# Deciphering the Biography of Massive Stars: Compact Object Mergers as a Rosetta Stone

The direct observation of gravitational waves (GWs) was one of the landmark discoveries in modern physics. Over the past four years, GW observations of binary black hole (BBH) and binary neutron star (BNS) mergers have provided an astrophysical laboratory for novel tests of general relativity, insights into the properties of extreme matter, an independent measurement of the expansion of the Universe, and demonstrated the connection between BNS mergers, short gamma-ray bursts (sGRBs), and kilonovae. However, we are only at the nascent stages of GW astrophysics. The imminent onset of the design-sensitivity Advanced LIGO/Virgo/KAGRA network [1–3] will observe a population of compact binary coalescences (CBCs) that will enable novel discovery and a revolutionize compact object astrophysics. *As a Hubble Fellow, I will develop the computational and statistical tools necessary to realize the full potential of GW astronomy in the era of large-scale populations.*

## Overview: Massive-Star Evolution in the Era of GW Astronomy

Over the next few years, the Advanced LIGO/Virgo/KAGRA network will have an order-of-magnitude increase in its observed population of CBCs [4]. This sample will be further bolstered by observations of electromagnetic (EM) transients that are attributed to CBCs, such as the $\approx$ 10 per year sGRBs detected by the *Neils Gehrels Swift Observatory* [5]. In anticipation of this growing population, two of the driving questions in astrophysics have become *where* and *how* did the progenitors of CBCs form and evolve?

The evolution of massive stars (particularly those in binary systems [6]) is poorly understood yet vital across many realms of astrophysics, ranging from nucelosynthesis to transients to galaxy evolution to cosmology. As the endpoint of massive-star evolution, CBCs encode unique information about their progenitor stellar systems, such as the types of galactic environments they were born in, the intricacies of stellar evolution that persisted throughout their lives, and the physics of the supernovae that marked their deaths. However, the detected population of CBCs likely results from many disparate formation channels, each with their own inherent evolutionary uncertainties. A key challenge over the coming years will be developing the tools and methodologies for properly leveraging the growing catalog of CBCs to disentangle formation scenarios and extract the underlying physics of their massive-star progenitors. Doing so will usher a golden era in our understanding of how massive stars evolve, and the environments that facilitate compact binary formation.

As a Hubble Fellow, **I will combine the growing catalog of CBCs identified via GWs and/or EM emission with state-of-the-art computational tools** to answer multiple key questions is GW astrophysics and binary stellar evolution:

1. What are the dominant formation channels for BBHs, and how can we constrain the physics of these channels with GWs?
2. How can we best identify CBCs with properties unique to a subset of formation channels and leverage these CBCs to elucidate merger rates?
3. How can the associations between compact object mergers (identified in GW or EM emission) and their host galaxies be used to understand the formation of their progenitors and the properties of their hosts?

## I. Constraining Astrophysical Models for BBH Formation

Ground-based GW observatories will detect more BBHs than any other type of CBC [4]. BBHs have the most disparate array of proposed formation mechanisms. The two canonical BBH formation channels, isolated evolution of a binary [e.g., 9] and dynamically assembly in a dense stellar environment [e.g., 10], each have subchannels with their own predictions of BH masses, spins, and redshift evolution. Another layer of complexity to deciphering the contribution from various formation channels comes from the poorly-constrained physical prescriptions that embed these models, such as mass transfer stability, common envelope evolution, the onset and outcome of pulsational pair-instabilities, and BH natal spins.

Meaningful astrophysical statements have already been made using only the 10 events from the first and second observing runs of Advanced LIGO/Virgo. Using phenomenological representations of the true, underlying BBH population, we have tentative evidence for an upper mass gap ($> 99\%$ of BBHs have component masses $\lesssim 45\,M_{\odot}$) and BHs with high spins aligned with the orbital angular momentum are strongly disfavored [11]. Recent studies [e.g., 12, 13] have investigated how GW detections can be exploited to infer uncertain physical prescriptions that affect BH populations. However, a robust and self-consistent investigation accounting for the impact of such parameter choices across a combination of formation scenarios has yet to be accomplished. Performing model selection using various self-consistent, state-of-the-art astrophysical models will be essential for deciphering the uncertain physical prescriptions that encompass massive-star evolution and compact object formation.

In [14], I found that with $\mathcal{O}(100)$ BBH observations we can determine *the relative contribution* of the two canonical formation channels to the total BBH population *as well as certain physical prescriptions* inherent to these channels (see Figure 1). Though these channels predict highly-overlapping distributions, as the catalog of BBH mergers grows, we will see a dramatic increase in inference power. During my fellowship, I will expand upon my previous work by **performing hierarchical inference on a full suite of state-of-the-art astrophysical simulations that encompass the numerous formation scenarios and physical prescriptions for BBH systems.** To accomplish this, I will start by modeling a grid of BBH populations formed through isolated binary evolution and dynamical assembly in globular clusters using population simulations that I helped develop and have significant experience working with (`COSMIC` [15] and `CMC` [16], respectively), properly accounting for selection effects and redshift evolution. I will then work with collaborators to model and include BBH population predictions from other formation channels (in particular, *chemically-homogeneous evolution* [17] and *hierarchical triples from the galactic field and galactic center* [18]), ensuring self-consistency across channels to allow for a side-by-side investigation.

For each channel, I will analyze the effect of three uncertainties in binary evolution that

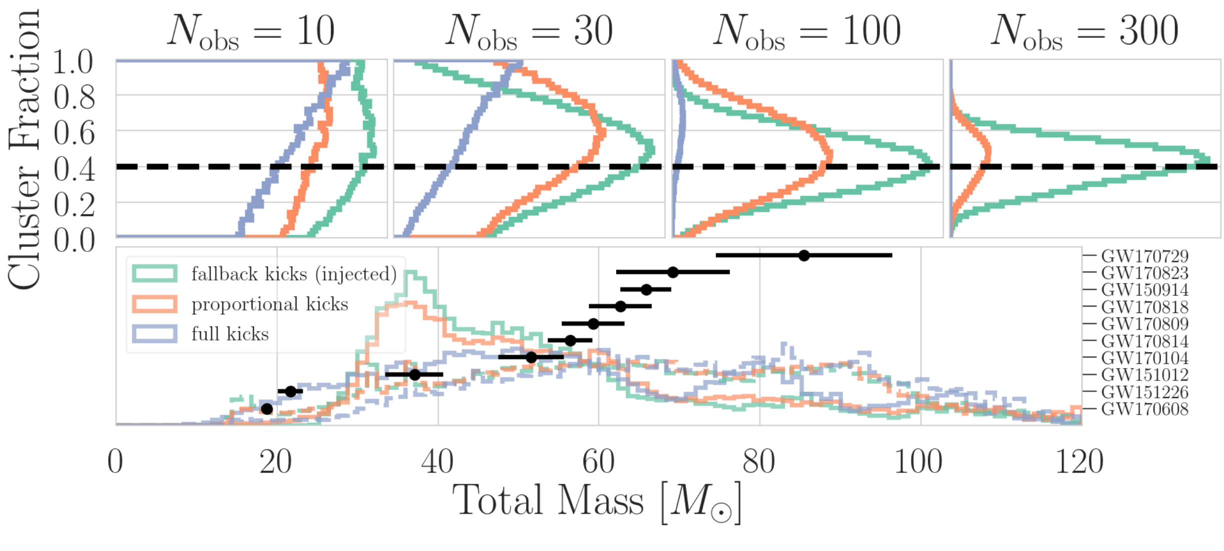


**Figure 1:** The growing population of GW observations provide an unprecedented opportunity for constraining massive-star evolution and BBH formation scenarios. *Bottom panel:* distributions of BBH total mass, accounting for selection effects, for two astrophysical models: isolated binary evolution (dashed histogram) and dynamical assembly in globular clusters (solid histogram). Colors show how these populations change due to variations in the prescription for BH natal kicks. Total masses of BBHs from GWTC-1 [7] are over-plotted for reference. *Top panel:* demonstrates hierarchical inference in a Universe where 40% of BBHs come from clusters, 60% come from isolated binary evolution, BHs are kicked via the *fallback* mechanism [8]; posterior distributions on the population-level parameters show strong preference for the correct branching fraction and kick prescription with $\mathcal{O}(100)$ BBH observations. As a Hubble Fellow, I will expand this inference to utilize an entire suite of self-consistent astrophysical models for BBH formation (e.g., triples, chemically homogeneous evolution) that each have their own unique physical uncertainties.

strongly affect the resultant population properties and rates: (i) the strength of BH natal kicks; (ii) the efficiency of common envelope evolution; and (iii) the natal spins of BHs at birth. After creating a grid of simulations, I will use machine-learning techniques (e.g., Gaussian processes) to interpolate the output distributions of BBH parameters, thereby cutting computational costs by not needing to perform a simulation at each unique point in parameter space [see e.g., 19]. **Using the catalog of GWs from LIGO/Virgo/KAGRA, I will then perform Bayesian hierarchical inference to jointly measure branching fractions and physical prescriptions of stellar evolution**. My experience in BBH population modeling, GW data analysis, and Bayesian inference makes me perfectly suited for this substantial endeavor.

As part of my fellowship, I will package this tool and accompanying database of population models, making them publicly available so the consistency and compatibility of any BBH formation channel can be easily assessed. This will allow such methodologies to be extensible to include other predicted formation scenarios, and be adaptable to model selection endeavors using mock populations in the context of future GW detectors, such as *LISA*, *Cosmic Explorer*, and *Einstein Telescope*.

## II. Quantifying the Selection Function for Eccentric Mergers

Hierarchical inference will be more powerful with the observation of BBH systems with parameters that are unique to a subset of formation channels. Globular clusters, for example, are predicted to produce a significant number ($\approx 1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ at $z < 1$ [23]) of systems with measureable eccentricities in the LIGO band [22–25, see Figure 2], whereas BBHs that inspiral in isolation over substantial timescales ($\gtrsim 10^4$ yr) will radiate away most of their orbital eccentricity by the time they enter the LIGO sensitive band. Therefore, the detection and measurement of an eccentric BBH will be indispensable for pinning down the globular cluster merger rate, and therefore also limit viable merger rates in isolated binary evolution (and physical prescriptions that affect merger rates).

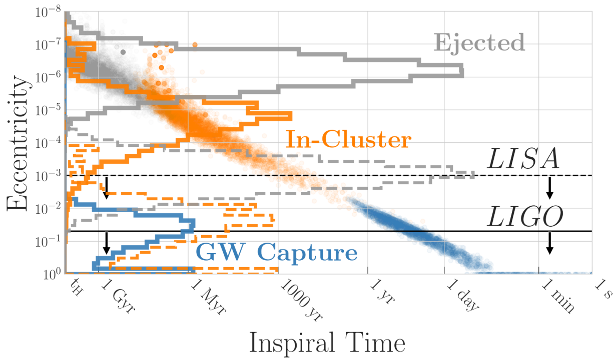


**Figure 2:** Strong gravitational interactions in dense stellar environments facilitate rapid-inspiral BBH mergers that retain appreciable eccentricity in the LIGO sensitive band. Solid (dashed) histograms show the eccentricity in the LIGO band [20] (LISA band [21]), with the minimum measurable eccentricity marked with a solid (dashed) black line. Colors differentiate the three main channels of BBH mergers that result from globular clusters — mergers that occur during strong, chaotic gravitational encounters (*GW captures*) have eccentricities measurable by LIGO, and will be key in discriminating BBH formation scenarios. Adapted from [22].

Though binaries with lower eccentricities will be easier to detect using the circular waveform templates in matched-filter searches, binaries with larger eccentricities will be easier to distinguish from their circular counterparts [26]. Development of eccentric waveforms and measurability of eccentricity has been an active topic of research. Though none of the BBH mergers in the current catalog have clear signs of eccentricity [27], recent work has found that GW159014-like systems with eccentricities of $e \gtrsim 0.05$ when entering the LIGO band [20] can be distinguished from analogous circular signals. Modeling of globular clusters shows that this is the case for $\sim$ 5% of cluster BBH mergers (see Figure 2). Quantifying the selection biases impinging the detection of eccentric binaries, on the other hand, has yet to be addressed thoroughly. Understanding this selection function is vitally important for determining rate of cluster binaries, in the case of both *detections* and *non-detections* of eccentric mergers. To this end, **I will perform a targeted injection study, where eccentric GW waveforms tuned to the properties of globular cluster binaries are placed in LIGO/Virgo noise realizations, and recovered using quasi-circular templates.** This will provide a selection function for eccentric BBHs, essential for understanding the astrophysical implications of detecting an eccentric BBH.

## III. Exposing Progenitors of Neutron Star Mergers via Host Associations

Host associations of GW mergers can also act to unveil the lives of their massive-star progenitors, as well as provide an important probe into the demographics of galaxies that host CBCs. In [28], I showed that via host associations and projected offsets, one can extract information about about the progenitors of BNS mergers, such as the natal kicks and mass loss in supernovae (see Figure 3). The second focus of my work will be to **investigate the kinematic evolution and progenitor systems of CBCs via their host galaxy associations.** Such kinematic modeling techniques will apply to both the expanding catalog of sGRBs with known host association, and CBCs with EM counterparts detected by LIGO/Virgo/KAGRA.

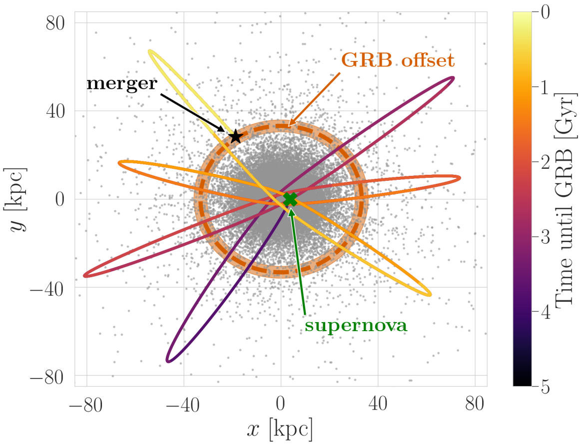


**Figure 3:** The location of CBCs with respect to their host galaxies provides insights into the mechanisms that led to their formation. The kinematic evolution of a BNS tracer that matches the offset of GRB 070809 is shown. The motion of the system through its host is significantly altered due to the supernova explosion(s) that formed the BNS, and therefore the merger location contains insights into the supernova mechanism itself. As a Hubble Fellow, I will pair such modeling with cosmological simulations to understand the progenitors and host properties of CBCs identified via GW and/or EM emission. Adapted from [28].

Rather than relying on semi-analytic prescriptions to approximate the evolution of the galactic, I will use the `Illustris` cosmological simulation suite [29] to identify analogs of CBC host galaxies, and follow the kinematic evolution of CBC progenitors through cosmic time, accounting for the full star-formation history and galactic growth. By comparing observed locations of mergers to these computational models, I will constrain aspects of CBC massive-star progenitors, such as delay times and supernova natal kicks.

I will expand upon my previous work to include *all* $\approx$ 30 sGRBs from a sample identified by *Swift*, which have galactic host associations characterized by *Hubble Space Telescope* (*HST*) photometry (see [30]). Based on the size, mass, redshift, and star formation rate of the hosts, I will find the $\mathcal{O}(10)$ best-matching galaxies in the `Illustris` simulations, populate tracers according to the galactic star formation history, determine their barycentric velocity after supernova kicks, and directly integrate their 3-dimensional kinematic evolution in the time-dependent galactic potential from birth until merger. Investigating these CBC progenitors will provide complementary constraints to those achieved from the sample of BNSs in the Milky Way, and will unveil the selection biases that impinge our ability to realize the true, underlying population properties of CBCs and their progenitors.

Though BNS detection rate at design sensitivity is $\sim 10\,\mathrm{yr}^{-1}$ [4], the detection rate of optical counterparts is much less certain. However, with the onset of dedicated counterpart surveys, there is a significant chance that during my fellowship at least one BNS or NSBH merger with an optical counterpart will be identified. At a distance of $\lesssim 200\,\mathrm{Mpc}$ from us, such systems will be prime targets for detailed galactic characterization, especially with the impending launch of *JWST*. **I will use these detailed galactic characterizations to identify local-universe analogs in the `Illustris` simulation suite, and collaborate with `Arepo` experts to perform zoom-in simulations of these galaxies embedded with compact binary tracers.** By exploring the kinematic evolution and offsets of these tracers, I will place novel constraints on the stellar progenitors of GW sources and explore the evolutionary history of galaxies that harbor CBCs, such as star formation history, galactic growth, and galaxy mergers.

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***The next few years will be a golden era for CBC discovery. My research will take crucial steps towards realizing the full potential of the proliferating GW population and unveil unprecedented information about the progenitors of CBCs through state-of-the-art astrophysical modeling.***

## Relevance to NASA Science and Missions

By combining observations of compact binary mergers with numerical simulations and statistical models, my work will elucidate the formation processes of BHs and NSs and disentangle the astrophysical scenarios and environments that lead to GW merger events, both goals of the Physics of the Cosmos (PCOS) program. My work modeling BNS systems in their host galaxies leverages the growing catalog of high-energy transients identified by PCOS missions such as *Fermi* and *Swift*, and relies on the detailed photometric and spectroscopic followup of their hosts using missions such as *HST* (and *JWST*). These missions, as well as future survey facilities such as *WFIRST*, are essential for identifying counterparts to GW events and allowing for multi-messenger constraints of their progenitors. In addition, numerical evolution of BNS progenitors representative host galaxies will help understand the distribution and dispersion of $r$-process for a panoply of galaxy types across cosmic time, a key goal of the Cosmic Origins program.

## Role of host and host institution

The Harvard-Smithsonian Center for Astrophysics (CfA) is the ideal institution for conducting my proposed research. The Institute for Theory and Computation (ITC) at CfA has leading experts in the broad range of fields that complements my planned research: binary stellar evolution, dynamics, transient observation, and galaxy evolution. My primary faculty contact, Selma de Mink, is an expert in massive-star evolution and the formation of LIGO sources. My work will also greatly benefit from Avi Loeb (dynamics), Edo Berger (sGRB observations and host characterization), and Lars Hernquist (galaxy evolution), all of whom are experts in crucial components to my proposed research. The ITC has access to the `Cannon` computing cluster, which boasts $\gtrsim 10^5$ cores, as well as a dedicated cluster with 1152 cores, which will be essential for my computationally-intensive research. In addition, I will retain my affiliation in the LIGO Scientific Collaboration through the neighboring MIT LIGO Lab, contributing 20% of my time working on LIGO data analysis and GW populations with Salvatore Vitale.

## Fellowship Timeline

***Year 1 (2020-2021):*** (i) run suite of BBH population simulations, develop model interpolation; (ii) publish population analysis for all localized sGRBs using semi-analytic galactic models; (iii) publish eccentric merger selection effects study
***Year 2 (2021-2022):*** (i) identify sGRB host analogs from cosmological simulations, perform kinematic evolution of tracers; (ii) publish model selection study (inference on BH natal spins, kicks, and common envelope efficiency); (iii) perform zoom-in galactic simulations and kinematic evolution for GW/EM events
***Year 3 (2022-2023):*** (i) create database to host BBH population models and API that allows hierarchical inference to be performed using new population models and the current catalog of GWs; (ii) publish results on sGRB/BNS population based on cosmological simulations, compare with properties inferred for Galactic BNS; (iii) perform zoom-in galactic simulations and kinematic evolution for GW/EM events

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