Prospects for Detection of Extragalactic Stellar Mass Black Hole Binaries in the Nearby Universe

Albert Mata, Jesus Hinojosa, Matthew Benacquista, Alexander Stroeer
Dept. of Physics, University of Texas at Brownsville

Introduction

Space-Based Gravitational Wave Observatories Like LISA (SBGWOLLs), will be sensitive to frequencies in the mHz range. Potential sources of gravitational waves at frequencies resolvable by SBGWOLLS include white dwarf, black hole, and neutron star binaries. Population synthesis of such compact object binaries indicate that the number of binary black holes within this frequency range in the Galaxy is on the order of 1 or less (Belczynski et. al.2010a). We consider only the field population of double black hole systems. However, these binaries may be formed dynamically and may have higher masses in low-metallicity environments. If high-mass binary black holes are detectable at greater distances, then the potential for detection increases with the increased number of host galaxies. Here, we explore the likelihood of detection based on the galaxy type as related to the number of binaries predicted in the galaxies documented by the Gravitational Wave Galaxy Catalog (GWGC) out to 30 Mpc.

About the GWGC

The Gravitational Wave Galaxy Catalogue, put together by Darren J. White, E. J. Daw, and V. S. Dhillon from the University of Sheffield, is one of the most complete galaxy catalogues within 100Mpc (White et. al. 2011). It contains sky position, distance, blue magnitude, major and minor diameters, position angle and galaxy type for 53, 225 galaxies.

Galaxies within 30Mpc

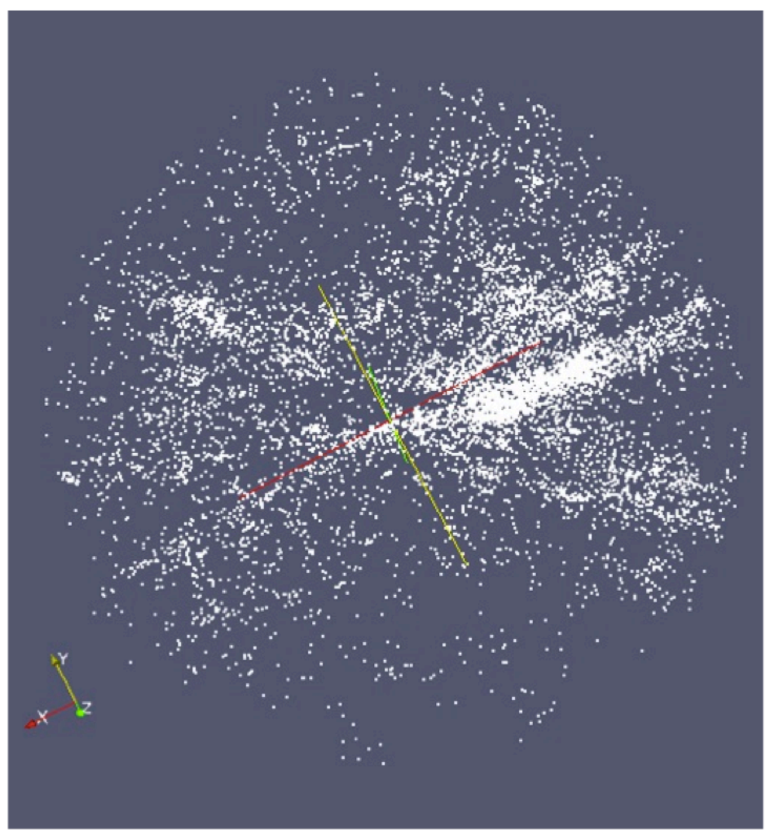

Figure 1. GWGC galaxies within 30Mpc plotted using Paraview with each point corresponding to one galaxy.

Initial Set-up

To ensure we have a realistic galaxy type distribution from the GWGC, we visualize the data by producing a histogram of galaxy (de Vaucouleurs Numerical Morphological) type as seen in Figure 2, and compare our data to theoretical expectations to find that indeed we have a distribution of galaxy types that agrees with theory. Next, to relate galaxy type to the number of expected binary black holes, we group spherical, elliptical, and irregular galaxies separately. To ensure we have correctly separated galaxy types, we visualize our data by producing a histogram of each respective galaxy type as seen in Figures 3, 4 and 5.

Abstract

Stellar mass black hole binaries have individual masses between 10-80 solar masses. These systems may emit gravitational waves at frequencies detectable at Megaparsec distances by space-based gravitational wave observatories. In a previous study, we determined the selection effects of observing these systems with detectors similar to the Laser Interferometer Space Antenna by using a generated population of binary black holes that covered a reasonable parameter space and calculating their signal-to-noise ratio. We further our study by populating the galaxies in our nearby (less than 30 Mpc) universe with binary black hole systems drawn from a distribution found in the Synthetic Universe to ultimately investigate the likely event rate of detectable binaries from galaxies in the nearby universe

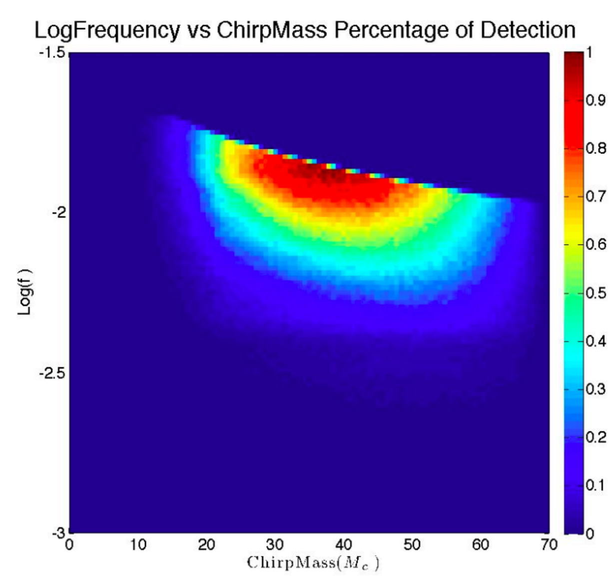

Figure 2. Percentage range increases and stays high along a band centered at 10 mHz when the chirp mass increases. The width of this band also increases with increasing chirp mass.

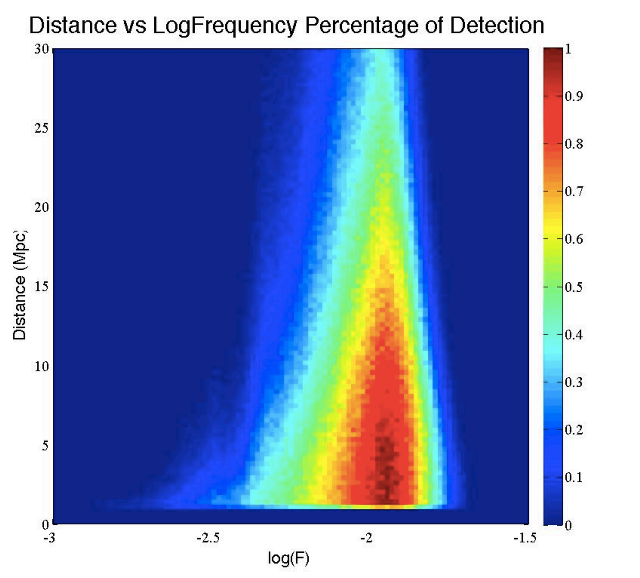

Figure 3. Percentage range increases and stays high along a band centered at 10 mHz when the chirp mass increases. The width of this band also increases with increasing chirp mass.

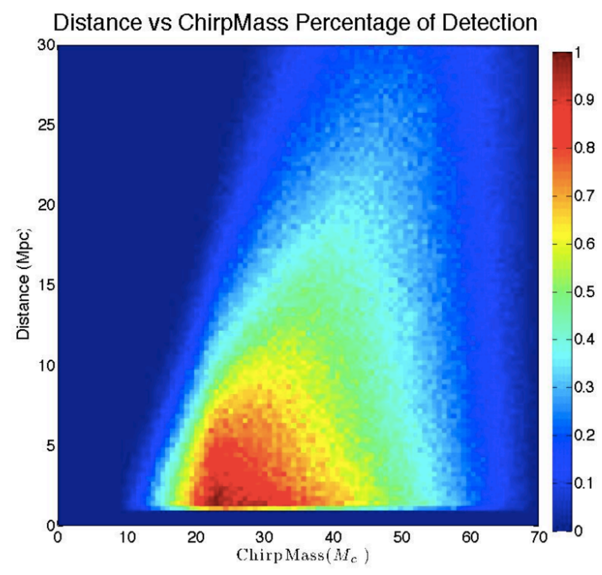

Figure 4. Histogram of galaxy type (in de Vaucouleurs Numerical Morphological classification system) of spherical galaxies in the GWGC within 30Mpc

Theory

Our approach to predicting the number of Binary Black Holes detected by SBGWOLLs begins by identifying nearby galaxies, sorting them by Hubble galaxy type, populating them with a synthetic Universe of Binary Black Holes, then evolving the binaries' periods forward in time to determine if it is detectable by SBWOLLs. To identify nearby galaxies, we used the Gravitational Wave Galaxy Catalog with all galaxies under 30Mpc. Then, we can use the galaxy type to predict the number of globular clusters within those galaxies respectively (Downing et. al. 2011) , and then relate the number of globular cluster to both the metallicity environment of the galaxy, and the number of binary black holes in the galaxy (Belczynski et. al. 2006). Next, we use a synthetic distribution of binary black holes generated by the Synthetic Universe database online to populate each nearby galaxy according to galaxy type. Lastly, we randomly pull binary black holes from the synthetic distribution, and evolve their period respectively forward in time.

References

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Period Evolution

The period distribution of this population can be determined by assuming a constant merger rate. The evolution of the period, P, of a binary after an arbitrary time T from birth due to gravitational radiation losses is given by:

$$P = [-k_0 T]^{3/8} \tag{1}$$

$$k_0 = \frac{96}{5}(2\pi)^{8/3}\frac{G^{5/3}}{c^5}m_1 m_2 (m_1 + m_2)^{-1/3} \tag{2}$$

We assume that a binary is detectable if it has an evolved period under a threshold of 1000 ($P < 2000$). Then, depending on the galaxy type, we use the Synthetic Universe to create a synthetic distribution of about 10,000 binary lack holes. Next, for every galaxy we randomly draw 100 binary black holes from this synthetic distribution of binary black holes generated by the Synthetic Universe and evolve their periods forward in time keeping T within 10 Gyr. For spherical galaxies $0 \leq T \leq 10$ Gyr., for elliptical galaxies $9 \leq T \leq 10$ Gyr, and for irregular galaxies $0 \leq T \leq 3$ Gyr. A time within these ranges is randomly generated and assigned to a synthetic binary black hole. We calculate k_0 from equation 2 using the appropriate parameters we calculate the evolved period for each randomly selected binary black hole.

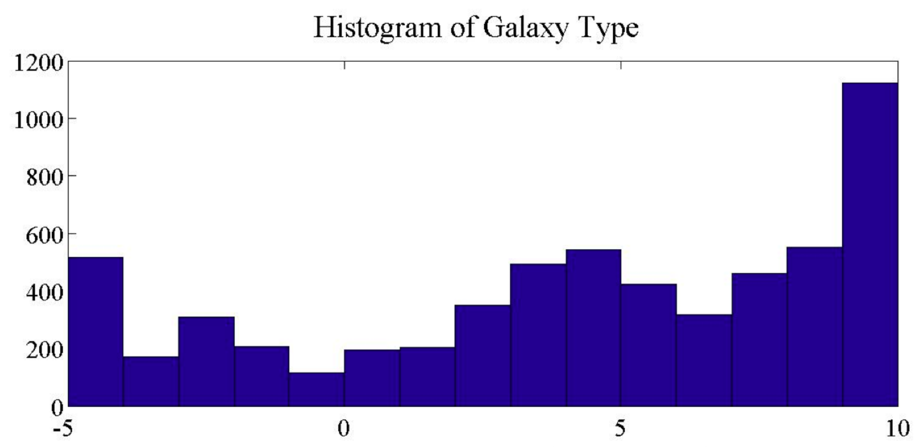

Figure 5. Histogram of galaxy type (in de Vaucouleurs Numerical Morphological Classification system) of irregular galaxies in the GWGC within 30Mpc

Conclusion

We have considered the field population of double black hole systems forming dynamically and explored the possibility that higher mass binaries forming in these low-metallicity environments would be detectable by SBGWOLLs at greater distances. Here we have populated galaxies by randomly drawing from a distribution of synthetic binary systems that depends on the galaxy type (spherical, elliptical, or irregular). For each galaxy in the GWGC we have randomly pulled 100 binary systems from the Synthetic Universe and evolved their period throughout time to determine the expected population of such binaries. We have demonstrated this distribution for Elliptical, Spherical, and Irregular galaxies and have found that none of the evolved periods are detectable by SBGWOLLs. Furthermore, from our results we deduce detecting a black hole binary with a SBGWOLL is highly unlikely even when considering binaries formed in low metallicity environments. Although our results might not support the idea of detecting binary black holes in nearby galaxies, they do agree with previous studies. (Belczynski et. al. 2010a).

Table 1: Probability of Detection from Galaxy Type Results

Galaxy Type	Galaxies	BBH	Probability of Detection (%)
Elliptical	689	708	0
Spiral	7137	22128	95.93
Irregular	1121	22276	82.12

Table 2: Probability of Detection from BBH systems Results

	Elliptical	Spiral	Irregular
Probability of Detection (%)	0	89.58	51.11
		1.70	2.05
		0.30	2.05
		2.17	17.22
		2.17	9.69
Total	0	95.93	82.12

In Conclusion, our results show that 10 extragalactic BBH systems were potentially detectable within 30 MPc. However, because we only ran the code that populated the universe once, this is not a statistically significant result. Generating the pool of evolved BBH took us about 13 days using a mulithreading 8 core server with 2 2.6 GHz Quad-Core Intel Xeon chips. After the three different pools were generated, we then ran a python code that would randomly assign BBHs to each galaxy and save only those whose orbital period was less than 2000 sec as described earlier. The generated pool of BBH systems started with the initial distribution from the Synthetic Universe. Future work for this project would be to run several more simulations to create statistical significant results. Also, a plot of the location in the sky of galaxies with detectable BBH systems with color coded percentages of detection could be produced for furthering this project.