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UNDERSTANDING THE PROGENITOR GALAXIES OF BINARY BLACK HOLES

R. Srinivasan[1,2], A. Lamberts[1,2] and M. A. Bizouard[2]

Abstract. The black holes detected by gravitational wave detectors have masses (typically 20-50 $M_{\odot}$) that are systematically heavier than those detected in X-ray binaries (5-20 $M_{\odot}$). This mass discrepancy suggests different progenitor stellar environments, especially metallicity, between X-ray binary and gravitational wave black holes. We have built a model Universe that represents star formation for different redshift, host galaxy mass, stellar metallicity and in which we incorporate a binary evolution model under different conditions (stellar-wind, mass-transfer, supernova kicks). We present our results on simulated binary black hole merger rates and binary evolution models which have black hole mass distributions consistent with the detected population. Our analysis shows that the majority of merging binary black holes in the Universe are small ($<$ 15 $M_{\odot}$) and formed at large redshift (2-3), in galaxies heavier than the Milky way with a high metallicity (0.5-0.9 $Z_{\odot}$) environment. In contrast, the gravitational-wave detectable population is predominantly comprised of larger black holes ($>$ 20 $M_{\odot}$), formed at lower redshifts (z $<$ 1), in dwarf galaxies with a low metallicity (Z $\simeq$ 0.02 $Z_{\odot}$) environment. The number of gravitational-wave observations will increase in the following years and will further constrain the comparison.

Keywords: metallicity, galaxy mass, gravitational-wave, merger rates, binary black-holes

1 Introduction

Since the first detection of gravitational-waves (GW) in 2015 (Abbott et al. 2016), there have been nearly a hundred confirmed detections of merging binary black holes (mBBH) by ground-based GW detectors (Abbott et al. 2021). The measured mass spectrum of GW black holes show a clear distinction from the masses inferred from electromagnetic observations. The former are typically 20-50 $M_{\odot}$while the latter are in the range of 5-20 $M_{\odot}$. This mass discrepancy could be because of different observational biases or different astrophysical formation environments including different galaxies and metallicity of star forming gas. While ground-based gravitational wave detectors provide information about the merging system, they do not provide information about the host galaxy, especially due to their large uncertainty in the source sky localization. For this purpose, we have designed a model universe which accounts for the star formation rate and binary evolution mechanisms to predict the progenitor host-galaxy properties for binary black hole mergers. However, there exist large uncertainties in the model of binary evolution and the star formation rates which can drastically vary the merger rates and black hole progenitors. In this presentation, we present preliminary results on the progenitors of merging binary black holes by implementing a typical model of the universe.

2 Methods

We create a model universe to explore the progenitor environment of mBBHs. Parameterized by the present-day host galaxy mass, $M_{\rm Gal}$, its metallicity Z, and redshift of star formation $z_{\rm f}$, the universe combines the star formation rate (SFR) with the binary evolution of stars to ultimately generate an astrophysical mBBH rate. Using COSMIC (Breivik et al. 2020), a rapid binary population synthesis (BPS) simulation code which builds on the BPS from Hurley et al. (2002), we can compute the efficiency of mBBH formation from binary star systems as function of the progenitor host-galaxy's metallicity. Convolving the SFR and the efficiency of mBBH formation, we create an astrophysical population of mBBH. Finally, we simulate gravitational wave

[1] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, France
[2] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, ARTEMIS, France

(GW) signals from the mBBH at the time of merger and determine the detection rate by the LIGO-Virgo three detector network, assuming the sensitivity from the third and most recent observing run. Thus, for both the astrophysical and detected mBBH populations, we can map back to their progenitor environment to establish their progenitor formation rates.

2.1 *Star formation rate (SFR)*

Based on observed connections between the SFR and the host-galaxy, we consider the SFR as a function of the present-day galaxy mass M_{Gal}, metallicity of star forming gas Z, and the redshift of formation z_f. As will be described in detail in §2.2, the metallicity of the star forming gas greatly influences the efficiency of mBBH formation. For this purpose, we adapt a simplified model of SFR by Lamberts et al. (2016).

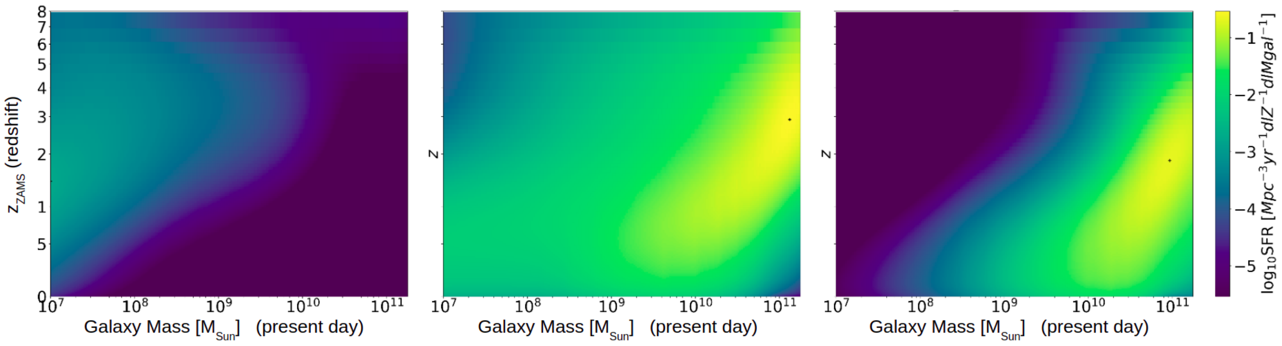

Fig. 1. Star formation rate (colorbar) as a function of present-day M_{Gal} and z_f for three ranges of metallicity: **left:** Z $< 0.02\ Z_\odot$, **center:** $0.02\ Z_\odot <$ Z$< 0.6\ Z_\odot$, **right:** Z $> 0.6\ Z_\odot$.

We optimize the SFR model for computational with 200 log-spaced bins of M_{Gal}, 22 log-spaced bins of Z, and $z_f$binned uniform in time in steps of 100 million years. Figure 1 shows that low-metallicity stars tend to be formed in dwarf galaxies have a nearly constant formation rate across z_f. In contrast, high metallicity stars are formed in present-day massive galaxies spanning lower redshifts ($z_f \leq 3$).

2.2 *Binary population synthesis*

For our analysis, we assume the fraction of stars that form in binary systems, ie., the binary fraction, to be 0.8. We simulate binary stellar evolution using COSMIC. BPS simulations model binary evolution processes like stellar winds, mass-transfer between the binary, and the supernova mechanism.

From the BPS simulation, we obtain the efficiency of formation of mBBH from binary stars as a function of their metallicity. The metallicity strongly influences the star mass lost due to stellar winds (Vink et al. 2001; Vink & de Koter 2005). This can drastically change the pre-supernova mass of the star which can affect the efficiency of black hole formation. Generally, lower the star metallicity, lesser the mass-loss, and vice-versa. In addition to mass-loss due to winds, mass-loss can also occur during an unstable mass-transfer phase characterised by the appearance of a common envelope surrounding the binary. This arises when the mass-transfer occurs on a dynamical timescale resulting in a non-conservative exchange of mass between the donor and accretor stars. The drag due to the common envelope brings the stars closer together which increases the likelihood of a merger while also favouring stellar mergers if the envelope fails to be ejected. Finally, relevant to our analysis, the supernova mechanism can influence the kick imparted to the black hole which widen the orbit, thereby decreasing the merger rate within the Hubble time.

2.3 *Merging binary black hole population*

Multiplying the SFR with the binary fraction and the efficiency of mBBH formation for the 3D volume of M_{Gal}, Z, z_f, we produce an astrophysical formation rate of mBBH progenitors. The astrophysical population of mBBH is obtained by first sampling N_s systems from the BPS simulation for every set of parameters in the 3D volume. Optimized for convergence and computation, we sample $N_s = 100$ systems and select those that merge within the present-day. The emerging astrophysical population has a progenitor formation rate of a given set of M_{Gal}, Z, z_f given by the product of the SFR density with the binary fraction and the efficiency of mBBH formation (§2.2 with units $Gpc^{-3} \cdot yr^{-1}$.

Upon simulating the gravitational waves from the astrophysical population, we determine the detected population based on a signal to noise ratio (SNR) criteria wherein an mBBH is deemed detectable if the individual SNR is greater than 6 and the network SNR greater than 12. We isotropically sample extrinsic binary parameters like the inclination angle and sky position. The luminosity distance is computed from the redshift of merger and our assumed cosmology with $H_0 = 67.74$ km/s, $\Omega_M = 0.3089$ and $\Omega_{Vac} = 0.691$.

3 Results

3.1 Astrophysical mBBH population

Fig. 2 shows the progenitor formation rate of astrophysical mBBH as a function of M_{Gal} and z_f. The peak formation rate occurs in massive galaxies that are larger than the Milky-Way ($M_{Gal} \simeq 10^{11}$ $M_\odot$) in the early universe ($z_f \simeq 3.5$). Comparing with Fig. 1, we see a large overlap between the SFR and the formation rate of mBBH indicating that the SFR predominantly influences the progenitor formation rate, with limited effects seen due to the binary evolution dynamics.

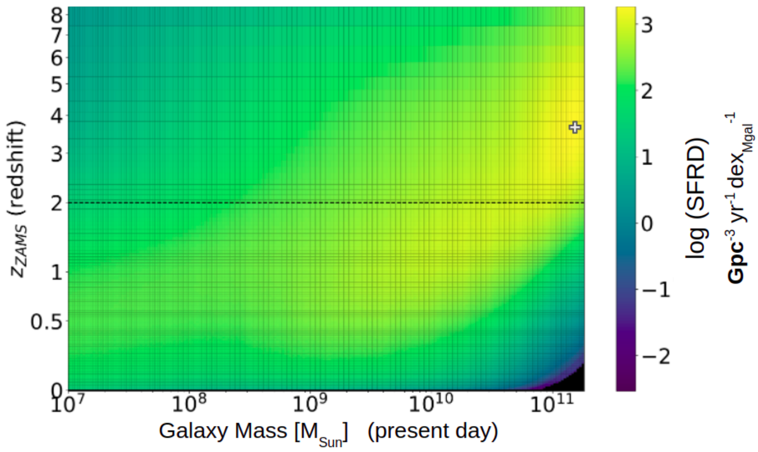

Fig. 2. Progenitor formation rate of mBBH (colorbar) as a function of M_{Gal} and z_f. The '+' represents peak formation rate. The majority of mBBH progenitors arise in large galaxies with $M_{Gal} \simeq 10^{11}$ $M_\odot$at $z_f \simeq 3.5$.

3.2 Detected mBBH Population

The detected mBBH population is simulated based on the SNR thresholds described in §2.3 and the progenitor formation rate is shown in Fig. 3. The majority of progenitors of detectable mBBH arise in both large galaxies with $M_{Gal} \simeq 10^{11}$ $M_\odot$at $z_f \simeq 3$ and in dwarf galaxies ($M_{Gal} < 10^9$ $M_\odot$) in the local universe ($z \simeq 0$).

Clearly, the detector bias towards nearby mergers from massive black holes plays a role in drastically altering the typical origin of the progenitors. Nearby mergers are more likely to arise from nearby progenitors, ie, $z_f < 0.2$. Moreover, large black holes arise from low metallicity systems due to the low mass loss from winds (discussed in §2.2). Dwarf galaxies have low gravitational potentials with low escape velocities. As a result, ejecta from metal-rich supernova are not contained within the galaxy. Thus, they maintain a low metallicity environment since their formation. Therefore, the detector bias favours dwarf galaxies in the local universe. The effect of the astrophysical formation rate can be seen the secondary peak in high mass galaxies (10^{11} M_{Gal}) at a high z_f (3.5).

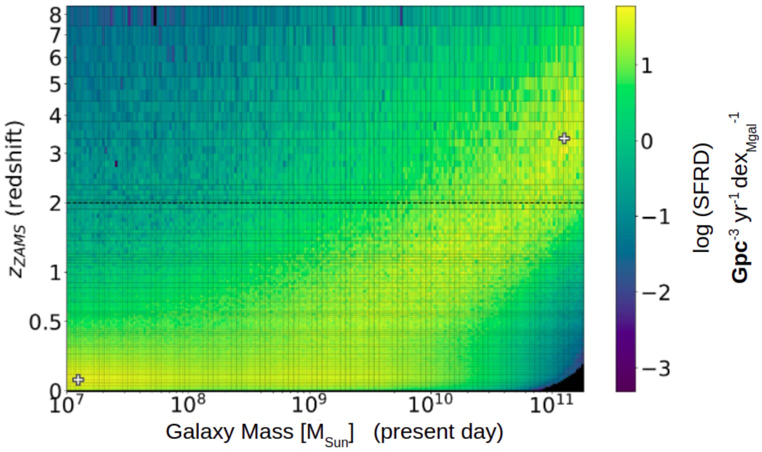

Fig. 3. Progenitor formation rate of detectable mBBHs (colorbar) as a function of M_{Gal} and z_f. The '+' represents local peak formation rates in both large galaxies with $M_{Gal} > 10^{11}$ $M_\odot$at $z_f \simeq$ 3 and in dwarf galaxies with present-day $M_{Gal} \simeq 10^7$ $M_\odot$.

4 Conclusions

Based on our simulation of a typical model universe, we have mapped mBBHs to their progenitor galaxy environment, parameterized by M_{Gal}, Z, z_f. The progenitors of mBBHs typically arise from large host-galaxies with $M_{Gal} \simeq 10^{11}$ $M_\odot$at $z_f \simeq 3.5$. A subset of these mBBH systems are detectable by ground-based GW detectors. Upon simulating GWs from mBBHs, we see that the progenitors of detectable mBBHs are usually from both large galaxies with $M_{Gal} > 10^{11}$ $M_\odot$at $z_f \simeq 3$ and in dwarf galaxies with $M_{Gal} \simeq 10^7$ $M_\odot$at the present day. Future analysis will explore different models of star formation and binary evolution, testing their consistency with rates from GW observations, and ultimately understand the effects of SFR and BPS models on the progenitor host-galaxy environment.

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