Rapid Premerger Localization of Binary Neutron Stars in 3G Gravitational-Wave Detectors

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Abstract

- We describe a novel combination of multiband matched filtering and semi-analytical localization algorithms to achieve early-warning localization of long binary neutron star (BNS) signals in 3G detectors.
- We show that it is possible to provide accurate sky localizations more than 30 minutes before the merger. With one month of observations, there could be ~10 (~100) BNS events localized within 100 deg2, 20 (6) minutes before merger.

1. Introduction

- Early electromagnetic (EM) observations could offer unique insights of phenomena in BNSs that happen prior to or near the merger. However, most EM telescopes need direction from GW localization.
- Current ground-based detectors can produce GW alerts ~seconds before the merger. Given the communication time delay between multimessenger community and the ~10–100s slew time of modern telescopes, it is impossible to have early EM observations of BNS in most bands.
- 3G detectors can detect BNS signals more than 30 minutes before the merger, rendering precise early-warning localization possible. However, the length of the signals, the modulation due to the Earth's rotation, and the large number of detections will make 3G data analysis extremely challenging.

2. Fast localization algorithm: SealGW

- Bayesian posterior for extrinsic parameters (α: ra, δ: dec)

$$p(\boldsymbol{\vartheta} \mid \mathbf{d}) \propto p(\mathbf{d} \mid \boldsymbol{\vartheta}) p(\boldsymbol{\vartheta}), \quad \boldsymbol{\vartheta} = \{\alpha, \delta, \boxed{t_c, r, \iota, \phi_c, \psi}\}$$

nuisance parameters

- Bayestar (Singer+ 1508.03634): five-fold numerical integral over nuisance parameters. Currently used by LVK for fast localization.
- SEmi-Analytical Localization for GWs (SealGW): parameter conversion + semi-analytical integral

numerical marginalized

$$\vartheta = \{\alpha, \delta, t_c, \boxed{r, \iota, \phi_c, \psi}\} \xrightarrow{A_{ij} = A_{ij}(r, \iota, \phi_c, \psi)} \vartheta = \{\alpha, \delta, \boxed{t_c}, \boxed{A_{11}, A_{12}, A_{21}, A_{22}}\}$$

analytical integrable

- Details of SealGW can be found in Hu+ 2110.01874.
- SealGW has been implemented into LVK detection pipeline SPIIR.

3. Multi-banding

- For long BNS signals, direct matched filtering is expensive, and it ignores the Earth's rotation in which sky location information is encoded.
- We employ multi-banding, i.e., chop the signal to many segments and perform matched filtering individually. Banding scheme is showed in Fig.1.
- Signal-to-noise ratio (SNR) from different bands can be coherently added (a linear combination with a phase factor), however, doing this will lose information contained in the changing time delays between detectors. Therefore, instead of directly adding SNR, we multiply likelihoods from every band before marginalization over nuisance extrinsic parameters - as if there are different detectors at different frequency bands.

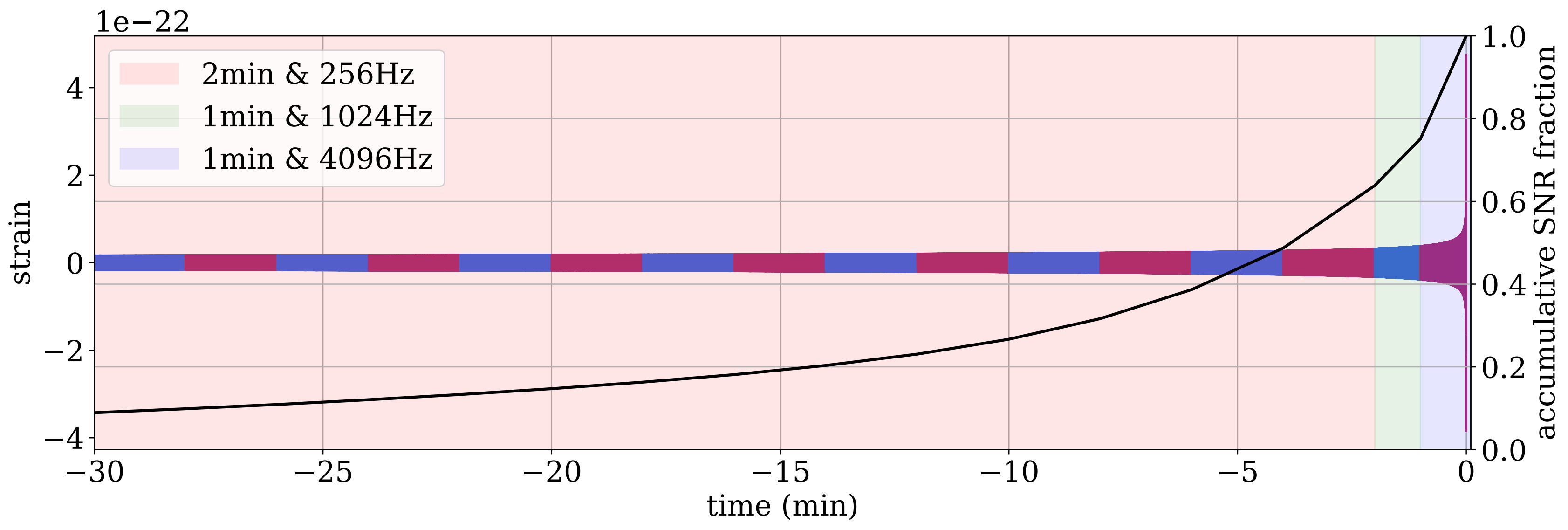


Figure 1: Multibanding scheme for this work. Left axis: an illustration of a chopped GW waveform that is alternately colored for different waveform bins and sampling frequencies. We use 2 minute segments with 256 Hz sampling frequency for waveforms from 60 minutes before merger to 2 minutes before merger, and 1 minute segments for the last 2 minutes with 1024 and 4096 Hz sampling frequencies, respectively. Right axis: the cumulative SNR of the signal, showing the contribution of SNR from each time segment.

4. Catalog simulation & tests

- Based on an astrophysical population of BNS (Oguri+ 1807.02584) and merger rate estimate from LVK, we simulate 68000 BNS sources within z=3, which corresponds to roughly one month of observations.
- We assume a triangular ET at Virgo's site, and 2 CE at Livingston and Hanford, all at design sensitivity. We further assume the noise is stationary Gaussian and we ignore signal overlaps.
- For each simulation, we perform multiband matched filtering from 60 minutes before merger with low-frequency cut-off at 5 Hz. We set cumulative SNR>12 as the detection criterion. We calculate and update skymap once a source is detected.
- In Fig.2 we show an evolving skymap of a BNS detected 30min before the merger. We also show the localization area evolution of all the detected events. Many events can be well-localized long before the merger.

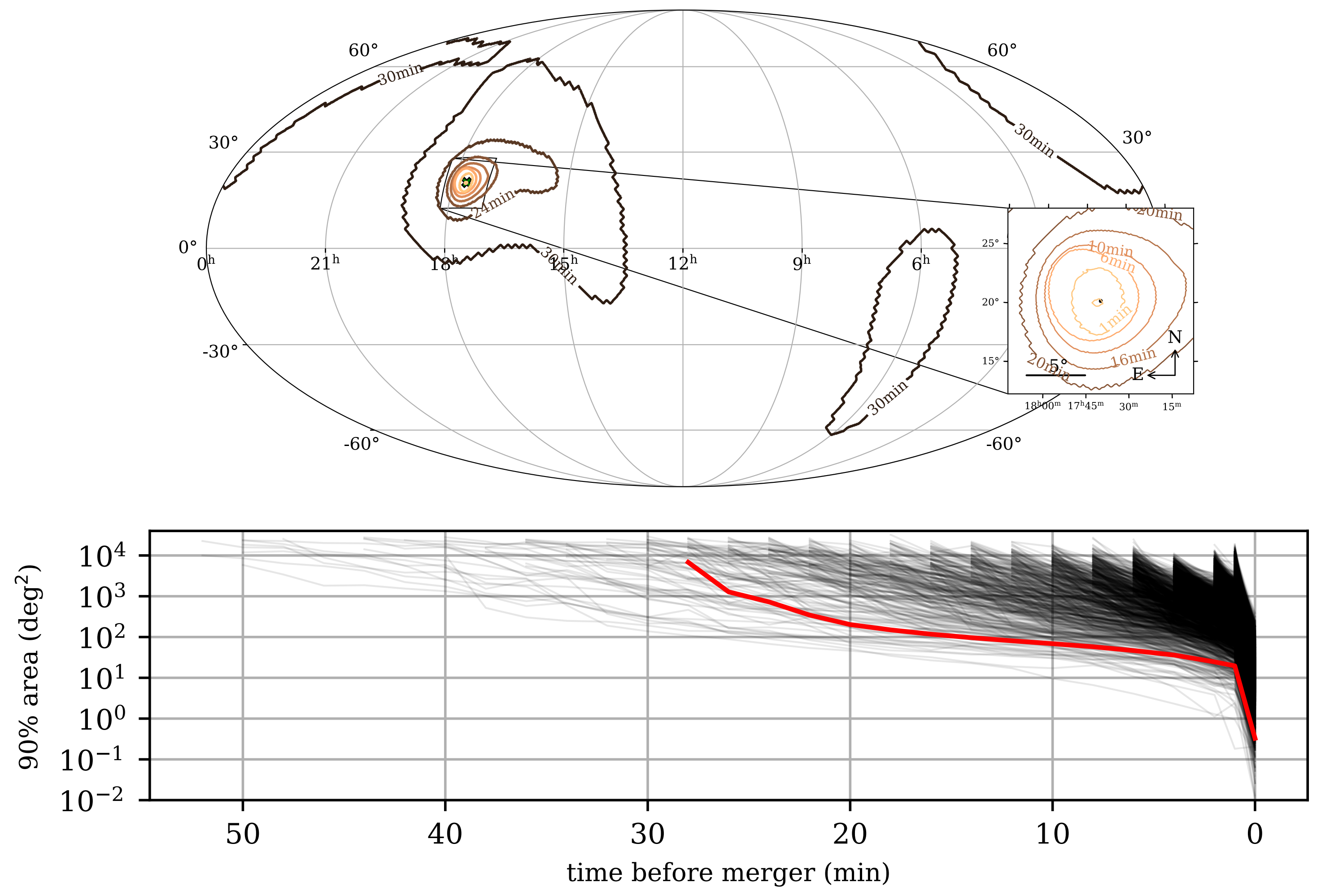
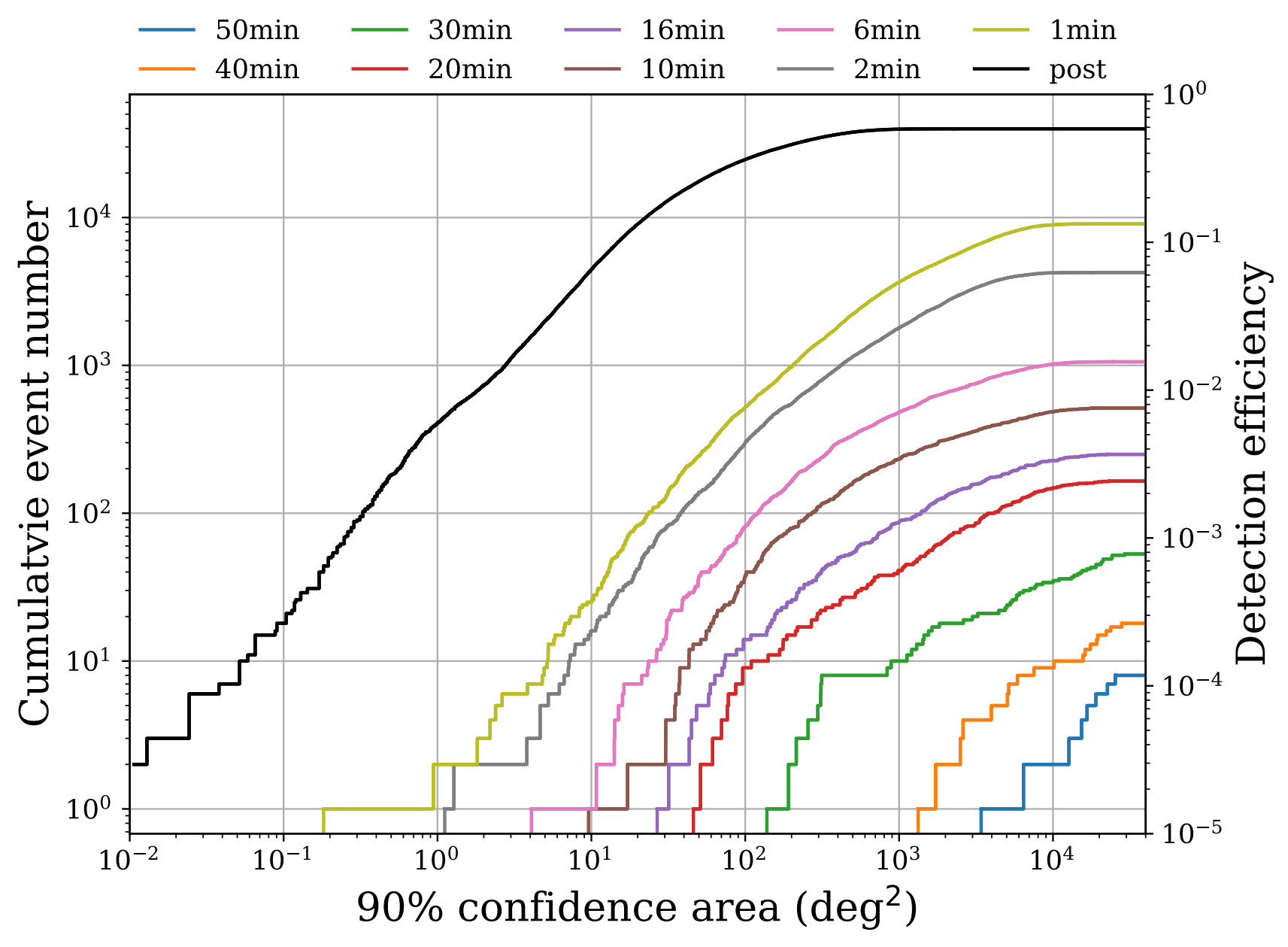


Figure 2: Sky map evolution. Upper panel: an example sky map for a 1.4 + 1.4Me BNS at 1000 Mpc detected 30 minutes before merger with a network SNR of 12. The SNR increases to 17 at 20 minutes before merger, 31 at 10 minutes, 95 at 1 minute and 130 after merger. We show the 90% localization contours at different negative latencies. The injection sky location is marked with a cross. Lower panel: evolution of 90% confidence localization areas of early-warning events in our simulation. The example in upper panel is plotted in red line.

5. Localization statistics

- Fig. 3 shows the cumulative number of events for different negative latencies. ~10 events can be localized within 100 deg2 20 minutes before merger, and 6 minutes before merger the number of events increases to ~100. Also, ~1–10 events can be localized within 10 deg2 up to 6 minutes before merger. Extreme early warnings are also possible.
- Fig. 4 shows the speed comparison between SealGW and Bayestar. SealGW is able to perform real-time localization with a low hardware requirement for large number of detections.



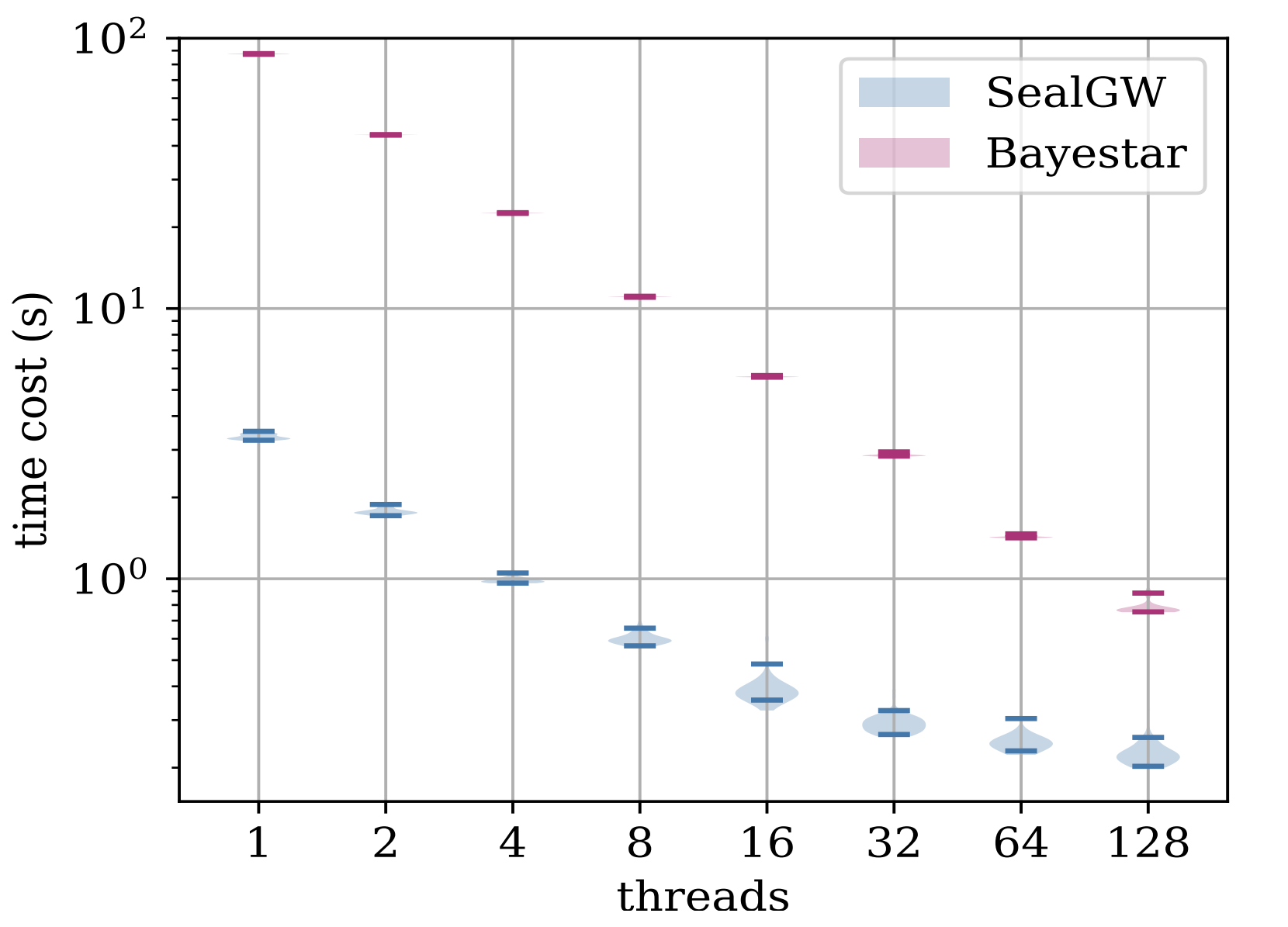


Figure 3 (left): Cumulative number of detections and 90% confidence sky localization areas for the 68,000 BNS simulations (roughly one month of observation). The corresponding detection efficiency is labeled in the right y-axis. We choose 10 different negative latencies (from 50 minutes to postmerger) and the curves show the cumulative distribution of 90% areas of events that are detected at those times.
Figure 4 (right): Time cost of running SealGW and Bayestar for ET+2CE network on a 2.44 GHz processor with different number of threads, excluding the time costs of matched filtering and data conditioning.

6. Data release & reproductivity

- Skymaps and detection statistics are available at Zenodo:8297806
- SealGW is pip installable: pip install sealgw. Code and simulation examples are available at https://git.ligo.org/spiir-group/SealGW

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