blue Mass - Stellar Mass Plot for Crossmatched GLADE galaxies

According to Figure 2, there is no linear relation between "blue" mass and stellar mass, thus we conclude that B band magnitude is not a good proxy for stellar mass of a galaxy.

3. GLADE GALAXY STELLAR MASS ESTIMATION BY BAYESIAN SED FITTING

GLADE catalog has been constructed (combined and matched) from four existing galaxy catalogs: GWGC1, 2MPZ2, 2MASS XSC3 and HyperLEDA4. GLADE associated B-band magnitudes and photometric redshifts for 548,876 2MASS [36] galaxies which lacked these properties with a regression algorithm teached on a subsample of the 2MPZ catalog (Dalya et al. 2016) [5]. Provided by this data, we can estimate stellar mass by Bayesian SED fittings between BJHK band photometry and the evolutionary population synthesis model by Bruzual Charlot (2003)(BC2003) [12]. We used a Bayesian SED fitting code called BayeSED (Han Han 2014) [41] to estimate stellar mass and metallicity for each galaxy in the GLADE catalog. For the BC2003 model used in BayeSED, the IMF of Chabrier (2003) [14] is adopted, and the SFHs of galaxies are assumed to be exponentially declining in the form of star formation rate (SFR) $\propto exp(t/\tau)$, where t is the time since the start of star formation and τ is the e-folding star formation timescale. A uniform screen geometry is combined with the dust extinction law by Calzetti et al. (2000) [13] to model dust attenuation effect.The BC2003 model library used in BayeSED covers a parameter grid with $log(\tau/yr)$ ranging from 6.5 to 11 in steps of 0.10, log(age/yr) ranging from 7.0 to 10.1 in steps of 0.05, Av ranging from 0 to 4 in steps of 0.2, and 4 different metallicities: 0.004, 0.008, 0.02, or 0.05. In total, BayeSED offers 243,434 model SEDs in the library, which we used to compare with observed galaxy SEDs. This process will take approximately 3 days for all 1,498,920 GLADE galaxies on CIT cluster.

4. WISEXSCOS CATALOGUE: GALAXY STELLAR MASS ESTIMATION USING W1 BAND PHOTOMETRY

WISExSCOS (WISE x SuperCOSMOS Photometric Redshift Catalog) (Bilicki et al. 2016) [9] is constructed by cross-matching between two largest all-sky photometric catalogs, mid-infrared WISE [39] and SuperCOSMOS all sky samples [24] and applying the artificial neural network approach (Collister Lahav 2004) [16], trained on the GAMA-II redshift survey (Driver et al. 2011; Liske et al. 2015) [19] [31]. The derived photometric redshifts have errors nearly independent of distance, with an overall accuracy of σz/(1+z) = 0.033, a typical precision of 15%. The WISExSuperCOSMOS catalog provides (after applying the cleaning mask) about 18.5 million galaxies with a median redshift of z=0.2, and a sky coverage of 3π steradians. Only those sources that have photometry data in at least four bands: W1 and W2 (3.4 and 4.6 m) in WISE, B and R in SCOS are selected into WISExSCOS from these two catalogs.

The W1 band of WISE is dominated by the light from old stars and can be used as an effective measure of galaxy stellar mass (Jarrett et al. 2013; Cluver et al. 2014 [15] ; Xiao-Qing Wen et al. 2013 [8]). According to Cluver et al. 2014 [15], the empirical relation between optically determined stellar mass (estimated from SPS models) and W1, W2 WISE measurements is:

$$\log_{10}(M_{stellar}/L_{W1}) = -1.96(W_1 - W_2) - 0.03$$

$$L_{W1}(L_{sun}) = 10^{-0.4(M-M_{sun})},$$

where M is absolute magnitude in W1, $M_{sun} = 3.24$, and $W_1 - W_2$ is observed color. We have associated optical stellar mass to each galaxy in WISExsuperCOSMOS by using W1, W2, redshift (z), and the equation in Cluver et al. 2014.

5. STELLAR MASS ESTIMATION ACCURACY TEST

In this section, the cross-matched catalog between GLADE and S82-MGC (See section 2 of this paper) will be used to test the stellar mass estimation in GLADE using BayeSED code. A cross-match between WISExSCOS and S82-MGC will be done, and the stellar masses estimated using W1, W2 band photometry in WISExSCOS will also be tested against stellar mass provided in S82-MGC.

6. MASS ESTIMATION FOR GALAXY CLUSTER CATALOGS

Our objective is a listing of large accumulations of mass in the distance range of the recent LIGO discoveries (100 Mpc to 1000 Mpc), so that mass can be used as a proxy for observational priority. In this section we review the ways astronomers have used to estimate the mass of galaxy clusters.

6.1. *Estimation Based on Cluster Richness*

It's possible to estimate the mass of a optical galaxy cluster in Abell catalog (1989) [2] and Northern Cluster Catalog (Gal+, 2009) [23] in three different ways, since richness (number of cluster members) is given for each cluster.

First, directly use the richness as a mass proxy, assuming the masses of galaxy in clusters are the same. Median velocity dispersions for MaxBCG clusters binned by N200 is shown in Figure 12 of Koester et al. (2007) [28] , where N200 is the number of galaxies enclosed by a circle of radius R200, inside which the average density is 200 times the critical density at the corresponding redshift. The increasing velocity dispersion is related to the increasing mass of cluster in the MaxBCG catalog, according to the virial theorem, reinforcing the idea that N200 is a useful proxy for cluster mass. This method gives us a relatively vague GC mass, because of the assumption that every galaxy is of the same mass.

Second, use the stacked velocity dispersion-richness relation derived using MaxBCG catalog data also in Koester et al (2007) [28] to get corresponding velocity dispersion of each cluster, and then use virial theorem to calculate the cluster mass.

$$M200 = \frac{5R200 * \sigma(N200)^2}{G}$$

The best-fit power law for the relation between stacked velocity dispersion (σ) and richness (N200) is given by

$$ln\sigma(N200) = (5.52 \pm 0.04) + (0.31 \pm 0.01)lnN200$$

This method is more precise than the first method, but only of the cluster is old enough to be fully virialized. Also we still need to make an assumption that cluster radius offered in Abell catalogue satisfies the definition of dynamical cluster radius (R200).

Third, we can use the central halo mass-richness relation shown in Equ.26 of Sheldon et al. (2007) derived by applying cross-correlation cluster lensing method on SDSS II data

$$M200(N200) = M200|20(N200/20)^{\alpha}$$

with

$$M200|20 = (8.8 \pm 0.4 \pm 1.1) \times 10^13h^-1Msun$$
$$\alpha = 1.28 \pm 0.04$$

The cluster mass can be estimated by applying the equations above on the richness N200 of each cluster. We may need to compare results from the second and the third method to see which method is more precise for our purpose.

6.2. *X-ray Detection of Galaxy Clusters*

We can't count the galaxy number of a X-ray detected GC, so all three mass estimating methods stated in last section won't work for them. In the case of MCXC [34] , M500 (the approximate total dynamical mass) for each cluster is given in the catalog. According to Piffaretti et al. (2010) [34] , the M500 is estimated from L500 (the approximate total luminosity) using the L-M relation given in Arnaud et al. (2010)

$$h(z)^{-7/3}\frac{L500}{10^{44}}ergs^{-1} = C(\frac{M500}{3 \times 10^14Msun})^{\alpha}$$
$$log(C) = 0.274$$
$$\alpha = 1.64$$

The adopted C and alpha values are derived from REXCESS luminosity data uncorrected for the Malmquist bias, hence, the M500 provided by MCXC depends on the assumption that on average the Malmquist bias for MCXC samples is the same as that of REXCEXX sample.

6.3. *Galaxy clusters from the SunyaevZel'dovich Effect*

In Planck (2015) [6] catalogue, M500 for 439 galaxy clusters are estimated using gravitational lensing as shown in von der Linden et al. 2014b and Hoekstra et al. 2015.

Up till now, we have ran MASSBUS on two galaxy cluster catalogues: MCXC and Planck (2015). J2000RA (decimal), J2000Dec, ID, redshift or distance, and M500 are downloaded for both catalogues from VizieR as CSV files. MASSBUS read in these files, and convert redshifts into distance using Hubble's law according to the ΛCDM model with $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$; MASSBUS will also be able to convert B magnitudes into stellar masses for galaxies after we finish the cross-matching test. The out put file contains ID, J2000RA (decimal), J2000Dec, mass, and distance (Mpc). The results of running MASSBUS on MCXC and Planck is shown in Figure 3 as a distance-mass scattering plot.

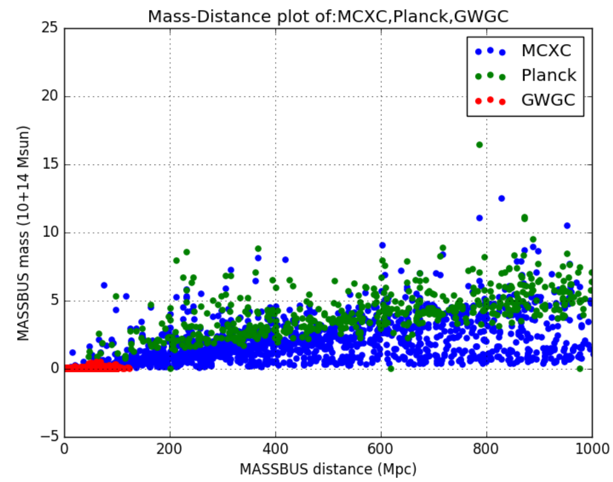

FIG. 3.— Distance-mass plot of MCXC and Planck: GWGC [38] is also shown in the plot for comparison. The stellar masses in GWGC are temporarily estimated by using blue luminosities and $_Ssun/L_Ssun$. More precise values will be used after the coming cross-matching test.

7. METALLICITY ESTIMATION

When building a prior for high-mass BBH, such as the $\sim 62M_{sun}$ BBH coalescence that was LIGO's first detection, metallicity becomes important. This is because stellar formation models cannot produce such high-mass black holes except from stars that formed from almost pure hydrogen (low metallicity). Thus a galaxy of low metallicity gets a higher astrophysical prior than a high-metallicity galaxy of the same mass.

For all GLADE-2MASS galaxies, metallicities are estimated together with stellar mass using the BayeSED. Metallicities of WISExSCOS galaxies, on the other hand, are derived from stellar mass using the empirical mass-metallicity relation (Ma et al. 2016) [32] :

$$12+\log(O/H) = 0.35(\log(M_{gal})-10)+0.93e^{-0.43z}+7.95$$

In this calculation, we assume that the metallicity of a galaxy is uniform and equals to the mean metallicity of the star forming gas in the galaxy. The mass-metallicity relation comes from high-resolution cosmological simulation suite FIRE (Hopkins et al. 2014) [26] , and it agrees with both gas and stellar metallicity measurements observed at low redshifts for $10^4 \leqslant M_{gal} \leqslant 10^{11}M_{sun}$ (Tremonti ert al. 2004 [37] ; Lee et al. 2006 [30]) as well as the data at higher redshifts (Erb et al. 2006 [20] ; Mannucci et al. 2009 [33]) (A. Lamberts etal. 2016) [29] .

8. SUMMARY

The objective of this project is to "process" a number of published catalogs of astrophysical sources, build reasonable astrophysical priors for that source as a progenitor of GW signals, and render that information into Skymap Viewer, a system for recommending observation priority for EM followup observations. This prior depends on the type of GW event being pursued, whether it is binary neutron star (where big, young stars are the progenitors), or binary black hole (where simple mass is the best prior). This latter case splits into lower and higher mass systems, because it is though that higher mass systems can only be produced in low-metallicity enviroments.

We have evaluated priors based on blue magnitude and on mass for several catalogs of galaxies and of galaxy clusters, and folded the results into Skymap Viewer. We have compared estimates of priors from different catalogs through crossmatch, and we have used SED (Spectral Energy Distribution) fitting to compute mass from colors.

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