1. A New Era of Astronomy

In February 2016, the astronomy community was thrown into frenzy when it received a major confirmation of Einstein's 1915 theory of general relativity. The first detection of gravitational waves (GW) came from a binary black hole (BBH) merger detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [1]. This discovery not only provided experimental validation of general relativity; it also gave birth to the era of multi-messenger[1] astronomy.

In nearly all scenarios, BBH mergers are not expected to emit electromagnetic (EM) radiation. The next most promising GW sources for EM radiation are the mergers of binary neutron stars (BNS) and black hole - neutron star pairs. While expected to emit GWs, these mergers are also the suspected sources of short gamma-ray bursts (GRB) [2]. These are intense, violent flashes of gamma-rays with a duration of less than two seconds and can be followed by a lower energy afterglow. The coincident detection of GW and short GRB signals is of extreme importance for establishing the connection between BNS mergers and short GRBs. The joint detection of GW and EM sources involves the: detection of a GW signal, sky localization of the source, and alerting EM observatories. BNS mergers are believed to be sources of GWs; therefore, the comparison between merger rate predictions and future GW detection rates will help put observational constraints on the galactic BNS merger rate, leading to a better understanding of the merging BNS systems.

2. Detection Rates

Unfortunately, for any science to be done with BNS mergers, they need to first be observed. At present, little is known about possible detection rates of BNS mergers. In the summer of 2017, I received funding to work in Pisa, Italy, in order to estimate these detection rates as a participant in the Department of Energy – Istituto Nazionale di Fisica Nucleare (INFN) Exchange Program. This is a cross-cultural, cross-generational exchange program that places students at various INFN facilities across Italy. I studied joint EM and GW detection rates alongside senior faculty in the INFN, as well as members of the Virgo Collaboration.

In order to estimate the joint detection rates of EM and GW signals of BNS mergers, I used a statistical simulation code for the BNS multi-messenger emission and detection by GW and gamma-ray instruments [3]. This pipeline consists of three primary stages. For the first stage, I generated a sample of Milky Way-like galaxies within a spherical volume of a set radius. I initialized the sample to be uniform in space, and then populated each galaxy with a set of merging BNS systems consistent with BNS population studies. For the second stage, I calculated the expected GW signal for each candidate, added in a Gaussian background noise, and simulated the GW detector responses to these signals. Then, I used statistical techniques to analyze the GW signals. For each GW candidate, I computed a sky localization area with the BAYESTAR soft-

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[1] Multimessenger astronomy is the coordinated observation of various astrophysical signals including EM, GW, and neutrinos. Each has a different production mechanism and reveals different information about the source.

ware package, which told me to some degree of certainty where the signal arose from on the sky. I then assumed that all BNS mergers were associated with a short GRB. In the final stage, using this assumption, I simulated the spectrum of the GRBs and their detection. The output of the simulation is a set of detections in a one-year period. In order to produce the estimates, I ran the simulation 100 times and averaged the results.

During this analysis, I made several assumptions which could limit the accuracy of the results. Most of these assumptions were conservative, so that the detection rates estimated served as a lower bound. My primary contribution to this project focused on investigating the effects on the detection rates of galaxy distributions within the sample—the real universe is not a uniform distribution of Milky Way-like galaxies. To carry out this investigation, I replaced the randomly generated galaxy sample with a catalog of real galaxies prepared particularly for use in EM follow-up studies of GW sources. This catalog, the Galaxy List for the Advanced Detector Era (GLADE), is constructed from four other pre-existing catalogs and contains all of the necessary information for EM follow-up studies. I then repeated the previous analysis and, with the aforementioned alterations made, found that the effects of galactic distribution on detection rates are negligible within the error bars associated with the assumptions originally made. This shows that the work of my colleagues and I at the INFN is applicable to the real universe.

In the coming years, additional GW detectors, namely KAGRA and LIGO India, will begin observing. The final phase of my project focused on evaluating the improvements that the detection rates may see when an additional detector begins operation. I once again altered the simulation, this time to include a fourth GW detector with LIGO-like sensitivities, and performed the analysis. Figure 1 shows the results of the sky localization of the GW source up to 90% confidence with four detectors observing.

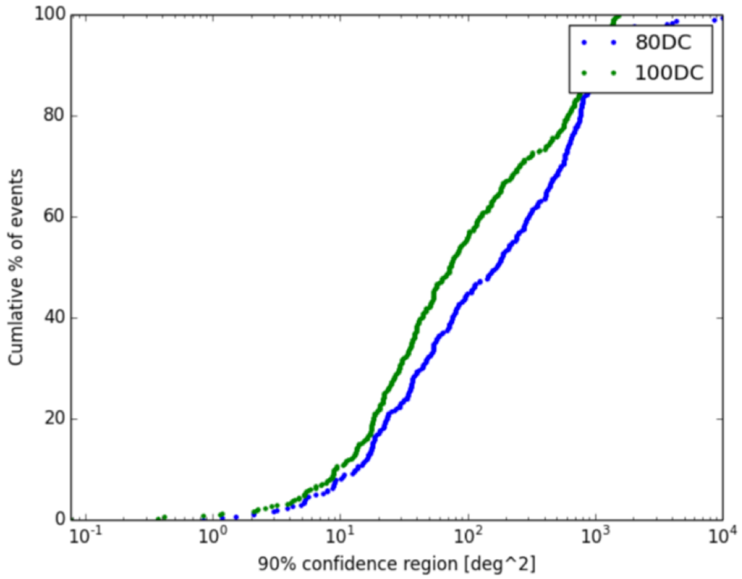

Figure 1: Cumulative histogram of number of GW detections with given sky localization, to 90% confidence for four detectors. 80% duty cycle (DC) means that a given detector has an 80% chance of being in operation. This represents the percentage of detected events that fall within a certain area on the sky, to 90% confidence. It is important for the EM follow-up to make the 90% confidence region as large as possible.

3. Results and Moving Forward

Initial results show improvements on the detection rates and localization areas. This means that moving forward, astronomers' abilities to precisely locate the direction of the GW signal in the sky will see improvements, which will directly influence the detectability of EM radiation from possible BNS mergers. In addition, the increased detection rates will increase the sample sizes, allowing for astronomers, as a community, to learn more about these events and the universe.

The sample size of detected merger events is still very small; consequently, the community knows very little of the detection and merger rates of merging BNS systems. My work has systematically produced a strong estimate of these rates. These results can be used by observatories in order to improve the quality of the EM follow-up when the next BNS merger detection happens. In fact, our study has been cited for this very reason in [4], in which the authors refer to our joint detection rates as justification for their methodology.

As I make the transition to graduate school, I will do so with cutting-edge knowledge of neutron star mergers. When paired with my background in computational astrophysics, I am in a unique position to use my skillset to build upon our understanding of neutron star astrophysics. The development of sophisticated simulations of neutron star mergers that include proper gravitational wave physics, for example, would be invaluable in studying the production of heavy elements within these mergers.

During Fall 2016, the Advanced Virgo detector began observations alongside LIGO, culminating in the first-ever joint detection of GWs from merging black holes. Additionally, in August 2017, just days after I travelled from Italy back to the US, LIGO saw the first-ever joint detection of GW and GRB signals from a BNS merger [5]. With this came the first observations of heavy element production in BNS mergers, confirming my expectations that this work could be used to study r-process nucleosynthesis in these events and leaving me with excitement for my future and the future of the field.

References

[1] Virgo, LIGO Scientific collaboration, B.P. Abbott et al., Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116 (2016) 061102.

[2] D. Eichler, M. Livio, T. Piran and D.N. Schramm, Nucleosynthesis, Neutrino Bursts and Gamma-Rays from Coalescing Neutron Stars, Nature 340 (1989) 126.

[3] B. Patricelli, M. Razzano, G. Cella et al., Prospects for joint observations of gravitational waves and gamma rays from merging neutron star binaries. JCAP 11(2016) 056.

[4] Om Sharan Salafia et al., Where and When: Optimal Scheduling of the Electromagnetic Follow-up of Gravitational-wave Events Based on Counterpart Light-curve Models, The Astrophysical Journal 846 (2017) 62

[5] LIGO Scientific collaboration, B.P. Abbott et al., GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. 119 (2017) 161101.