LIGO, DECam, and galaxies
May 31, 2015

We investigate the use of DECam to detect the optical counterparts of the gravitational wave sources detected by advanced Ligo.

Introduction

Galaxies, light, or mass

The easiest way to localize a GW event is to look near a galaxy, but as galaxies cover a range of masses from 10^5 to 10^{12} and the census of galaxies orbiting even the Milky Way is incomplete we rapidly reach the conclusion that "a galaxy" is too lose to be useful. One could use luminosity to weight the galaxies and get quite close, but if one is selecting a proxy for the number of binary neutron stars present the simpliest by far is the stellar mass.

Integrating the stellas mass function

Baldry, Driver, Loveday et al (Baldry et al., 2012) use GAMA data to measure the stellar mass function, parameterizing it as:

$$\phi_M \, dM = e^{-M/M^*} \left[\phi_1^* \left(\frac{M}{M^*} \right)^{\alpha_1} + \phi_2^* \left(\frac{M}{M^*} \right)^{\alpha_2} \right] \frac{dM}{M}$$

where $\phi_M dM$ is the number density of galaxies with mass between M and M+dM, and with $\alpha_1 < \alpha_2$ so that the second term dominates at the faintest magnitudes. Their table 1 gives the galaxy stellar mass function.

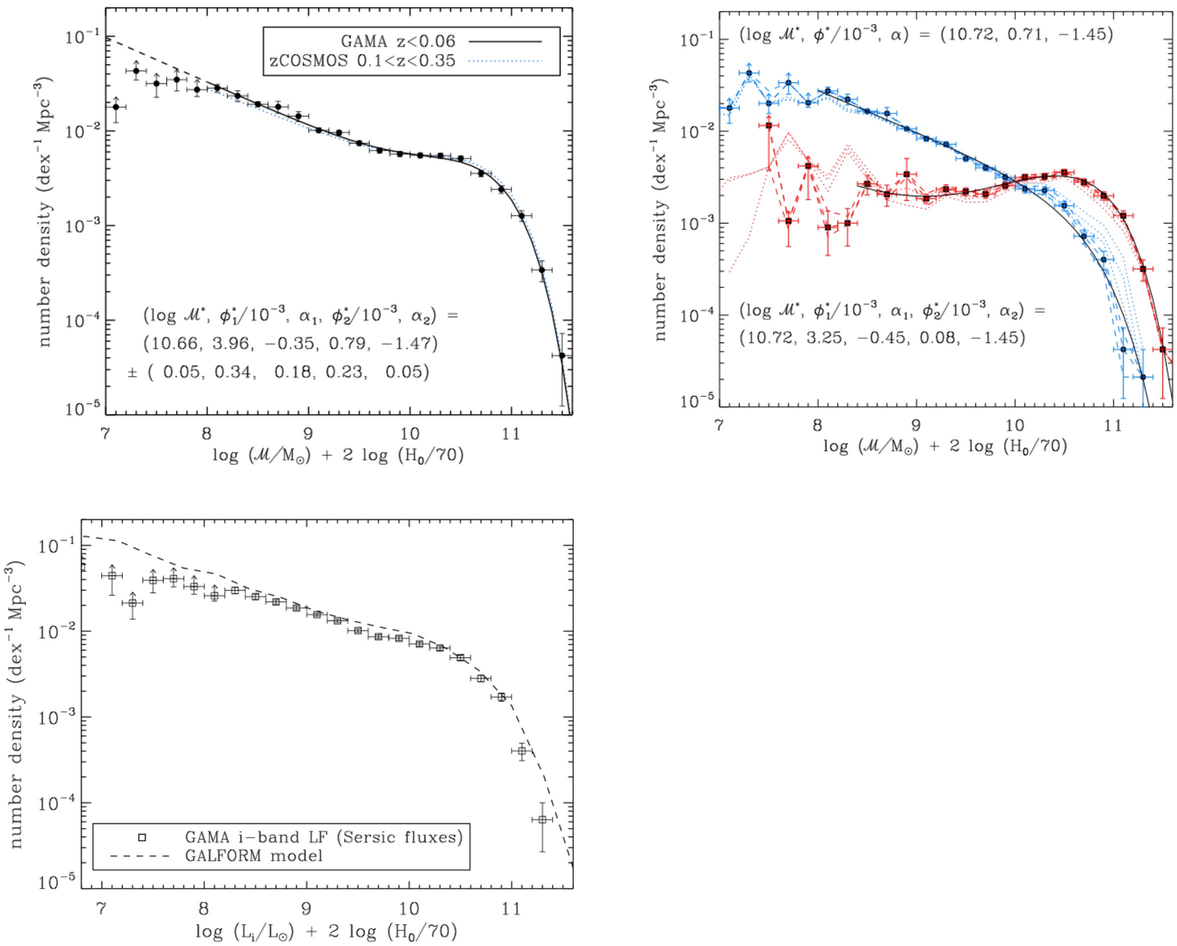

Figure 1: GSMF with a double Schechter fit from Baldry et al analysis of the GAMA survey. In the middle the population has been split into red and blue galaxies and the blue fit by a single SF while the red is fit by a (coupled to the blue) double SF. On the right is the i-band luminosity function.

In the first approximation: Let us ignore the second, fainter component for the moment. Then the Baldry et ala mass function is $logM^* = 10.66$, $\phi* = 4.0 \times 10^{-3}$, and $\alpha = -0.35$. Fractions of the total mass above M are given by

$$\frac{\Gamma(-0.35 + 2, M/M^*)}{\Gamma(-0.35 + 2)}$$

where $\Gamma(1.65) \approx 0.900$. Fractions of 68%, 90% and 95% of the total mass are at $0.61M^*$, $0.35M^*$ and $0.225M^*$. The first point is that one can safely ignore low mass galaxies.

Having found the limiting mass needed to find 95% of the stellar mass, we can approximate the luminosity at that limiting mass. Let us use space density matching to convert these stellar masses back to r-band luminosities. The 68%, 90% and 95% limits correspond to $\log(M) = 10.45, 10.20, 10.01$. The mass function is flat in this part of mass space, and all three have space densities of 5.5×10^{-3} ($5.5 \times 10^{-3}, 5.5 \times 10^{-3}, 5.6 \times 10^{-3}$ Mpc^{-3}, respectively), corresponding to log(L) = 10.3, just about L^* in the luminosity function. The second point is that one can safely ignore low luminosity values.

In the second approximation: In the next level of approximation, the actual value of the lower limit is sensitive to the α parameter, and the lower mass galaxies have a steeper slope than the more massive ones, hence ignoring the second SF biases the limit high. Let us instead just work with the actual data in Baldry et al table 1. One can sum the space densities (column 3) multipled by the mass mid point (column 2) to find the total mass, and then numerically work downwards the mass function to find the 68%, 90% and 95% mass points. These are at 10.5, 9.8, 9.3, corresponding to space densities of 5.2, 6.0, 9.59$\times 10^{-3}$ Mpc^{-3} (and per bin width, which are uniform down to 8.0). These are the space densities that we need to work down to.

Luminosities can be found again by space density matching. The Blanton et al (Blanton et al., 2003) luminosity function gives $i^*_{0.1} = -21.6$ (for h=0.7), and Blanton later (Blanton et al., 2005) gives a convenient form to convert to $z = 0$, $i = i_{0.1} - 0.19$, so $i^* = -21.8$. This has a space density of 4.5×10^{-3} (Blanton et al., 2005), (table 4, using $-20.82 - 0.19$ and $5\log(0.7) = -0.77$). (5.2, 6.0, 9.59$\times 10^{-3}$ Mpc^{-3} corresponds to $\Delta M = 0.1, 0.4, 1.1$ from M^*, or 0.9, 0.7, 0.4L^* (where now M refers to absolute magnitude, not mass).

If we take the 90% mass, then the corresponding luminosity threshold is 0.7L^*, or $M^* + 0.4$ magnitudes, or $i = -21.4$. 90% of the stellar mass is in galaxies with luminosities of 0.7L^*; at 100 Mpc the apparent mag limit is i=13.6, and at 200 Mpc, the limit is i=15.1. These are bright.

If we take the 95% mass, then the corresponding luminosity threshold is 0.4L^*, or $M^* + 1.1$ magnitudes, or $i = -20.6$. At 100 Mpc the apparent mag limit is i=14.4, and at 200 Mpc, the limit is i=15.9.

The Local Galaxy Distribution

Let us start with the galaxies in the 2MASS Photometric Redshift Catalog. As 2MASS (The two Micron All Sky Survey) covered the whole sky in extinction insensitive J,H,K bandpasses, the 2MASS galaxy catalog is very complete. (Complete to apparent magnitudes that are bright compared to current optical surveys, but this need not concern us here.) The 2MASS Photometric Redshift catalog (2MPZ) contains one million galaxies, constructed by cross-matching the near-IR 2MASS catalog with the thermal-IR WISE catalog, and the optical photographic plate based SuperCOSMOS catalog, all whole sky, and employing the artificial neural network approach to perform the photo-z using training samples from the SDSS, 6dFGS, and the 2dFGS. The derived photometric redshifts have errors nearly independent of distance, with an all-sky accuracy of $\sigma_z = 0.015$ and a very small percentage of outliers.

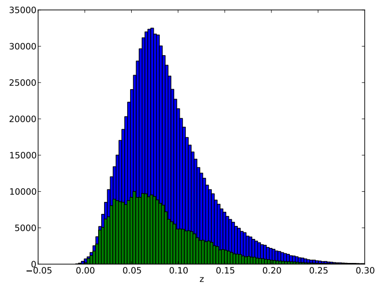

Figure 2: The galaxies of the 2MPRC: in blue is the distribution of photometric redshifts and in green is the distribution of spectroscopic redshifts. There are 927,752 galaxies with photo-zs. Of these, 309,892 have spectroscopic redshifts.

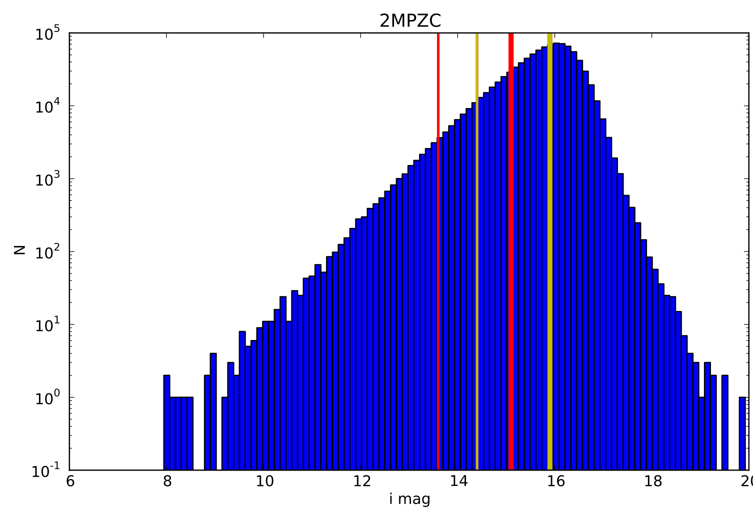

Figure 3: The i-band magnitude of the galaxies of the 2MPRC. The 90% mass limit at 100 and 200 Mpc are in red, the 95% mass limit is in yellow.

The catalogs

Take H_o = 70 km/s/Mpc. Then $d = cz/H_o$. The LIGO horizon distances in 2015, 2016 are 100, 200 Mpc, which correspond to z=0.023, 0.046.

We'll have to combine 4 catalogs.

We start with an empty list. Then we add galaxy's α,δ, distance, redshift and errors onto the list, starting with catalogs with distances or redshifts.

EDD: The galaxies of the Extragalactic Distance Database (Tully et al., 2009) (Tully et al., 2013) have real distances. Our table was downloaded in Dec 2014, and is the Cosmicflows-2 dataset. It has 8162 objects whose distances are known by a variety of methods but centered around Tully-Fisher measurements.

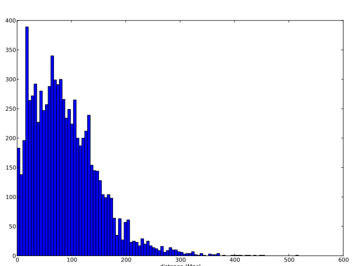

Figure 4: The galaxies of the Extragalactic Distance Database are histogrammed in distance.

NED-D A Master List of Redshift-Independent Extragalactic Distances is useful. Our version is Version 9.4.0 from December 2014. NED will be more up to date than EDD, though we believe EDD distances are to be preferred. Our NED-D list is all objects on NED-D that are galaxies, have d < 250Mpc, and not in Cosmicflows-2 (matched withing 45″).

NED: NED will be the most up to date repository of the world's redshifts, modulo data releases from surveys like SDSS-3 and Oz-DES. For those galaxies in 2Mpz without spectroscopic redshifts we will search NED. Unfortunately, NED is a mess. We match all galaxies from NED at z < 0.092 to 2MASS J < 15.1 catalog, and remove matches against NED-D (10″) and Cosmicflows (45″).

SDSS DR12: We then use the SDSS DR12 z < 0.1 catalog. Our SDSS catalog removed matches against NED (15″), NED-D (10″), and Cosmicflows (45″).

Now we turn to photometric redshift catalogs.

2Mpz: The galaxies in the Two Micron All Sky Survey Photometric Redshift Catalog (Bilicki et al., 2014) (we use version 1) in the range -0.02 < z <0.09 are taken to have gaussian pdfs of mean z_p and σ=0.015, unless they have a spectroscopic redshift, in which case the mean is z_s and σ=0.001.

*z = 0.09: three σ away from being in the sample: 0.023+3*0.015 = 0.068 (0.091)*

We take this as the starting master photometry and redshift list. We match 2Mpz against our SDSS catalog (10″) and check if the distance error is lessened using SDSS redshifts; is so replace redshift. Next we match 2Mpz against NED (10″) and check if distance error is improved. Then against NED-D (30″), and then Cosmicflows-2 (45″).

There will be objects in Cosmicflows-2 that are not in 2Mpz, for example Cosmicflows[0], α, δ=(23.08764 0.11739), z=0.01486, which is not in the 2MASS catalog, either extended or point source. Why not? Likely it is too faint- at i= 15.6 it has an absolute magnitude of -18.4, a good two magnitudes below our 90% mass threshold.

2Mpz incompleteness: While the 2Mpz incompleteness is low, it is systematically low redshift bright galaxies that are missed. This is the result of image processing problems when the galaxy image is complicated.

We can add back into the sample those things we know about. This operation is about magnitudes, not distances. We'll use the SuperCosmos/SSA B and I data, which form the basis of the 2Mpz but are distinct from that catalog, and the SDSS DR12 i <18 photometric galaxy catalog, and the 2MASS Extended Source Catalog.

For those Cosmicflows-2 that were not matched using the 2Mpz catalog, we search for matches (30″) in the SDSS i<18 catalog. and then for matches in the XSC (checking to see if there are SSA B/I colors). (30″).

Then the same process again for NED-D galaxies.

Final computations: The resulting galaxy catalog has the stellar mass computed using Taylor's form for M/L ($M/L = -0.68 + 0.7(g - i)$; we use (B-I) if (g-i) is not available), as

$$\mathrm{mass} = \mathrm{M/L} - 0.4(\mathrm{M} - 4.58)\ .$$

Information on each galaxy is added from the 2MASS XSC: J, radius, position angle, b/a.

The catalog

```
# the one catalog
#   disterr = 28.57142857 is a magic number for distance from redshift
#   disterr = 64.28571428 is a magic number for distance from photo-z
#
#   object flags:
#       flags[0]  True: zspec, False: zphoto
#       flags[1]  True: dist set to 10 Mpc, as zphot < 2 Mpc
#       flags[2]  True: dist set to abs(dist) as zspec < 0, and Virgo vel disp
#       flags[3]  True: b-i truncated to |b-i] = 4
#       flags[4]  True: SDSS i and g-i
#       flags[5]  True: i mag is (XSC_J +1.3), b-i is from SSA
#       flags[6]  True: i mag is (XSC_J +1.3), b-i = 1.2
#       flags[7]  True:
# check a flag by np.unpackbits(flag[i])
#  or: np.unpackbits(np.array([128,]).astype("uint8"))
# flags = np.unpackbits(flags)

    ra,dec,dist,disterr,imag,bi,absmag,mass,flags, \
        xj, xrad, xkphi, xkba, xname  = np.genfromtxt("to200mpc.txt", unpack=True)
    flags = np.genfromtxt("to200mpc.txt", unpack=True, usecols=(8),dtype="uint8")
    xname = np.genfromtxt("to200mpc.txt", unpack=True, usecols=(13),dtype="str")

    ra2,dec2,dist2,disterr2,imag2,bi2,absmag2,mass2,flags2, \
        xj2, xrad2, xkphi2, xkba2, xname2  = np.genfromtxt("to200mpcx.txt", unpack=True)
    flags2 = np.genfromtxt("to200mpcx.txt", unpack=True, usecols=(8),dtype="uint8")
    xname2 = np.genfromtxt("to200mpcx.txt", unpack=True, usecols=(13),dtype="str")
    return ra,dec,dist,disterr,imag,bi,absmag,mass,flags,xj, xrad, xkphi, xkba, xname, \
        ra2,dec2,dist2,disterr2,imag2,bi2,absmag2,mass2,flags2, xj2,xrad2,xkphi2,xkba2,xname2
```

The existing catalogs

We need to compare against the existing LIGO galaxy catalogs. I don't think this is complete: For r < 10Mpc, see Karachentsev, Makarov and Kaisina, 2013. For r < 100 Mpc, see White, Daw, and Dhillon 2011, the Gravity Wave Galaxy Catalog.

The local universe

Using H_0 = 70 km/s/Mpc, r= 500 Mpc at z=0.12, and r=200 mpc at z=0.05. There is some thought that the r<200 Mpc regime is lower density than normal, thus explaining the higher local H_0 vs the CMB H_0. Three apers on the subject have reached my attention: Testing for a Large Local Void by Investigating the Near-infrared Galaxy Luminosity Function, (Keenen, Barger, Cowie et al 2012); & The Cosmic Core-collapse Supernova Rate Does Not Match the Massive-star Formation Rate, (Horiuchi, Beacom, Kochanek, et al, 2011), & The Local Hole revealed by galaxy counts and redshifts, (Whitbourn, Shanks, 2013)

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