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Gravitational waves from mergers of Population III binary black holes: roles played by two evolution channels

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The gravitational wave (GW) signal from binary black hole (BBH) mergers is a promising probe of population III (Pop III) stars, which are more efficient at producing massive black holes (BHs) than their population I/II (Pop I/II) counterparts. To fully unleash the power of the GW probe, one important step is to understand the relative importance and unique features of different evolution channels. We implement two channels, i.e., isolated binary stellar evolution (IBSE) and nuclear star cluster-dynamical hardening (NSC-DH), in the semi-analytical model A-SLOTH to predict the properties of Pop III BBH mergers under various assumptions on Pop III initial mass function (IMF), binary statistics and high-z nuclear star clusters (NSCs). In the NSC-DH channel, Pop III BBHs fall into NSCs by dynamical friction and are driven to merge by dynamical hardening from binary-single encounters. The NSC-DH channel contributes 8-95% of Pop III BBH mergers across cosmic history, with higher contributions achieved by initially wider binary stars, more top-heavy IMFs, and more abundant high-z NSCs. The stochastic GW background (SGWB) produced by Pop III BBH mergers has a peak value of 1-8*10^-11 around observer-frame frequencies 10-100 Hz, which can be a non-negligible (~2-32%) component in the total SGWB below 10 Hz. The estimated detection rates of Pop~III BBH mergers by the Einstein Telescope are ~6-230 and ~30-1230 events per year for the NSC-DH and IBSE channels, respectively. BBH mergers in NSCs are more massive than those from IBSE, so they dominate the Pop III SGWB below ~20 Hz in most cases. Besides, the detection rate of Pop III BBH mergers involving at least one intermediate-mass BH above 100 Msun by the Einstein Telescope is 0.5-200/yr in NSCs but remains below 0.1/yr for IBSE.

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