Optimizing XG detector networks for Galactic astrophysics

SUMMARY

While detection of gravitational waves (GWs) from extragalactic compact binary coalescences (CBCs) has now become commonplace, we have yet to observe GWs from non-CBC sources. Our own Galaxy is host to a multitude of GW sources associated with massive stars and compact objects throughout their lives. Next-generation (XG) ground-based GW detectors offer an unprecedented opportunity to discover, observe, and probe the entire Galactic GW zoo. Due to their directional sensitivity, XG detectors should be placed and oriented to best observe the Galactic plane, in aid of improving detection prospects and science outputs for both continuous and transient GW sources.

Key question(s) and scientific context in brief

While the coalescence of compact objects has long been the most promising source for ground-based GW observatories due to their (comparatively high) expected rates, there exists a plethora of prospective sources in the tens-of-hertz to kilohertz regime right in our very own cosmic backyard – the Milky Way galaxy.

The main questions to be addressed concern whether next-generation (XG) observations of Galactic GW sources can be used to probe the physics of:

- Core-collapse supernovae (CCSNe; see, e.g., [39, 7, 35, 36, 18]),
- Pulsar glitches [17],
- Magnetar flares [14, 13],
- Spin-down of isolated neutron stars [40, 13, 12],
- The Galactic stochastic GW background [11, 38],
- Thorne–Żytkow Objects (TŻOs; [16]),
- Accretion onto compact objects in binaries [23],
- Accretion-induced collapse of white dwarfs [6] and neutron stars [34, 27],

Potential scientific impact of XG detectors on the key questions

While numerous targeted GW searches have been performed using data taken during the first three science runs of aLIGO, AdVirgo, and KAGRA (see, e.g., [1, 30, 11, 28, 4, 3, 5, 2, 41]), no GW emission from a Galactic (or non-CBC) source has yet been detected. The reasons for this are that the prospective Galactic sources highlighted here – in comparison with compact binary systems – emit significantly weaker (and poorly modelled) GWs. Also, most of the power from the known population of Galactic pulsars is at low frequencies (below 100 Hz; see, e.g., [26]), and thus beyond the reach of current GW observatories.

However, the significant increase of sensitivity to be achieved by XG detectors offers an unprecedented opportunity to observe GWs from the entire zoo of Galactic GW sources, and probe the physics governing their central engines. For example, Woan et al. [40] found evidence for a minimum ellipticity in Galactic millisecond pulsars and concluded that LIGO–Virgo at design sensitivity might be able to detect GW emission from only the strongest few of these millisecond pulsars, with an SNR $\lesssim 10$, while CE–ET would detect emission from many of these millisecond pulsars, some with SNR of order 100. This is one example of how an XG detector network is likely to make Galactic GWs a secure and scientifically rich observational target.

Benchmarks for XG detectors to enable the scientific impact

As GW interferometers are directionally sensitive, and as the Galactic GW source distribution is anisotropically distributed on the sky, the placement and orientation of new GW observatories affects the performance of the XG network. Given the variety of Galactic sources, many of which are poorly modelled, we strive for benchmarks that are largely source-agnostic. We propose the following benchmarks, both following the work in Gossan, Hall, and Nissanke [19]:

- **The mean, polarization-averaged network antenna power weighted by the galactic stellar mass density on the sky and averaged over the sidereal day.** This benchmark captures the performance of the XG network for accumulating information on continuous Galactic sources, such as deformed pulsars.
- **The fifth percentile of the distribution of polarization-averaged network antenna power on the sky, weighted by the galactic stellar mass density and averaged over the sidereal day.** This benchmark is meant to capture how (un)likely the XG network is to miss a rare event such as a galactic CCSN due to unfavorable orientation of the detectors relative to the expected Galactic source distribution.[1]

A more fine-grained iteration on these benchmarks could additionally weight the distribution by the expected duty cycle of nodes in the network, similar to the discussion in Szölgyén et al. [37].

SCIENTIFIC IMPACT OF XG DETECTORS

- Potential first observation of a Galactic GW transient.
- Improved prospects for probing the central engine driving CCSN explosions.
- Opportunity to explore the history and structure of the Milky Way through a population of observed Galactic GW sources.
- Augmented understanding of the spin-down process in pulsars.
- Constraints on the maximum neutron star mass and the physics of compact objects.

Dependencies on other multi-messenger capabilities

The use of multimessenger counterparts to externally trigger GW searches results in improved sensitivity in comparison to all-sky, all-time analyses. Of the Galactic sources potentially detectable by ground-based GW observatories mentioned above, the majority are expected to be accompanied by electromagnetic and/or neutrino counterparts (see, e.g., [13, 34, 31, 32, 33, 21, 22, 39, 16, 3, 29]), from which one can localize and have temporal information about the event if the source is transient in nature. Such externally-triggered searches will be reliant upon the network of electromagnetic and neutrino observatories (e.g., ZTF [15, 20], LSST [24], ASAS-SN [25], HyperK [8, 9], JUNO [10], to name but a few) expected to be online concurrently in the 2030s alongside XG GW detectors.

XG DETECTOR AND NETWORK REQUIREMENTS

- The mean, polarization-averaged network antenna power weighted by the galactic stellar mass density on the sky and averaged over the sidereal day.
- The fifth percentile of the distribution of polarization-averaged network antenna power on the sky, weighted by the galactic stellar mass density and averaged over the sidereal day.

[1] The percentile to choose here is not precisely motivated. Five was chosen because it is of the same scale as the fraction of network downtime (3%) for LIGO–Virgo during the third observing run. In other words, we treat the worst 5% of Galactic observations as an effective network downtime.

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