Unveiling the Lives and Deaths of Stars through Compact Object Mergers

Over my graduate studies, gravitational-wave (GW) astronomy went through an observational revolution. Due to the unprecedented sensitivity of the *Advanced LIGO/Virgo* network, in less than $\sim$5 years the field has evolved from speculating about the properties of compact binary mergers to having a population that facilitates astrophysical discovery.

For my PhD research, **I combined the growing catalog of GWs and other high-energy transients with computational modeling to investigate the formation and evolution of compact binary systems, providing novel constraints on massive-star evolution and compact binary formation channels.** In addition, as part of the LIGO Scientific Collaboration I contributed to the data analysis and parameter estimation for a number of significant GW triggers, and played a key role in astrophysical interpretation and population statements for the current catalog of GW events. In anticipation of the $\mathcal{O}(100)$ binary black hole (BBH) mergers and $\mathcal{O}(10)$ binary neutron star (BNS) mergers that will be detected via GWs and/or electromagnetic (EM) radiation over the next few years [1], my research has set the groundwork for using these populations to illuminate the formation pathways of compact binary coalescences and constrain uncertainties in massive-star evolution. These results have broader impacts in virtually all realms of astrophysics and impact various objectives in the Physics of the Cosmos (PCOS) and Cosmic Origins (COR) programs.

I. Where and how do LIGO's black holes form? [2, 3]

Multiple astrophysical channels have been proposed for forming BBHs that can merge within a Hubble time and be detected by the LIGO/Virgo/KAGRA network. These typically fall under two broad formation scenarios: *isolated binary evolution*, in which a massive-star binary progenitor evolves in isolation and significantly hardens its orbit via one or more mass transfer phases [e.g., 4] or chemically homogeneous evolution [e.g., 5], and *dynamical assembly*, in which strong gravitational interactions in dense stellar environments facilitate the formation of orbital hardening of BBH systems [6].

Modeling of these channels predict distinct, but overlapping distributions of black hole masses, spins, and merger redshifts, as well as rates comparable to the local BBH merger rate measured by LIGO/Virgo ($\approx 20-100\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, see [7]). However, the intrinsic parameters of BBHs predicted in these models are sensitive to a variety of evolutionary processes that lack precise constraints, such as the stability of mass transfer, the supernova natal kicks, and metallicity evolution over cosmic time [8]. The growing catalog of BBHs observed via GWs offer an unprecedented view into these physical processes, though our ability to extrapolate information about progenitors is muddled by the true population likely resulting from a complicated combination of many formation channels.

Bayesian hierarchical inference has proven a useful tools for elucidating such population parameters [9]. Though this technique has been utilized for constraining individual models of BBH formation (e.g., a universe where *only* isolated binary evolution contributes to the measured BBH population [10]), these estimations will be biased if contamination from other channels is not accounted for. **I developed a analysis that leverages hierarchical inference to constrain population-level parameters self-consistently across various BBH formation models, while simultaneously measuring the relative contribution that each model has on the total BBH population [2]**. We showed that we will begin to unravel the contribution of isolated binary evolution models versus dynamical formation models with $\mathcal{O}(100)$ observations, which will be realized within the next 2-3 years by the Advanced LIGO/Virgo network [1]. Moreover, physical prescriptions inherent in the modeling (e.g., the supernova kicks imparted at birth) can be ruled out with $\mathcal{O}(10)$ observations. This study lays the groundwork for future population inference exploring more uncertain physical properties and additional formation channels (see §1 of Research Proposal), which will **further elucidate massive-star evolution, binary interactions, and compact-object formation**, all goals of the PCOS program.

One promising method for distinguishing dynamically-assembled BBHs from their isolated counterparts is orbital eccentricity. Eccentricity has been relatively unexplored in the context of LIGO/Virgo; GWs emission quickly damps eccentricity as the orbit decays ($e \propto a^{12/19}$). If BBHs evolve unperturbed for any appreciable amount of time ($\gtrsim 10^4$ yr) they will be efficiently circularized and not show any semblance of eccentricity in the LIGO/Virgo/KAGRA sensitive band. However, recent work has shown that when general relativistic effects are properly accounted for, chaotic 3-body and 4-body encounters involving black holes in the segregated cores of globular clusters can facilitate rapid ($\lesssim 10^2$ yr) and highly-eccentric ($e_{10\,\mathrm{Hz}} \gtrsim 0.05$) mergers [3, 11–13]. In [3], I performed post-Newtonian N-body experiments of strong black-hole encounters from state-of-the-art globular cluster simulations, for the first time account for the contribution of higher-multiplicity encounters. **I showed that $\approx 10\%$ of BBH mergers from globular clusters will occur during strong binary-single and binary-binary encounters, with $\sim$50% of these having eccentricities that LIGO/Virgo can distinguish as non-zero.** Furthermore, the low-frequency sensitivity of the space-based LISA detector will be able to discriminate between BBHs that merge within a cluster compared to those that are ejected from the cluster. Since this prediction an outcome of solely two-body relaxation and N-body dynamics, eccentricity in cluster BBHs is robust to many assumptions about initial cluster properties and uncertainties about black hole natal properties (e.g., spins). Therefore, **eccentricity will be a key discriminate of BBHs formed in isolation and those formed in dynamical environments** — a single detection of an eccentric system would be indispensable for understanding BBH formation channels. However, to properly assess the impact of observing an eccentric merger on BBH populations, it is imperative that we understand the selection biases afflicting the detection of eccentric signals (see §2 of Research Proposal).

II. Understanding BNS progenitors through GWs, GRBs, and r-process [14–16]

Unlike BBH, BNS mergers emit radiation across the EM spectrum, allowing for precise localization and host associations. Even Gyr after their EM emission has faded, BNS mergers can still have an imprint on their explosion environments through the heavy elements that were synthesized in the neutron-rich ejecta of kilonovae. The other focus of my research focuses on interpreting these pieces of evidence to decipher the evolutionary processes that lead to BNS mergers.

Short gamma-ray bursts (sGRBs) have long been hypothesized to result from BNSs [17, 18]. Strong evidence for this origin came from the follow-up and localization of sGRBs detected NASA's *Neil Gehrels Swift Observatory* [19]. sGRBs push to high offsets (with $\approx 30\%$ having offsets $\gtrsim 10$ kpc), consistent with the broad delay times and subjection to kicks at birth in the compact binary paradigm [20]. GW170817/GRB170817A solidified this theory, providing direct evidence for the connection between BNS mergers, sGRBs, and kilonovae [21].

The association between cosmic explosions and their galactic hosts holds clues to the evolution and formation of their progenitors. In particular, **the spatial offsets of BNS mergers is a probe for understanding properties of supernovae and compact object formation**. By pairing the observed offset of GW170817 (≈ 2 kpc in projection) with kinematic modeling of BNS systems in the galactic potential of NGC 4993, **I led a study for the LIGO/Virgo collaboration in which we placed the first multi-messenger constraint on the progenitor of a compact binary** [14]. By identifying progenitor parameters that led to an offset matching GW170817, I calculated viable natal kick magnitude, pre-supernova orbital separation, and mass-loss in the supernova.

Mergers with high offsets from massive host galaxies provide more stringent constraints on the formation mechanisms of BNS. In [16], I implemented a similar kinematic modeling technique to examine the progenitor constraints of two highly-offset sGRBs — GRB 070809

($\approx$ 30 kpc) and GRB 090515 ($\approx$ 75 kpc). Using ground-based and *HST* photometry of the galactic hosts, I constructed time-dependent, semi-analytic models of the sGRB host galaxies, accounting for evolution along the star formation main sequence and galaxy growth over time. Combining this with state-of-the-art population modeling[1], **we found that the progenitor of GRB 090515 required a natal kick of $\gtrsim$ 200 km s^{-1} — larger than any known BNS system [23]**. Performing this analysis for the full catalog of sGRBs (and future GWs with EM counterparts) is paramount to fully resolving the progenitor properties and formation mechanisms of BNS systems (see §3 of the Research Proposal).

GW170817 also firmly established the connection between BNS mergers and kilonovae, and long-term observations of the kilonova lightcurve indicated significant lanthanide production, pointing to BNS mergers as one of the prime sites for *r*-process nucleosynthesis [e.g., 24]. In [15], explored the viability of BNS mergers explaining the *r*-process enrichment in metal-poor globular clusters, finding that **the *only* way BNS mergers can explain *r*-process enrichment in certain environments is through a poorly-constrained phase of mass transfer involving a naked He-star donor**, a direct contribution to the objectives of the COR program.

III. Characterizing LIGO data with machine learning and citizen science [25]

Throughout my PhD, I also played a key role in developing methods for combining citizen science and machine learning for astronomical data analysis. Citizen science has proven effective in data analysis endeavors across multiple scientific disciplines [e.g., 26]. However, the exponential growth of data acquisition necessitates a smarter way to perform citizen science. I was a main developer of *Gravity Spy* [25], an interdisciplinary citizen science project that couples human classification with machine learning models in a symbiotic relationship to classify and characterize transient noise in GW detector data[2]. We developed a novel feedback loop: human volunteers provide large, labeled sets of images to train machine learning algorithms and identify new types of noise, while convolutional neural networks learn from human classifications and guide how information is provided back to participants. This system proved successful; the project has accumulated $\gtrsim$1.6 million classifications from $\gtrsim$15,000 registered volunteers, and discovered and characterized dozens of new types of transient noise that afflict the observation of GWs. By integrating human and computer classification, citizen science can scale with the ever-increasing datasets of the future, and give non-specialists insights into the scientific method.

References

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[1] Using `COSMIC` [22], an open-source, version-controlled binary population synthesis code for which I am one of the main developers.

[2] www.gravityspy.org