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Multipole measurements through gravitational waves of compact object binaries

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The inaccessibility of a black hole's internal structure, due to the one-way nature of the event horizon, remains a fundamental challenge in astrophysics. Nevertheless, gravitational interactions can bridge our understanding between the black hole's internal structure and the external spacetime. Specifically, the spacetime structure is characterized by its multipole moments, which vary distinctly among different black holes. According to general relativity, black holes exhibit the no-hair property, uniquely defining their multipole moments. Gravitational waves (GWs) serve as carriers of this multipole-moment information from the spacetime of black holes. In this study, we analyze mock samples of binary black holes calibrated to the GWTC-3 catalog to investigate the measurement and associated degeneracies of their multipole moments using individual and joint observations from next-generation ground-based and space-based detectors. Our results show that measuring higher-order multipole moments, such as the octupole, remains challenging for individual detectors due to strong parameter degeneracies. However, multiband joint observations mitigate these degeneracies, improving the precision of multipole parameter estimation by approximately an order of magnitude. This advancement underscores the critical role of multiband gravitational-wave networks in probing black-hole spacetime properties and testing the no-hair theorem.

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