Multi-messenger Parameter Inference of Gravitational-Wave and Electromagnetic Observations of White Dwarf Binaries

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Background and Motivation

Gravitational Waves (GWs) are 'ripples' in spacetime produced by orbiting objects which are detected by measuring very small oscillations in distances they induce as they pass by. GWs were first directly observed in 2015 by the detectors at LIGO, which opened up new possibilities in the field of astrophysics such as observing GWs emitted by black holes, neutron stars, and white dwarfs in binary systems. The upcoming GW detector known as **LISA** (Laser Interferometer Space Antenna) [1] will enable observation of lower frequency GWs than current detectors are able to observe, such as those emitted by white dwarf binaries.

White Dwarfs are highly dense, earth-sized stars left behind by sun-sized stars after they run out of fuel and expel their outer layers. **White Dwarf Binaries** (WDBs) are systems of two white dwarfs orbiting each other. WDBs stand out from other GW sources because they emit enough **electromagnetic** (EM) radiation at any given time to easily be observed and studied by modern telescopes.

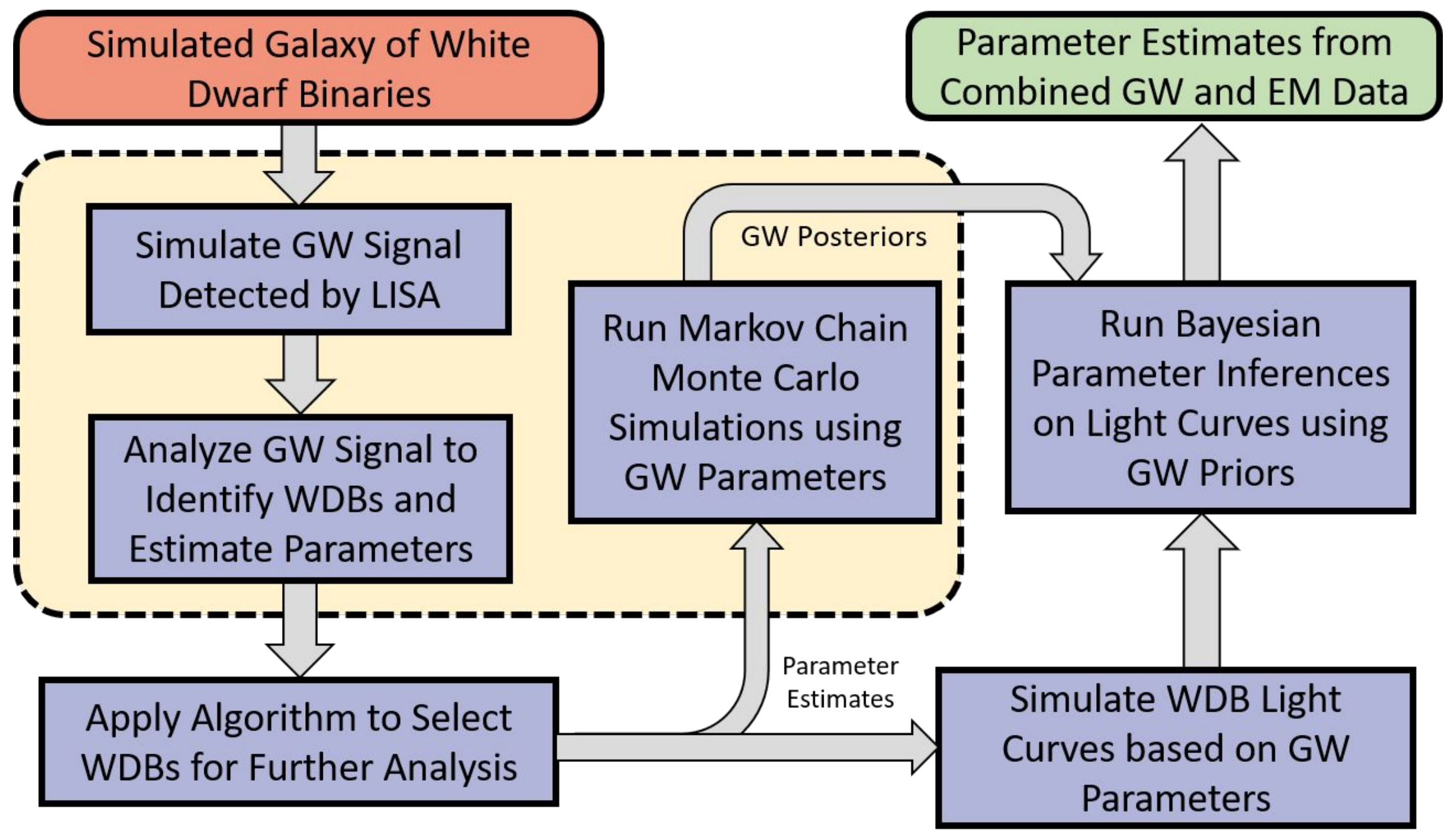
As GWs are emitted by WDBs, they carry energy away from the system, causing the orbital period to decrease. By measuring the orbital period and the rate at which the orbital period decreases, a measure of the combined mass of the binaries known as the **chirp mass** can be determined for each system. Other parameters of the WDBs that can be measured include the **period**, how long it takes the white dwarfs to complete an orbit, the **inclination**, the angle of the system relative to the observer, and the **mass ratio**, the ratio of the primary mass to the secondary mass.

Our work focuses on using computer simulations to explore the improvements in parameter estimates for WDBs gained by performing joint analyses of gravitational-wave and electromagnetic information. We aim to expand on previous parameter space studies [2] incorporating Fisher Information matrix methods by applying more sophisticated Bayesian inference methods. **Bayesian inference** is a statistical method which takes an initial "guess" for a parameter distribution called a **Prior** and updates that prior based on a new piece of information to obtain an updated distribution called a **Posterior**.

Data Analysis Pipeline

Our work centers around a data analysis pipeline as shown in Fig. 2. The pipeline begins with a simulated Milky Way galaxy consisting of WDBs which is used to simulate the signal that LISA would detect over a period of 8 years of observation. The combined GW signal due to all the binaries is then decomposed and parameter estimates are made for each binary [3].

The previous step recovers ~20,000 binaries, but even several hundred binaries takes a considerable amount of processing time to run through the rest of the pipeline. This issue was solved by producing an algorithm to cut down the number of binaries by taking into consideration factors such as the orbital period, the inclination, and the **Signal-to-Noise Ratio** (SNR); a measure of how well the GW signal stands out from the background noise.



Simulated Galaxy of White Dwarf Binaries

Simulate GW Signal Detected by LISA

Analyze GW Signal to Identify WDBs and Estimate Parameters

Apply Algorithm to Select WDBs for Further Analysis

Parameter Estimates

Run Markov Chain Monte Carlo Simulations using GW Parameters

GW Posteriors

Simulate WDB Light Curves based on GW Parameters

Run Bayesian Parameter Inferences on Light Curves using GW Priors

Parameter Estimates from Combined GW and EM Data

Figure 2: A flowchart showing each step of the data analysis pipeline. The tan box encloses the most computationally expensive steps of the pipeline.

Markov Chain Monte Carlo (MCMC) simulations [3], a kind of randomized computer simulation frequently used in astrophysical simulations, were used to construct probability distributions for each of the GW parameters based on the original parameter estimates for the narrowed down set of binaries.

The EM observations of the binaries are simulated by producing light curves [4] using the GW parameter estimates for each binary. Two different scenarios are explored, an analysis using only EM information and joint analyses of the GW and EM information. For the purely EM analysis a set of broad priors is used whereas for the combined GW and EM analysis, the GW posterior distributions produced by the MCMC simulations are taken as priors for analyzing and reconstructing parameters from the simulated light curves. Bayesian inference [5] is used to combine the GW and EM information to produce an updated set of posterior parameter distributions.

The final piece is simulating radial velocity measurements obtained through spectroscopic information. We perform another Bayesian inference on the EM only and combined EM and GW posteriors with this new information to obtain a new set of posteriors. These inferences enable us to narrow down the possible values of the otherwise poorly constrained mass ratios, enabling us to infer the individual white dwarf masses.

Results

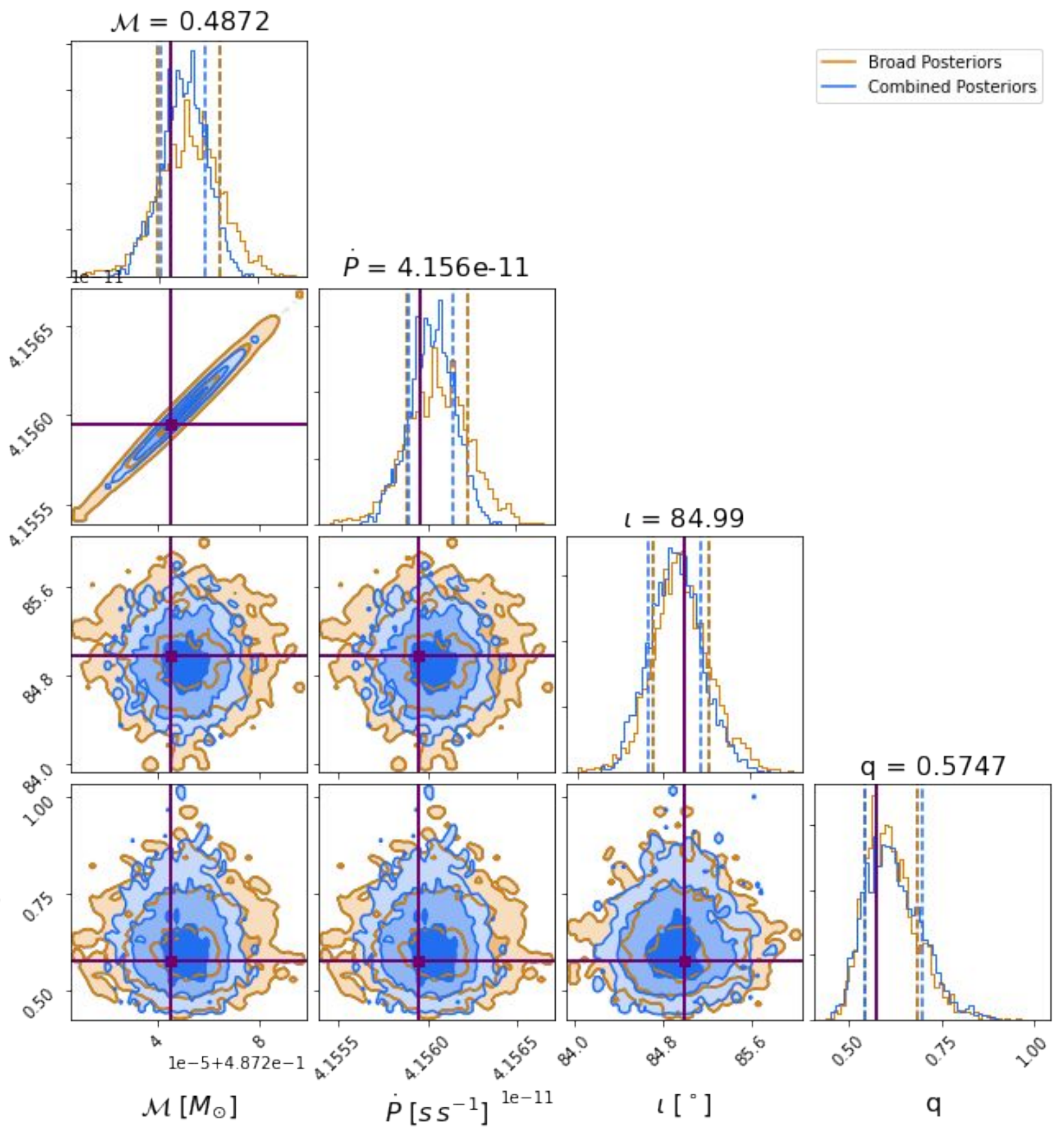


Figure 1: A corner plot displaying recovered posterior parameter distributions for EM only, and combined GW and EM simulations for a sample eclipsing binary. From left to right the parameters are chirp mass, the rate of change of period, inclination, and mass ratio

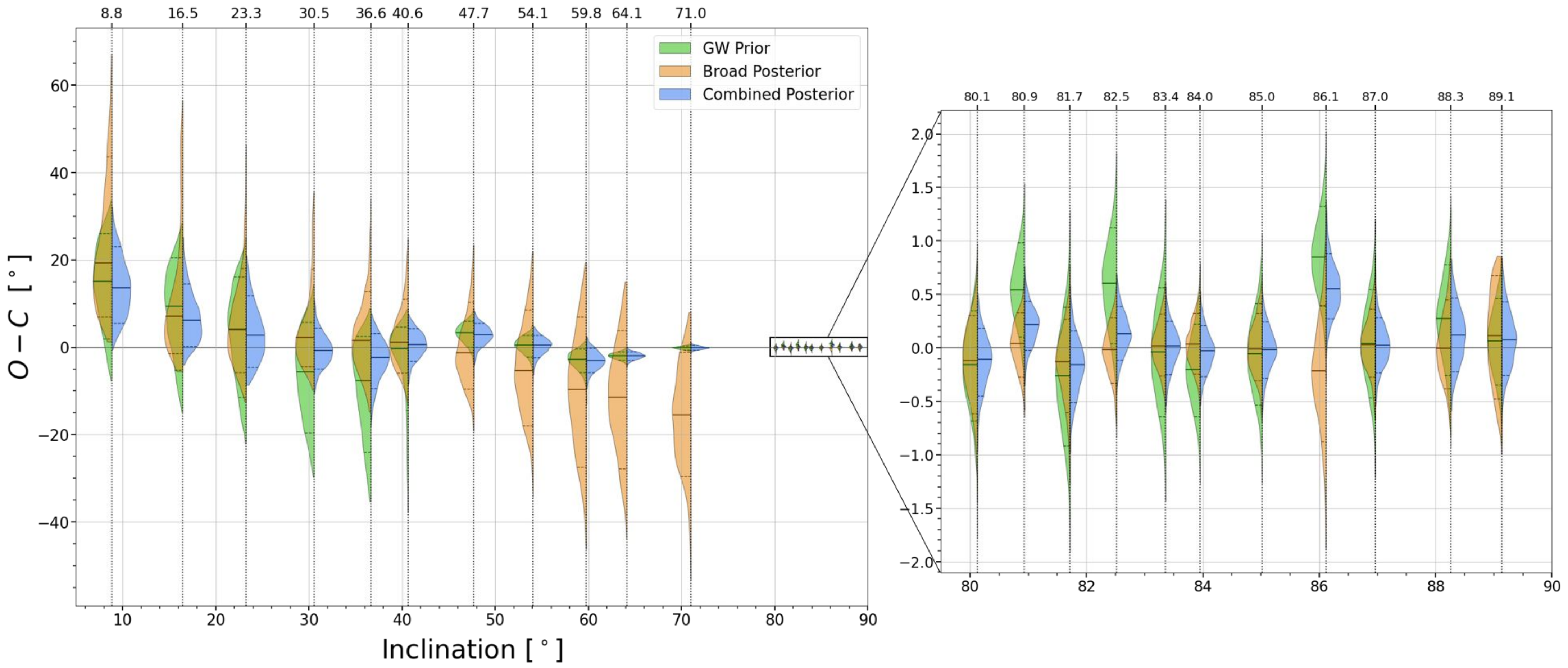


Figure 3: A set of violin plots comparing a sample of the inclination distributions. Each violin is placed along the horizontal axis to display the true inclination. The O-C values (Observed - Computed) are given by the true inclinations subtracted from each value of inclination. Each half of a violin displays a relative probability distribution over the set of possible (O-C) inclinations for the associated binary. The horizontal lines in each segment of the violin correspond to the 10th, 50th, and 90th percentiles of the associated distribution.

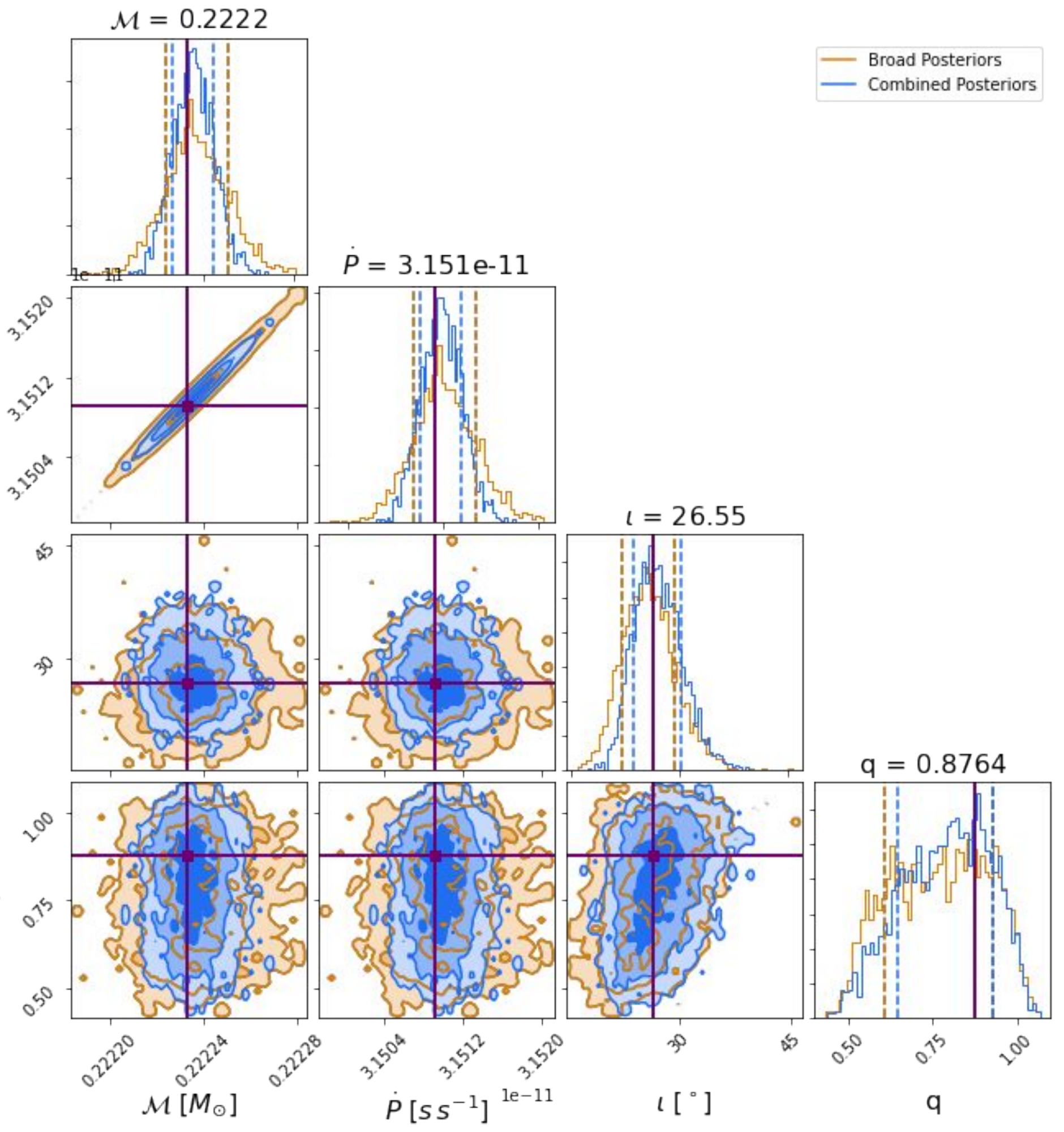


Figure 2: A corner plot displaying recovered posterior parameter distributions for EM only, and combined GW and EM simulations for a sample non-eclipsing binary. From left to right the parameters are chirp mass, the rate of change of period, inclination, and mass ratio

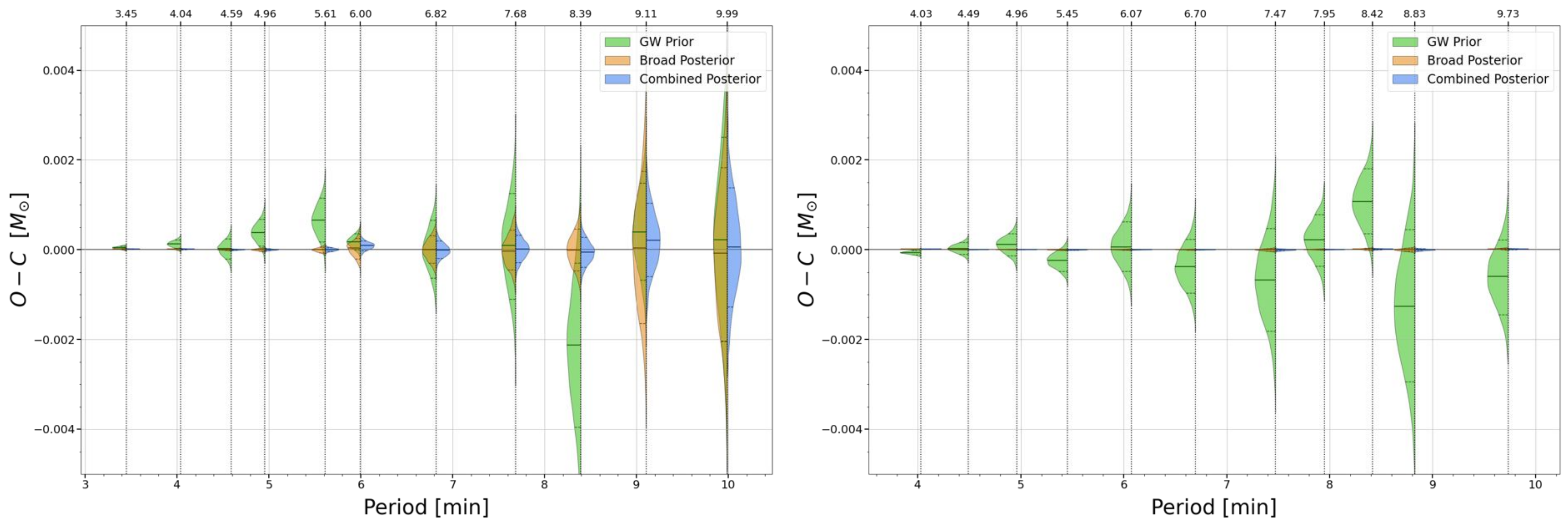


Figure 4: A set of violin plots comparing a sample of the chirp mass distributions. Each violin is placed along the horizontal axis to display the true initial orbital period. The O-C values (Observed - Computed) are given by the true chirp masses subtracted from each value of chirp mass. Each half of a violin displays a relative probability distribution over the set of possible (O-C) inclinations for the associated binary. The horizontal lines in each segment of the violin correspond to the 10th, 50th, and 90th percentiles of the associated distribution.

Conclusion

We found that the inclination and chirp mass parameter estimates displayed the most improvement for the joint GW and EM analysis. The inclination data in Fig. 3 shows that the inclination is constrained better by the EM data than the GW data for eclipsing binaries, whereas for non-eclipsing binaries, the GW and EM data produce constraints of similar size, leading to robust improvements in inclination estimates when combining GW and EM data for non-eclipsing binaries.

The chirp mass data in Fig. 4 demonstrates that the joint analysis has a larger impact for longer period, non-eclipsing binaries when it comes to recovering the chirp mass.

Overall, we were able to demonstrate that GW and EM data can be jointly analyzed to obtain better constraints. Through our research we now have a better idea of how to prepare and what measurements to make for when LISA comes online.

References

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