What we need from XG observatories to unveil the birth, life and death of massive stars – Part 2: life

SUMMARY

The next-generation of gravitational-wave (GW) observatories have the potential to solve key questions about massive stellar evolution. In this second part, we focus on their ability to help us understand binary interactions, in particular, place constraints on mass transfer episodes: the stability of mass transfer, the conservativeness and the physics of common envelopes. To make significant progress on these topics, we argue that we need a near-complete population of $\gtrsim$ 1,000 binary neutron star (NSNS) mergers out to $z \sim 1$ to probe Common Envelope Physics, and a near-complete population of BHBH mergers out to $z \sim 2$ to probe the stability of mass transfer

Key questions in massive binary stellar evolution: 2. How do massive stars evolve and interact?

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, much 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?*

Here we discuss how XG detectors can help address: **How do massive stars evolve and interact?**

Potential scientific impact of XG detectors

More than $\gtrsim 70\%$ of all massive stars are born with at least one gravitationally bound companion and will interact by exchanging mass (a mass transfer phase) in its life [17, 13]. These interactions drastically alter the evolution of the stars and can lead to a plethora of phenomena such as stellar mergers, (ultra) stripped-stars, x-ray binaries, millisecond pulsars, and the formation of a Double compact object (DCO): a binary system consisting of two compact objects each either a BH or NS [16, 19, 21]. It is of critical importance to better understand the underlying physical processes of such evolutionary stages including the stability of mass transfer, common envelopes (CE) physics, and angular momentum and mass loss processes during mass transfer. GW astrophysics can play a unique role in probing these intermediate phases of massive star evolution which is otherwise challenging to constrain.

Mass transfer can broadly be classified as dynamically stable or unstable, but the details of mass-transfer stability are complex and unknown (e.g., [25, 15, 10]). During stable mass transfer or RLOF, the companion star can possibly accrete (part of) the donated companion envelope (cf. [11]). How much of the donated mass is accreted by its companion, and the specific angular momentum carried by the transferred mass, determine the orbital evolution [e.g., 18]. On the other hand, unstable mass transfer is expected to lead to a 'common envelope' phase (see e.g., reviews by [7, 8]). This will dramatically shrink the binary orbit, and lead to very close orbit systems, or even stellar mergers. Recent studies have shown that the different physical processes leave imprints on the expected properties and rates of GW sources [e.g., 20, 14]. GW observations can thus be a unique probe of the physics of these evolutionary stages in the lives of massive stars. We mention two examples below.

SCIENTIFIC IMPACT OF XG DETECTORS

Constraints on the physical processes underlying Common Envelope phases, and an 'unbiased' catalog of post-common-envelope properties of NSNS GW sources.

Constraints on the fraction of binary black hole (BHBH) and black hole-neutron star (BHNS) systems that formed through *only* stable mass transfer phases versus experiencing at least one common-envelope phase. Constraints on mass loss and angular momentum loss during mass transfer phases

Benchmarks for XG detectors to enable the scientific impact

1. A complete population of 5,000 NSNS Mergers to $z \sim 1$ as Probe of Common Envelope Physics

Despite the many uncertainties in the modeling of formation pathways of GW sources [e.g., 2, 12], there is broad support in the literature that the majority of *NSNS* mergers experience a common-envelope phase and that detections of NSNS mergers are a good probe for common-envelope physics [3, 1, 4, 9, 24, 22]. Figure 1 gives an example showing the majority of recent literature studies expect almost all NSNS to go through a common-envelope phase. However, common-envelope phases are still a complex and one of the most uncertain physical processes [e.g., 5] meaning that addressing Common Envelope physics relies crucially on having a *complete* and unbiased survey of systems that experience a CE event. **Crucially, only XG detectors are expected to provide a complete and unbiased population of NSNS mergers out to redshift $z \sim 1$ consisting of $\gtrsim 5000$ sources with sub-percent measured mass properties [6].** The mass measurements can be used as a proxy for the post-CE masses, which can be combined with approximations for the post-CE separations (using luminosity distances and delay times) as a unique population for CE physics.

2. A near complete set of BHBH mergers out to redshift $z \sim 2$ and BHNS out to redshift $z \sim 1$ to answer whether the majority of BHBH and BHNS mergers undergo unstable mass transfer phases.

For BHBH and BHNS mergers, on the other hand, there is an increasing debate about whether the majority of GW mergers experience a common-envelope phase or instead only undergo stable mass transfer phases (see Figure 2). It is expected that experiencing a stable or unstable mass transfer phase will lead to unique imprints on the properties of the BHBH and BHNS mergers as well as on the typical delay time distributions [e.g., 23]. XG GW detectors uniquely can provide sub-percent measurements of the masses of a near-complete population of BHBHs out to redshift 2, and for BHNS systems out to redshift 1 [6]. Combined with a mapping of the supernova physics this will provide an understanding of the pre-supernova masses of binary stars forming GW sources, this will provide unique insights in mass transfer physics.

XG DETECTOR AND NETWORK REQUIREMENTS

A near-complete population of $\gtrsim$ 1,000 NSNS Mergers out to $z \sim 1$ to probe of Common Envelope Physics

(Sub-)percent measurements of the masses of a near-complete population of BHBHs out to redshift $z \sim 2$, and BHNS systems out to redshift $z \sim 1$ to probe the stability of mass transfer.

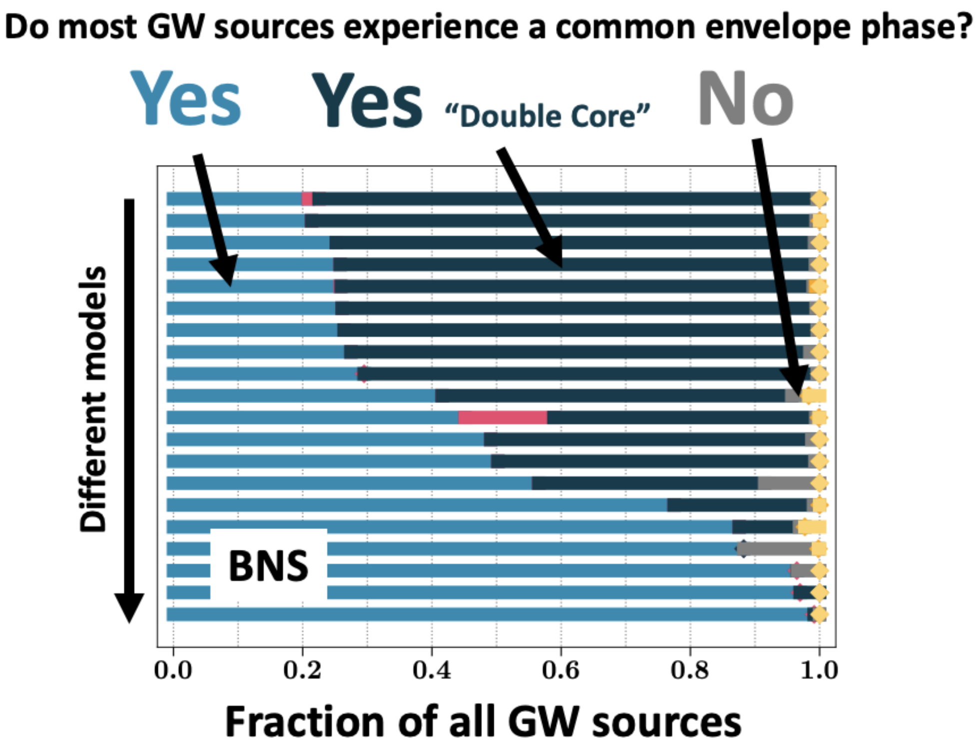

Figure 1 Fraction of GW NSNS detections that are expected to experience a common-envelope (CE) phase for different population synthesis simulations (models) from the literature. In all models, the vast majority of NSNS mergers are expected to experience a CE phase.

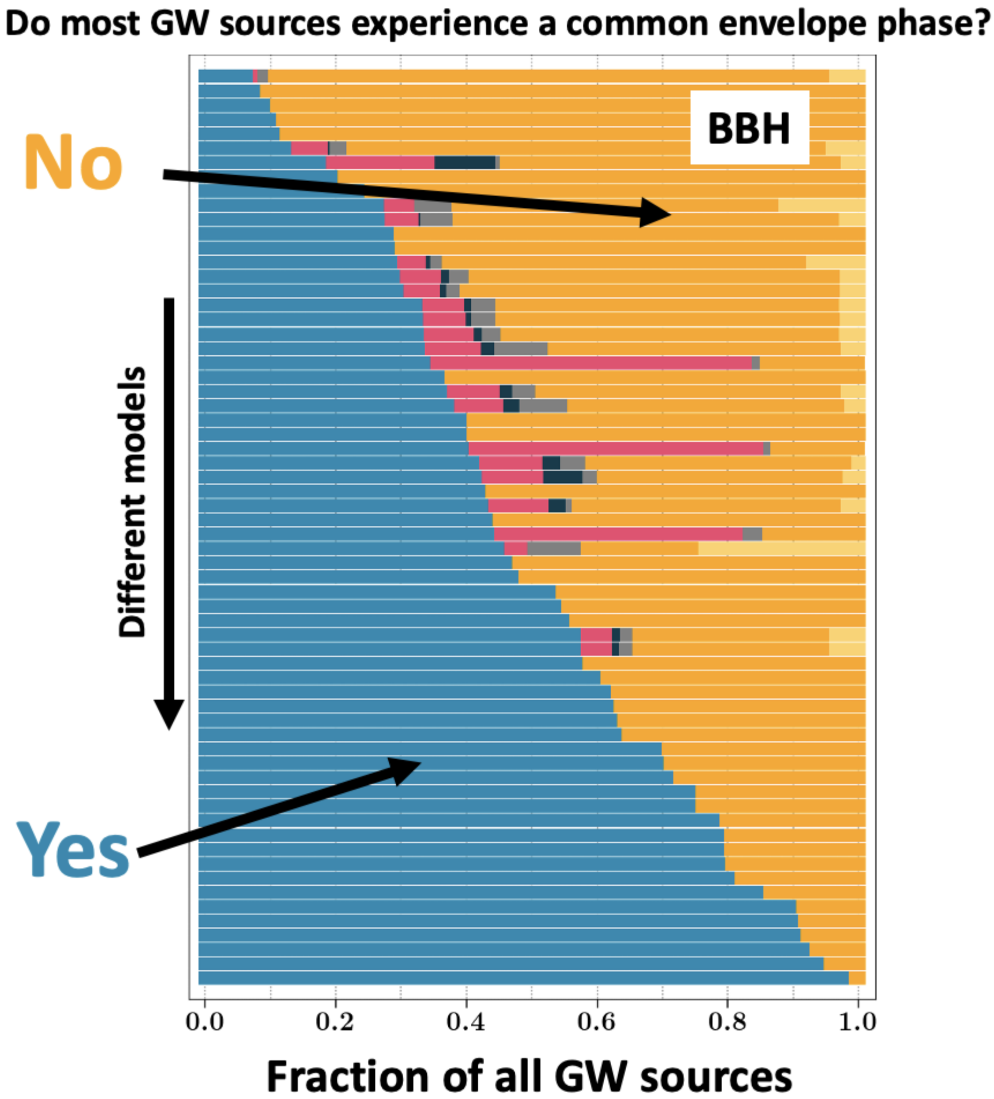

Figure 2 Fraction of GW BHBH detections that are expected to experience a common-envelope (CE) phase for different population synthesis simulations (models) from the literature. Most importantly, different models disagree strongly on whether the vast majority of BHBH mergers are expected to experience a CE phase.

Authors

Floor Broekgaarden[1], floor.broekgaarden@cfa.harvard.edu

Lieke van Son[1 2], lieke.van.son@cfa.harvard.edu

Salvatore Vitale[3], svitale@mit.edu

Thomas Callister[4] Tom thomas.a.callister@gmail.com

[1]Center for Astrophysics | Harvard & Smithsonian,60 Garden St., Cambridge, MA 02138, USA,

[2]Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098XH, NL

[3]LIGO Laboratory, Massachusetts Institute of Technology, 185 Albany St, Cambridge, MA 02139, USA

[4]Kavli Institute for Cosmological Physics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60615, USA

Bibliography

[1] Hans A. Bethe and G. E. Brown. "Evolution of Binary Compact Objects That Merge". In: ApJ 506.2 (Oct. 1998), pp. 780–789. DOI: 10.1086/306265. arXiv: astro-ph/9802084 [astro-ph].

[2] Floor S. Broekgaarden et al. "Impact of massive binary star and cosmic evolution on gravitational wave observations - II. Double compact object rates and properties". In: MNRAS 516.4 (Nov. 2022), pp. 5737–5761. DOI: 10.1093/mnras/stac1677. arXiv: 2112.05763 [astro-ph.HE].

[3] G. E. Brown. "Neutron star accretion and binary pulsar formation". In: ApJ 440 (Feb. 1995), pp. 270–279. DOI: 10.1086/175268.

[4] Jasinta D. M. Dewi, Ph. Podsiadlowski, and A. Sena. "Double-core evolution and the formation of neutron-star binaries with compact companions". In: MNRAS 368 (2006), pp. 1742–1748. DOI: 10.1111/j.1365-2966.2006.10233.x. arXiv: astro-ph/0602510 [astro-ph].

[5] Ryosuke Hirai and Ilya Mandel. "A Two-stage Formalism for Common-envelope Phases of Massive Stars". In: ApJ 937.2, L42 (Oct. 2022), p. L42. DOI: 10.3847/2041-8213/ac9519. arXiv: 2209.05328 [astro-ph.SR].

[6] Francesco Iacovelli et al. "Forecasting the Detection Capabilities of Third-generation Gravitational-wave Detectors Using GWFAST". In: ApJ 941.2, 208 (Dec. 2022), p. 208. DOI: 10.3847/1538-4357/ac9cd4. arXiv: 2207.02771 [gr-qc].

[7] N. Ivanova et al. "Common envelope evolution: where we stand and how we can move forward". In: A&A Rev. 21, 59 (Feb. 2013), p. 59. DOI: 10.1007/s00159-013-0059-2. arXiv: 1209.4302 [astro-ph.HE].

[8] Natalia Ivanova, Stephen Justham, and Paul Ricker. *Common Envelope Evolution*. 2514-3433. IOP Publishing, 2020. ISBN: 978-0-7503-1563-0. DOI: 10.1088/2514-3433/abb6f0. URL: http://dx.doi.org/10.1088/2514-3433/abb6f0.

[9] Stephen Justham, Philipp Podsiadlowski, and Zhanwen Han. "On the formation of single and binary helium-rich subdwarf O stars". In: MNRAS 410.2 (Jan. 2011), pp. 984–993. DOI: 10.1111/j.1365-2966.2010.17497.x. arXiv: 1008.1584 [astro-ph.SR].

[10] Jakub Klencki et al. "It has to be cool: Supergiant progenitors of binary black hole mergers from common-envelope evolution". In: A&A 645, A54 (Jan. 2021), A54. DOI: 10.1051/0004-6361/202038707. arXiv: 2006.11286 [astro-ph.SR].

[11] E. Laplace et al. "The expansion of stripped-envelope stars: Consequences for supernovae and gravitational-wave progenitors". In: A&A 637, A6 (May 2020), A6. DOI: 10.1051/0004-6361/201937300. arXiv: 2003.01120 [astro-ph.SR].

[12] Ilya Mandel and Floor S. Broekgaarden. "Rates of Compact Object Coalescences". In: *arXiv e-prints*, arXiv:2107.14239 (July 2021), arXiv:2107.14239. arXiv: 2107.14239 [astro-ph.HE].

[13] Stella S. R. Offner et al. "The Origin and Evolution of Multiple Star Systems". In: *arXiv e-prints*, arXiv:2203.10066 (Mar. 2022), arXiv:2203.10066. DOI: 10.48550/arXiv.2203.10066. arXiv: 2203.10066 [astro-ph.SR].

[14] A. Olejak, K. Belczynski, and N. Ivanova. "Impact of common envelope development criteria on the formation of LIGO/Virgo sources". In: A&A 651, A100 (July 2021), A100. DOI: 10.1051/0004-6361/202140520. arXiv: 2102.05649 [astro-ph.HE].

[15] K. Pavlovskii et al. "Stability of mass transfer from massive giants: double black hole binary formation and ultraluminous X-ray sources". In: MNRAS 465.2 (Feb. 2017), pp. 2092–2100. DOI: 10.1093/mnras/stw2786. arXiv: 1606.04921 [astro-ph.HE].

[16] Konstantin A. Postnov and Lev R. Yungelson. "The Evolution of Compact Binary Star Systems". In: *Living Reviews in Relativity* 17.1, 3 (May 2014), p. 3. DOI: 10.12942/lrr-2014-3. arXiv: 1403.4754 [astro-ph.HE].

[17] H. Sana et al. "Binary Interaction Dominates the Evolution of Massive Stars". In: *Science* 337 (July 2012), pp. 444–. DOI: 10.1126/science.1223344. arXiv: 1207.6397 [astro-ph.SR].

[18] G. E. Soberman, E. S. Phinney, and E. P. J. van den Heuvel. "Stability criteria for mass transfer in binary stellar evolution." In: A&A 327 (Nov. 1997), pp. 620–635. arXiv: astro-ph/9703016 [astro-ph].

[19] T. M. Tauris et al. “Formation of Double Neutron Star Systems”. In: ApJ 846.2, 170 (Sept. 2017), p. 170. DOI: 10.3847/1538-4357/aa7e89. arXiv: 1706.09438 [astro-ph.HE].

[20] T. M. Tauris et al. “Formation of Double Neutron Star Systems”. In: ApJ 846, 170 (Sept. 2017), p. 170. DOI: 10.3847/1538-4357/aa7e89. arXiv: 1706.09438 [astro-ph.HE].

[21] Thomas M. Tauris and Edward P. J. van den Heuvel. *Physics of Binary Star Evolution. From Stars to X-ray Binaries and Gravitational Wave Sources*. 2023.

[22] L. A. C. van Son et al. “No Peaks without Valleys: The Stable Mass Transfer Channel for Gravitational-wave Sources in Light of the Neutron Star-Black Hole Mass Gap”. In: ApJ 940.2, 184 (Dec. 2022), p. 184. DOI: 10.3847/1538-4357/ac9b0a. arXiv: 2209.13609 [astro-ph.HE].

[23] L. A. C. van Son et al. “The Redshift Evolution of the Binary Black Hole Merger Rate: A Weighty Matter”. In: ApJ 931.1, 17 (May 2022), p. 17. DOI: 10.3847/1538-4357/ac64a3. arXiv: 2110.01634 [astro-ph.HE].

[24] Alejandro Vigna-Gómez et al. “On the formation history of Galactic double neutron stars”. In: MNRAS 481.3 (Dec. 2018), pp. 4009–4029. DOI: 10.1093/mnras/sty2463. arXiv: 1805.07974 [astro-ph.SR].

[25] T. E. Woods and N. Ivanova. “Can We Trust Models for Adiabatic Mass Loss?” In: ApJ 739, L48 (Oct. 2011), p. L48. DOI: 10.1088/2041-8205/739/2/L48. arXiv: 1108.2752 [astro-ph.SR].