Forecast for cosmological parameters in the era of the third-generation gravitational-wave detectors

SUMMARY

The study of cosmology has achieved great accomplishments over the past decades. Nevertheless, the study of cosmology still has many unresolved issues, such as the Hubble tension and the nature of dark energy. Therefore, in the current cosmology, an important mission is to precisely the Hubble constant and the equation of state of dark energy. Recent forecasts show that the third-generation gravitational-wave detectors would lead to breakthroughs in solving the Hubble tension and revealing the nature of dark energy.

Key question(s) and scientific context in brief

Key questions: (i) Hubble constant is 67 or 74? (ii) What is the nature of dark energy?

For the measurement of the Hubble constant, the values of the Hubble constant inferred from the observations of the $Planck$ cosmic microwave background (CMB) anisotropies (a 0.8% measurement, assuming a flat ΛCDM cosmology) Aghanim et al. 2020 and determined from the Cepheid-supernova distance ladder (a 1.4% measurement) Riess et al. 2022 are highly inconsistent, with the tension reaching 5σ significance. Using the standard siren method (bright siren), the multi-messenger GW observation GW170817 has given an independent measurement of the Hubble constant with about 14% precision B. P. Abbott et al. 2017, 19% precision for the dark siren method R. Abbott et al. 2021. While for the measurement of dark energy, the CMB+BAO+SN data have given the tightest constraint to date, with the constraint precision being about 3% Brout et al. 2022. The measurements of the Hubble constant and dark energy are far away from helping solve the Hubble tension and explore the nature of dark energy.

Potential scientific impact of XG detectors on the key questions

The standard siren observation (bright siren, GW-EM observations) from XG detectors is expected to constrain the Hubble constant to a precision of $(0.1)\%$ level Jin, He, et al. 2020; Zhang et al. 2019; Belgacem et al. 2019 and the dark energy to a precision of $(10)\%$ level Jin, He, et al. 2020; Zhang et al. 2019; Belgacem et al. 2019. For the dark siren method, the Hubble constant is expected to be constrained to $(0.1)\%$ level Muttoni et al. 2023; Jin, T.-N. Li, et al. 2022 and dark energy to be $(0.1)\%$ level Jin, T.-N. Li, et al. 2022; Del Pozzo, T. G. F. Li, and Messenger 2017. The XG detector network could help solve the Hubble tension and explore the nature of dark energy.

Benchmarks for XG detectors to enable the scientific impact

Based on the current proposed sensitivities of XG detectors, the forecasts show the strong ability of XG detectors to measure the cosmological parameters. For the detection of bright sirens (binary neutron stars), if the GW source can be located within $10\,\mathrm{deg}^2$ (corresponding to the field of view of LSST) a few minutes before the merger, it will be very beneficial for the subsequent search for the electromagnetic counterparts.

SCIENTIFIC IMPACT OF XG DETECTORS

Solve the Hubble tension.

Explore the nature of dark energy.

XG DETECTOR AND NETWORK REQUIREMENTS

According to the recent forecasts, for the dark siren method (tidal deformation of neutron star), three years are probably enough to precisely measure the Hubble constant ($\mathcal{O}(0.1)\%$ precent level) and dark energy (better than 1%). For the bright siren method (GW+EM observations), ten years are probably enough to precisely measure the Hubble constant and dark energy.

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