

Toward estimating supermassive Black Hole Binary Distributions via Higher- Order Statistics of the Gravitational Wave Background

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Recent progress in gravitational wave observations has been significant. Pulsar Timing Arrays (PTAs) aims to detect the Gravitational Wave Background (GWB) formed by sources that cannot be individually resolved in the nanohertz band. The sources of the GWB are considered to be orbital motions of Supermassive Black Hole Binaries (SMBHBs). Extracting physical information, such as the mass and redshift of SMBHBs, from GWB observations is crucial for understanding galaxy evolution and the formation processes of supermassive black holes. However, the observed GWB is significantly stronger than predictions from existing theoretical models. The statistics of the GWB energy density spectrum have been studied previously. While it was shown that statistics (mean, variance, skewness, kurtosis) follow a power law with frequency, the variance and higher-order statistics were known to diverge. This divergence was caused by setting the lower limit of the redshift integration to $z=0$. In this study, we devised a method to avoid this divergence by setting the integration lower limit based on the detector sensitivity for individual sources. We analytically derive that these higher-order statistics can be expressed as weighted averages of SMBHB physical parameters, such as mass and redshift. This framework enables the extraction of SMBHB distribution information directly from GWB observations, without relying on population synthesis simulations such as merger tree models. As a first application, we demonstrate that the SMBHB mass distribution can be recovered with reasonable accuracy by solving the inverse problem using our analytical expressions.

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