Detecting Gravitational-waves from Collapsar Cocoons with the Cosmic Explorer

SUMMARY

The next-generation (XG) of the gravitational-wave (GW) observatory network may detect the first stochastic GW sources, which are considerably more difficult to detect compared to inspiral sources. The brightest predicted stochastic GW source known to date in XG frequencies is shocked jets ("cocoons") in collapsing stars (Gottlieb et al. 2022). This class of GWs may have a promising detection rate of $N \sim 10\ \mathrm{year}^{-1}$, with a detection horizon of $D \gtrsim 100$ Mpc in the Cosmic Explorer (CE). Detecting these GWs will open a new window to understanding the mechanism of magnetic-driven stellar explosions. Analytic and numerical models are required to connect the emerging GW signal to the underlying physics.

Key question(s) and scientific context in brief

Core-collapse supernovae (CCSNe) provide a unique opportunity to study the last stages of stellar life-cycles, the synthesis of heavy elements, the birth of compact objects, and the launch of relativistic jets (Burrows and Lattimer 1986; S. Woosley and Janka 2005). While the opaque stellar envelope limits the prospects for learning about the underlying physics of the explosion mechanism from electromagnetic (EM) signals, CCSNe also produce GWs that carry information from the stellar core to the observer with negligible interference along the way. However, with a small fraction ($E_{\rm GW} \sim 10^{46}$ erg) of the CCSN energy emerging as GWs, the XG network will only be able to detect those sources within our Galaxy (Srivastava et al. 2019).

A special class of CCSNe – collapsars (S. E. Woosley 1993) are driven by jets launched from a newly formed black hole (BH). The jets produce gamma-ray bursts (GRBs) – the most luminous phenomenon in the Universe, and emit GWs at sub-Hz frequencies (Sago et al. 2004). During the jet propagation in the collapsing star, it shocks the dense stellar material and form a cocoon – an energetic hot and turbulent hourglass-shape structure that envelops the jet. The cocoon generates strong GWs, which unlike the jet, peak at the frequency bands of the XG detectors. The strong EM cocoon emission makes it one of the most promising multi-messenger sources in XG detectors, through which we can study the physics of the most powerful stellar explosions.

Potential scientific impact of XG detectors on the key questions

The detection of a few multi-messenger cocoons will shed light on long-standing issues such as the relation between the jet and stellar progenitor properties, and the abundance of jetted explosions in CCSNe (right panel of Figure 1). The GRB/CCSNe rate will constrain the main production sites of heavy elements in the Universe (Siegel, Barnes, and Metzger 2019). With a larger cocoon-powered GW detection sample in XG detectors, we can study the stellar explosion mechanism, the magnetic field structure in pre-collapse stars, and the natal spin and recoil properties of BHs. With dozens of multi-messenger detections, we will be able to distinguish the Hubble constant from other surveys (Hotokezaka et al. 2019), if compact object mergers will not provide such opportunity beforehand – although their GWs are stronger, their EM emission is weaker than collapsars.

Benchmarks for XG detectors to enable the scientific impact

- Characteristic strain sensitivity between 10 and 100 Hz (left panel of Figure 1).

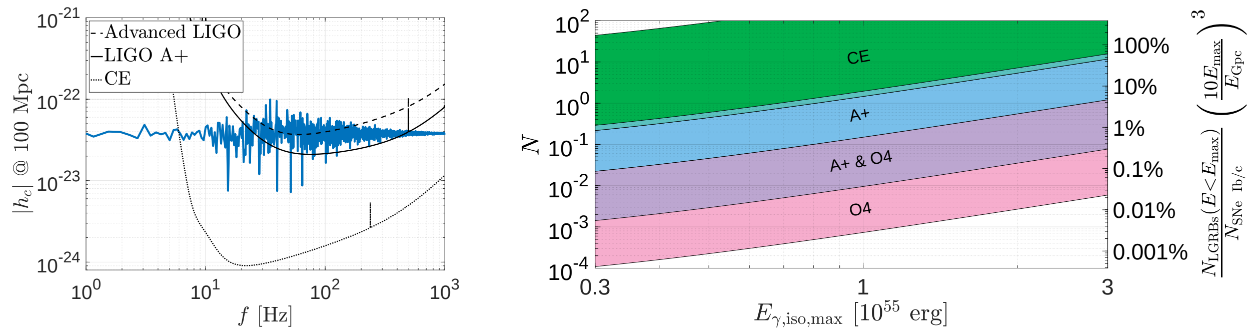

Figure 1: Left: the characteristic strain amplitude of collapsar cocoon-powered GWs observed off-axis. Right: number of detectable GW events in CE (green) in 1 year, in O5 (A+; blue+purple), and O4 (pink+purple) runs, as a function of the maximum isotropic equivalent γ-ray energy $E_{\gamma,\mathrm{iso,max}} \approx 10^{55}$ erg (Burns et al. 2023). The calculation assumes wobbling jets, matched-filtered SNR values, minimum SNR for detection of 20. A detection is unlikely by present-day detectors, but CE may reveal $N \sim 10$ year^{-1} events. The GW detection rate also indicates the GRB rate in SN Ib/c progenitors (right axis). Taken from Gottlieb et al. 2022.

- Number of cocoon-powered GWs detected per year with signal-to-noise ratio (SNR) > 20 is $N \sim 10$ (right panel of Figure 1), assuming detector sensitivity in figure 3.3 of Evans et al. 2021.
- Horizon distance for cocoon-powered GWs is $D \gtrsim 100$ Mpc.
- The signal duration is expected to be comparable to the jet engine time, $t \approx 10 - 100$ s.
- For isotropic GW emission, the GW efficiency and energy are $E_{\mathrm{GW}} \sim 10^{-3} E_{\mathrm{tot}} \sim 10^{50}$ erg.

SCIENTIFIC IMPACT OF XG DETECTORS

As this source was predicted just a short while ago, follow-up studies are imperative for improving our understanding of the physics that can be extracted from GW detections. Ultimately, these could elucidate how massive stars explode - neutrino-driven or magnetically; the physics of relativistic jets – how astrophysical jets are launched; the properties of newly born BHs - recoil and natal spin; the rate of jetted explosions – directly relates to the origin of heavy element nucleosynthesis in the Universe; and may reveal cocoon-powered GWs from other cataclysmic events driven by jets, such as compact object mergers, fast blue optical transients and more, potentially yet to be discovered, explosions.

Dependencies on other multi-messenger capabilities

The GW signal is likely accompanied by a wide range of EM counterparts powered by the CCSN explosion and the cocoon: shock breakout in γ- and X-rays (seconds to minutes), cooling emission and radioactive decay in UV/optical/IR (days to months), and broadband synchrotron (afterglow) emission (days to years) (Lazzati et al. 2017; Nakar and Piran 2017). For close-by CCSNe, neutrino detection is also possible, and will place even stronger constraints on the expected time of the GW signal. Thus, GRBs are rich multi-messenger sources. In the relevant distances of $\lesssim 100$ Mpc, all events should produce detectable multi-messenger counterparts, which will provide some localization of the source, and enable a targeted search for the GW signal.

XG DETECTOR AND NETWORK REQUIREMENTS

More work is needed to directly assess the required capabilities for XG detectors to address each scientific question. However, estimates of the required rates for addressing different questions have been mentioned above, assuming the sensitivity of the CE in Evans et al. 2021.

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