What we need from XG observatories to unveil the birth, life and death of massive stars – Part 1: birth

SUMMARY

The next-generation of gravitational-wave (GW) observatories have the potential to solve key questions about massive stellar evolution. In this first part, we focus on how they will help us understand the formation of massive stars out to redshifts far beyond the capabilities of electromagnetic (EM) observations. To achieve this, we need a significant population of high S/N detections out to $z > 15$ such that we can constrain the branching ratio of different formation channels as a function of redshift, and use this to map the merger rate to the star formation rate (SFR).

Key questions in massive binary stellar evolution: 1. How do massive stars form?

Massive stars impact *every* part of modern astrophysics; their ejecta, shocks, outflows, and ionizing photons shape their environments, they trigger and regulate star formation, and drive the chemical evolution of the Universe that enables the formation of elements like oxygen, and the more complex molecules necessary to facilitate life. Despite their importance, the formation, lives, and explosive deaths of massive stars are still a mystery. They are rare and short-lived, making it extremely challenging to observe a statistically significant population and learn about their properties, especially in environments outside our Milky Way. GW astrophysics provides a new frontier to study the lives and deaths of massive stars throughout cosmic history and can help solve key questions in massive star evolution: *1. How do massive stars form?*, *2. How do massive stars evolve and interact?*, and *3. How do massive stars end their lives?*.

1. How do massive stars form? A myriad of astrophysical phenomena depends critically on the rate of star formation throughout the cosmic history of the Universe. Exotic transient phenomena, including (pulsational) pair-instability supernovae, long gamma-ray bursts and GW events appear to be especially sensitive to the metallicity at which star formation occurs at different epochs throughout the Universe [15, 13, 1]. This *metallicity-dependent* cosmic star formation history is particularly difficult to constrain see e.g., [10, 5, 9]. Even at low redshifts, the low metallicity part of the distribution is poorly constrained [11].

Potential scientific impact of XG detectors

The fact that the yield of double compact object formation is a strong function of metallicity [4, 18, 14], implies that the population properties of DCO mergers can in principle be used to learn about the metallicity-dependent cosmic star formation history, and the chemical evolution of galaxies. Next-generation gravitational wave detectors promise high precision measurements of BHBH mergers beyond redshift 15 [16, 12, 21, 20, 7]. For reference, constraints on the SFR from EM observations are very sparse above $z = 6$ (e.g., [2]), with the highest constraints at about $z = 7 - 8$ (e.g., [6, 3]). Vitale et al. (2019), [23] showed how such detections can provide a measurement of the SFR, even without knowing the functional form of the SFR and delay time distribution. However, for a high-precision measurement of the star-formation rate beyond $z = 10$, we need to know the delay time: the time spanned between the birth of a binary star system and the moment of a double compact object merger. Although the delay time is not a direct observable, we expect distinct relations between observables (like masses) and delay times for different formation channels [22, 19]. Addressing this question consists of two components: first we need to measure the DCO merger rate out to $z = 15$, and second we should calculate the branching ratios of different formation channels as a function of redshift. The latter will allow us to link delay times to observed systems, thereby providing a precise measurement of the SFR.

SCIENTIFIC IMPACT OF XG DETECTORS

Measurement of the branching ratios of different formation channels. Measurements of the star-formation rate far beyond the capabilities of EM observations (i.e. out to $z \sim 15$). An independent measurement of the low vs high metallicity star formation rate out to cosmic noon.

Benchmarks for XG detectors to enable the scientific impact

To achieve this scientific impact, we need:

1. **A horizon for BHBH mergers that allows for a complete set of measurements out to $z = 15$.** This step is most crucial, as it will allow us to map the rate evolution with redshift, providing insights into the early Universe. Furthermore, measurements at higher redshifts reduce uncertainties surrounding maximum delay times, as they extend our observations to earlier cosmic eras.
2. **To ensure 10% detections of BHBH mergers with a S/N of at least 100 beyond cosmic noon.** Parameters such as mass ratios, spins, and orbital eccentricities have been repeatedly proposed as

discriminators between different formation channels (see e.g., [17] and references therein), but the reliable determination of these properties requires high S/N events. By capturing a substantial population of high S/N events, we can determine the branching ratios of different formation channels as a function of redshift, thereby linking delay-time distributions to the observed population of merging BBHs.

3. **A population of NSNS mergers detected out to cosmic noon.** While BHBH formation is particularly sensitive to low metallicity star formation, NSNS mergers offer insights into the total star formation rate density (e.g., [8]). By determining both the NSNS rate and BHBH rate up to cosmic noon and understanding the delay time distribution for each population, we can gain new constraints on the expected distribution of high- versus low-metallicity star formation.

XG DETECTOR AND NETWORK REQUIREMENTS

A complete measurement of the BHBH merger rate out to redshifts of $z = 15$, including a significant population (about 10% of the total sample) of high S/N detections. A measurement of the NSNS merger rate out to cosmic noon.

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