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The Formation of Early Supermassive Black Holes and Their Gravitational Wave Signatures

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The rapid formation of supermassive black holes (SMBHs) in the early universe (z > 6) remains one of the most significant mysteries in the Universe. Observations of SMBHs with masses reaching ~ $10^{10} M_{\odot}$ within the first billion years challenge our understanding of black hole (BH) formation and growth. Despite significant insights from the James Webb Space Telescope (JWST), the mechanisms driving this rapid evolution remain uncertain. In this study, we apply the Cosmic Archaeology Tool (CAT), a semi-analytical model, to simulate the coevolution of galaxies and their central BHs from redshift 24 to 4. CAT explores BH growth via multiple accretion processes, including Eddington-limited accretion at the Bondi-Hoyle-Lyttleton (BHL) rate, as well as super-Eddington accretion triggered by a slim disk during gas-rich galaxy mergers. The model also adopts diverse BH seeding scenarios—ranging from light to medium to heavy seeds—and tracks the formation of binary black holes (BBHs) through dynamical friction and gravitational wave (GW) emission.
A key focus of this research is the GW signatures of BBH systems and their potential detection by next-generation observatories. Advanced ground-based detectors like the Einstein Telescope (ET) and space-based interferometers such as the Laser Interferometer Space Antenna (LISA) and the Lunar Gravitational-Wave Antenna (LGWA) will enable multiband GW observations, probing intermediate-mass black holes (IMBHs) and SMBHs across different frequency ranges. LISA, operating in the millihertz band, will capture the early inspiral phase of IMBH binaries and SMBH mergers, while ET, with its high sensitivity in the decihertz to kilohertz range, will observe the later phases of IMBH and SMBH binaries, bridging the gap between space- and ground-based detectors for a comprehensive multiband GW analysis. This makes ET crucial for completing the picture of BH evolution and GW signals across different frequencies.
By comparing CAT's predictions with upcoming GW observations, this study aims to shed light on the formation and evolution of SMBHs, offering critical insights into the early universe's BH population and the underlying physical mechanisms governing their growth.

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