What we need from XG observatories to unveil the birth, life and death of massive stars – Part 3: stellar death

SUMMARY

The next generation of gravitational-wave (GW) observatories have the potential to solve key questions about massive stellar evolution. In this last part, we discuss how next-generation measurements of the remnant mass distribution can constrain supernova physics and nuclear reaction rates in the final stages of a massive star's life. To achieve this we need to push our detection frequency down to 5 Hz and detect 10,000 double compact object (DCO) mergers with masses below $10 M_\odot$ and a S/N above 100.

Key questions in massive binary stellar evolution: 3. How do massive stars end their lives?

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 is 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?*.

How do massive stars end their lives? Modeling the final moments of a massive star's life presents a significant challenge, yet it is crucial for our understanding of phenomena such as supernovae (SN), long-duration gamma-ray bursts, and pulsational pair-instability supernovae (PPISN) that are prevalent throughout our Universe. Extensive research has been conducted on SN explosions, but the precise mechanism behind stellar core collapse and the physical engine driving the subsequent explosion remain elusive. Moreover, it is uncertain whether BHs experience significant natal kicks and to what extent material falls back when a star explodes, leading to the formation of a neutron star (NS) or a black hole (BH).

Potential scientific impact of XG detectors

Accurate measurements of the mass distribution of NS and BHs offer invaluable insights into the aforementioned topics. Next-generation detectors present a unique opportunity for significant advancements in several ways:

Firstly, Xg ground-based detectors will provide access to much lower frequencies, reaching as low as 5Hz compared to the current limit of 20Hz for present-day detectors [17, 5, 6]. This allows us to observe more cycles of the inspiral phase of massive events (such as for GW190521 [1]), removing doubt about their observed source properties. Moreover, at $z \sim 1$ this will enable us to detect BBH merger with masses up to $M_{tot} \lesssim 1000\mathrm{M}_{\odot}$ [6] (instead of $M_{tot} \leq 110\mathrm{M}_{\odot}$). Mapping the mass distribution of merging BBHs with masses up to $M_{tot} \approx 1000\mathrm{M}_{\odot}$ in detail will reveal *both edges* of the PISN mass gap, which can be used to measure the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate [7]. This measurement, in turn, can be used to can refine our predictions for the lower end of the mass spectrum.

Secondly, there will be no bias towards higher-mass systems since typical sources will not be detected at threshold [22]. This will allow us to place unprecedented constraints on the source properties of NSNS, NSBH, and low-mass BHBHs. Currently, due to low signal-to-noise (S/N) observations, our studies are restricted to analyzing chirp mass or total mass. However, the anticipated increase in the number of extreme S/N detections facilitated by next-generation detectors will allow us to precisely determine the mass ratio and, consequently, the component masses [23, 24, 5]. This will facilitate a detailed measurement of the mass distribution of low-mass DCOs, which will allow us to distinguish between various proposed theories that seek to explain the shape of the remnant mass distribution, and with it the long-debated existence of a NS-BH mass gap [4, 10, 18, 8, 16, 25, 13, 20]. These theories include the fallback mechanism [9, 11], the failed supernova scenario [15, 14], binary evolutionary effects [21], or details in the compactness of stellar cores at core collapse [19].

Lastly, the lower noise floor will allow us to directly detect GW signals from core-collapse supernova [12, 2, 3]. GWs from supernovae contain information about I) the dynamics of the central engine, II) the explosion mechanism III) reveal the structure and rotation of the innermost regions of the core that are inaccessible through other observations.

SCIENTIFIC IMPACT OF XG DETECTORS

The first measurement of both edges of the PISN mass gap, and a corresponding measurement of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ nuclear reaction rate. Constraints on the abundances of intermediate-mass BHs. Detailed (sub solar mass precision) measurement of the low-mass distribution of NSNS, and BHBH component masses. The direct detection of GWs from SNe and consequently new constraints on the physics of both succesful and failed core-collapse SNe.

Benchmarks for XG detectors to enable the scientific impact

1. **A minimum detection frequency that reaches down to 5Hz, to constrain the mass distribution above the PISN-mass gap.** To constrain the mass distribution above the PISN-mass gap, it is crucial to achieve a minimum detection frequency of 5 Hz. By attaining this level of sensitivity, we can uncover the width and location of the PISN gap down to 5% accuracy, which will, in turn, allow a measurement of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ nuclear reaction rate. Additionally, lower frequencies enable us to observe more cycles of all higher-mass BHBH mergers, thereby reducing source property uncertainties associated with high-mass systems. Moreover, this will allow us to approach the population of intermediate-mass BHs from the stellar-mass side, shedding the first light on this previously unknown population.
2. **10,000 detections with S/N > 100 and masses below 10$\mathrm{M}_{\odot}$, to probe supernova physics.** Systems with low masses and/or extreme mass ratios are particularly disfavored by current-day detector networks. Yet they will be crucial to distinguish between different proposed scenarios for the shape of the remnant-mass distribution and the corresponding supernova physics. We need a large set of systems with high SNR events with low masses and/or high mass ratios, such that we can place exact constraints on the component masses. This is achievable with XG detectors [17]. Specifically, about 10,000 events with component masses between 1-10$\mathrm{M}_{\odot}$, would roughly lead to a precision of 3% per bin of 1000 events.

XG DETECTOR AND NETWORK REQUIREMENTS

A network of detectors that extends to lower frequencies of about 5Hz, and with a noise floor that is a factor 10 lower than the capabilities of current detectors.

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