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Near Real-Time Gravitational Wave Data Analysis of the Massive Black Hole Binary with TianQin

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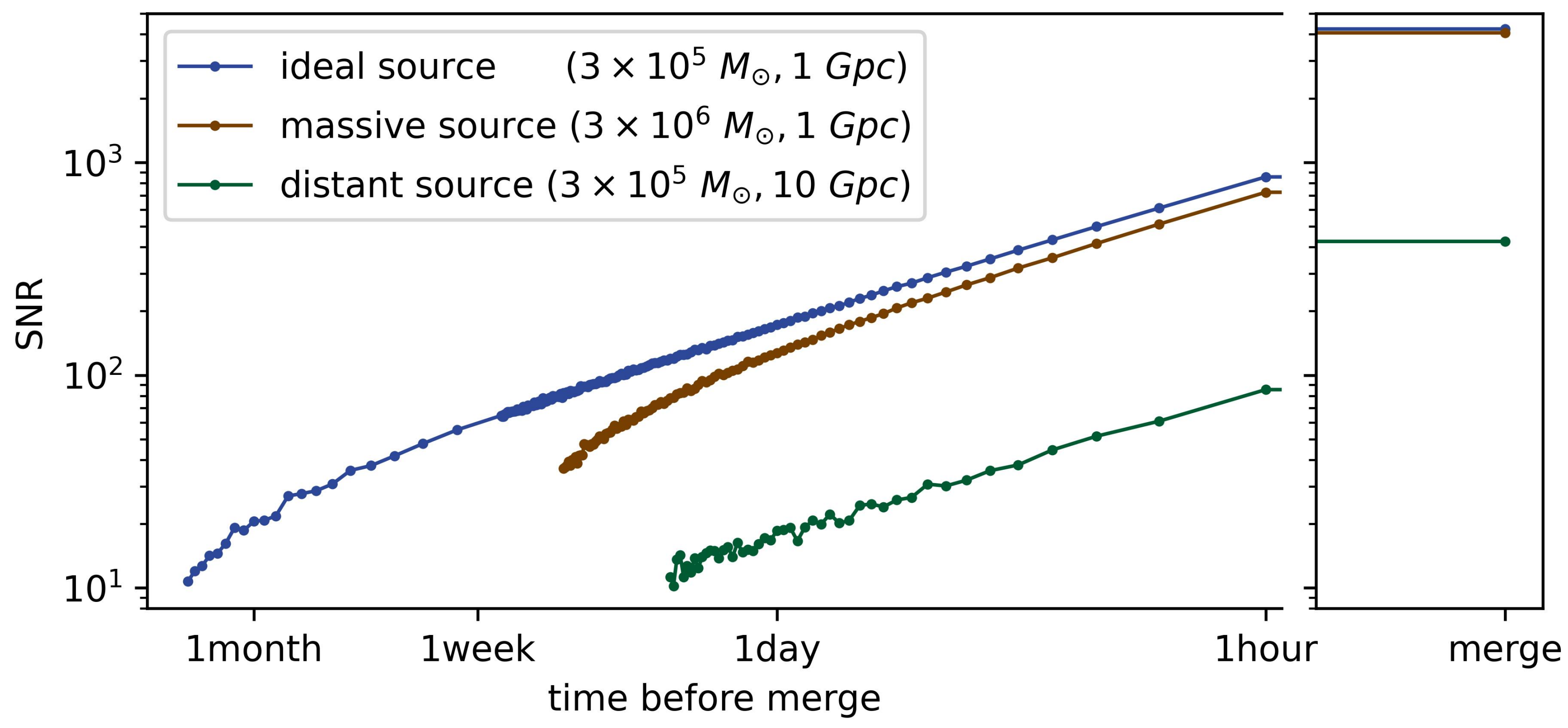
Space-borne gravitational wave detectors can detect sources like the merger of massive black holes. The rapid identification and localization of the source would play a crucial role in multi-messenger observation. The geocentric orbit of the space-borne gravitational wave detector, TianQin, makes it possible to conduct real-time data transmission. In this manuscript, we develop a search and localization pipeline for massive black hole binaries with TianQin, under both regular and real-time data transmission modes. We demonstrate that with real-time data transmission, it is possible to accurately localize the massive black hole binaries on-the-fly. With the approaching of the merger, the localization rapidly shrinks, and the data analysis can be finished at a speed comparable to the data downlink speed.[1]

BACKGROUND

Massive Black Hole Binary (MBHB) can merge in gas-rich environments and have the potential to cause strong electromagnetic (EM) radiation, making MBHBs promising targets for multi-messenger astronomy.

In this case, gravitational wave (GW) need to be used to locate the MBHBs in the inspiral phase, otherwise it is difficult to observe the merger of MBHBs by EM alone. However, the SNR of a MBHB accumulates in a highly non-linear way, the last hour signal contains up to 99% of the total SNR[1] (as shown in the figure below, note that the SNR follows the law of accumulation of squares), and the sky localization area shrinks significantly as the MBHB approaches merger[2]. Therefore, **the localization of MBHBs prior to the merger raised a new challenge of near real-time speed for the data downlink as well as for the data analysis.**



TIANQIN DATA DOWNLINK

Compared with other heliocentric orbital space gravitational wave detectors, TianQin[3] has a unique advantage, that is, the convenience of data transmission brought by the geocentric orbit. If inter-satellite communication is enabled and/or multiple ground facilities are available to ensure data downlink, **TianQin is possible to expect reliable and near real-time data downlink.**

METHOD

Throughout the work, we adopt the aligned spin IMRPhenomD waveform[4] for the MBHB signal. The waveform $h(\theta)$ is described by a set of parameters:

$$\theta = \{M_c, \eta, \chi_1, \chi_2, D_L, t_c, \phi_c, \lambda, \beta, \psi, \iota\}.$$

We adopt the Bayes framework to obtain the posterior distribution. To efficiently explore the parameter space, we adopt Monte Carlo Markov chain (MCMC).

REFERENCES

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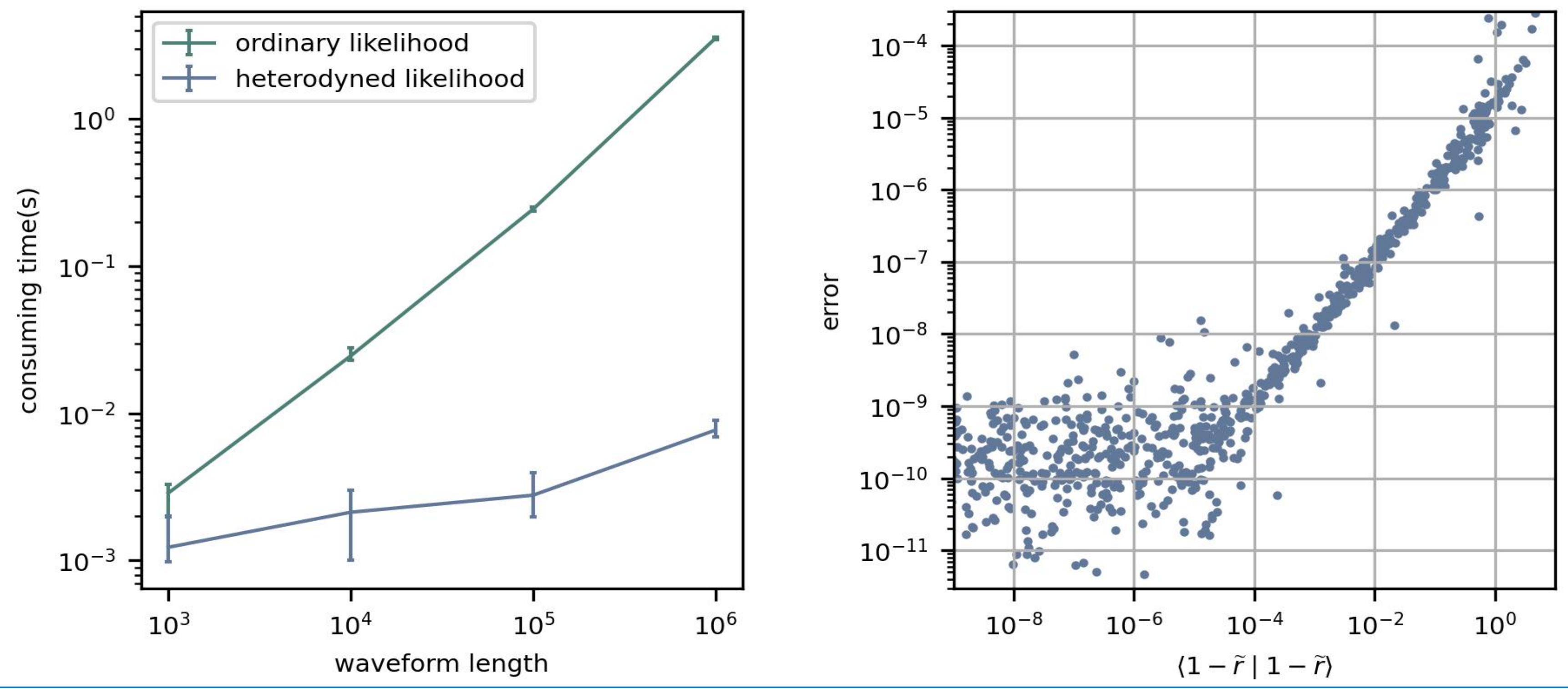
HETERODYNED LIKELIHOOD

The main cost of the algorithm is the likelihood. In heterodyned likelihood[6], by introduct a reference waveform h_0, one can use the ratio $r = h\,/\,h_0$ to separate the two inner products as:

$$\langle d|h(\theta)\rangle = 4\Re\int_0^\infty \frac{d\cdot h_0}{S_n} r(\theta)df\,, \qquad \langle h(\theta)|h(\theta)\rangle = 4\Re\int_0^\infty \frac{|h_0|^2}{S_n}|r(\theta)|^2\,df\,,$$

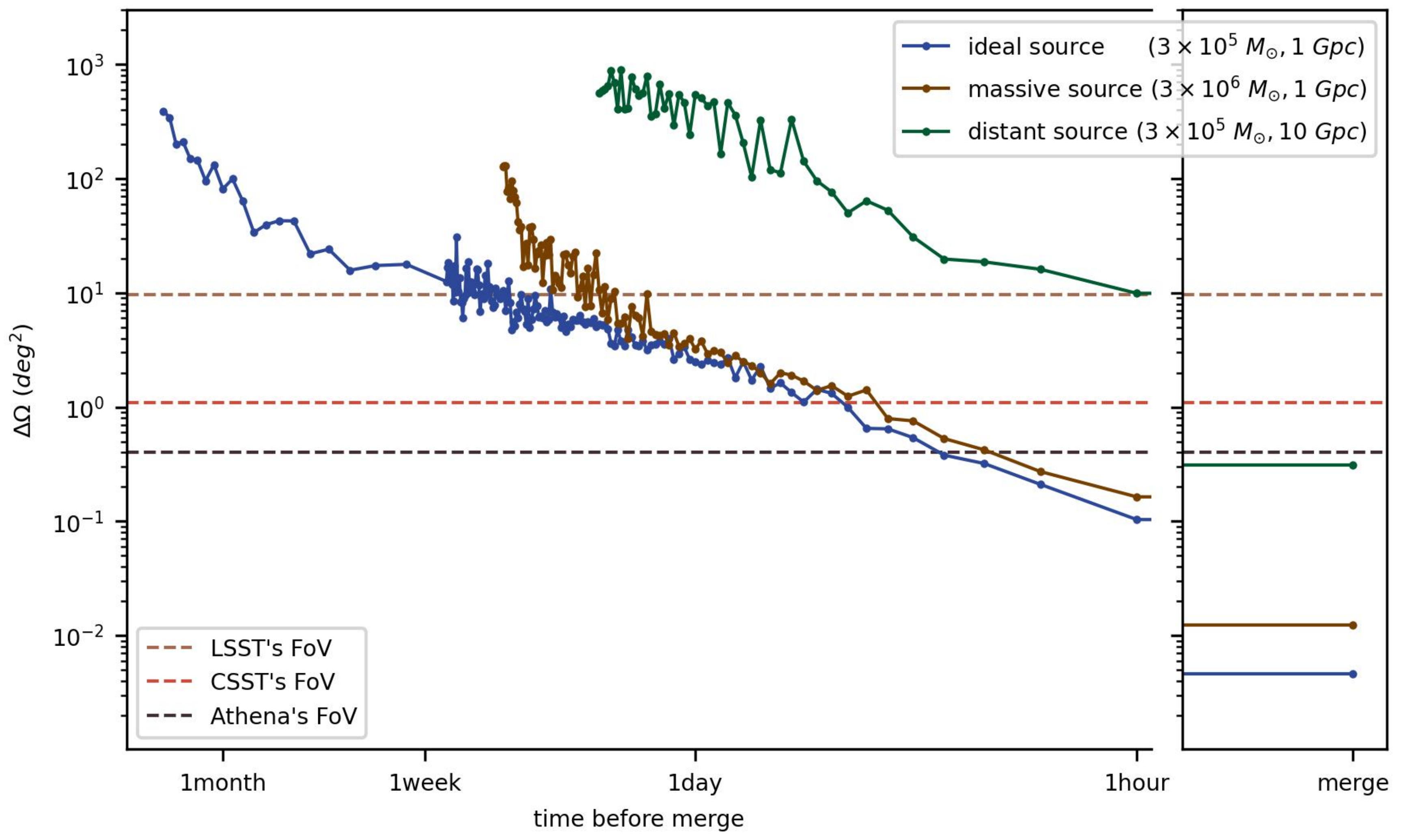
with S_n being the one-sided power spectral density (PSD) of the noise. Then fast changing terms can be calculate once before sampling, while the slow changing terms can be calculate in a sparse frequency grid. For IMRPhenomD waveform, this approach can significantly reduce computing time (left) without sacrificing precision (right).



RESULT

By MCMC and heterodyned likelihood, we achieved rapid identification and localization of MBHBs. This figure show the time evolution of the 90% confidence interval of sky localization uncertainty of the three injected sources. And the fields of view (FoV) of LSST, CSST, Athena are shown using dash line for reference.

This Figure demonstrates the necessity for real-time transmission, without which it would be nearly impossible to precisely locate MBHBs prior to merger.



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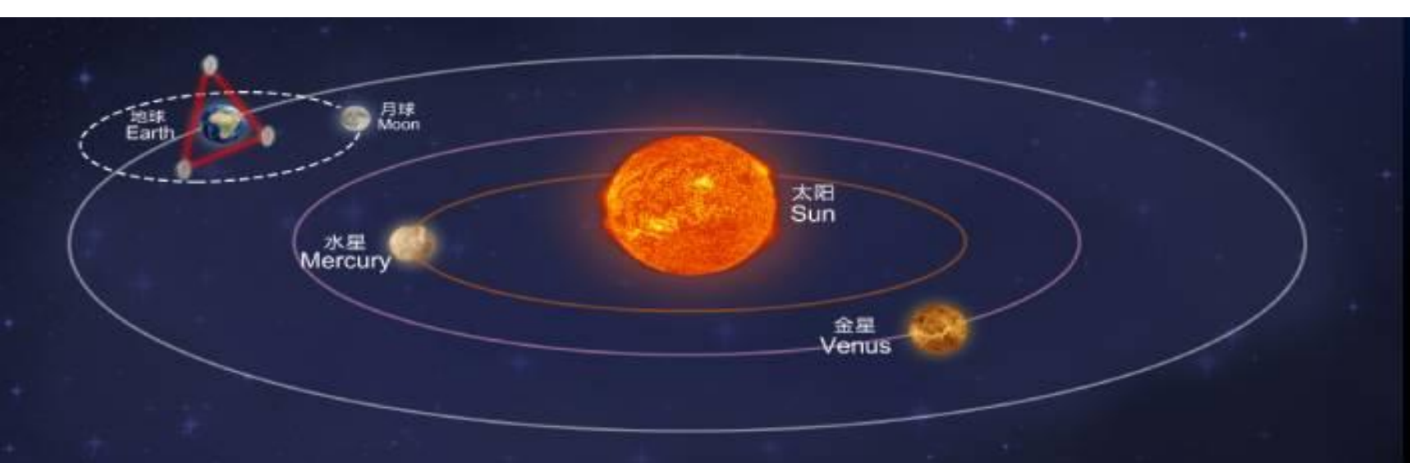

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