Cosmological parameter measurement and neutral hydrogen 21 cm sky survey with the Square Kilometre Array

YiDong Xu¹, and Xin Zhang^{2*}

¹Key Laboratory for Computational Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China;

²Department of Physics, College of Sciences, Northeastern University, Shenyang 110819, China

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Through decades of continuous efforts by the whole community of cosmology, a standard cosmological model known as the Λ cold dark matter (Λ CDM) model has been established, in which the total energy budget consists of 5% ordinary matter, 27% cold dark matter, and 68% dark energy described by a cosmological constant Λ , and the inflation process in the very early universe yielded adiabatic, Gaussian, nearly scale-invariant primordial density perturbations, and possibly detectable primordial gravitational waves. The Λ CDM model with several ansatzes can fit the observational data of cosmology with breathtaking precision. Actually, the Planck satellite mission has implemented unprecedentedly precise measurements for the cosmic microwave background (CMB) anisotropies, and the latest observational results of the CMB power spectra strongly favor a “base” version of the Λ CDM model that has only six basic cosmological parameters and a number of well-tested ansatzes.

However, although the base- Λ CDM cosmology seems to be able to explain various cosmological observations quite well, some cracks still appear in the model. Recently, it was found that the Planck results for the base- Λ CDM cosmology are in tension with some low-redshift observations. For example, the amplitude of the fluctuation spectrum in the base- Λ CDM cosmology, constrained by the Planck observation, is found to be higher than that inferred from some analyses of cluster counts, weak

gravitational lensing, and galaxy clustering; more importantly, the Planck base- Λ CDM results are in significant, $4\text{--}6\sigma$, tension with local measurements of the Hubble constant (which prefer a higher value) [1]. These discrepancies in observations imply that the current standard model of cosmology is tantalizingly incomplete, and needs to be extended. Theorists have designed a variety of wild theories beyond the standard model, introducing new physics and additional parameters into the extended models.

Nevertheless, the CMB observation is a two-dimensional measurement of the early universe, and thus cannot provide tight constraints on the parameters that concern the physical effects of the late universe. The CMB-alone constraints will always lead to significant degeneracies between cosmological parameters (including, in particular, the newly introduced parameters) in the extended cosmological models. Therefore, late-universe astrophysical observations are needed to be combined with the Planck CMB observation to break the parameter degeneracies. The most typical low-redshift cosmological probes include the type Ia supernovae (SN) and the baryon acoustic oscillations (BAO). The SN observation can provide cosmological “standard candles”, and the BAO observation can provide a cosmological “standard ruler”. Using the standard candles and the standard ruler, one can establish the distance-redshift relation for the cosmos, which embodies the expansion history of the universe, and thus can be used to constrain the properties of dark energy. In addition, other important cosmological probes also include the

*Corresponding author (email: zhangxin@mail.neu.edu.cn)

measurements for the Hubble constant, redshift-space distortions (RSD), weak lensing (WL), and clusters of galaxies. The RSD, WL, and clusters observations mainly aim to measure the structure growth history of the universe, and thus are important for the tests of modified gravity theories. In the next one to two decades, the Stage IV dark energy experiments, such as DESI, LSST, and Euclid, will greatly improve the measurements for the parameters of dark energy and other cosmological parameters, by performing optical or near-infrared sky surveys.

Notwithstanding, with the great advancements in electronics, engineering, and computer science, new cosmological probes are being developed, in addition to those traditional galaxy surveys. In our opinion, the most important new cosmological probes mainly include gravitational-wave (GW) standard siren observation and neutral hydrogen (HI) 21 cm radio observation. The future GW observations will play a crucial role in the studies of cosmology [2]. Meanwhile, radio observations of the HI 21 cm signal from different cosmic epochs will also become a new powerful cosmological probe in the future. With the cosmological 21 cm signal as one of the main science drivers, the ambitious big-science facility, the Square Kilometre Array (SKA), is scheduled to be constructed in the near future.

The SKA will comprise of two arrays, i.e., a mid-frequency dish array (SKA-MID) to be built in South Africa, and a low-frequency array of log-periodic antenna elements (SKA-LOW) to be built in Australia, totally covering the frequency range from 50 MHz to 20 GHz. The phase 1 of SKA (denoted as SKA1) will begin construction in 2021 (lasts from 2021 to 2028), and the phase 2 of SKA (denoted as SKA2) will start construction after 2028.

The primary science objective of the SKA is to explore the first billion years of the universe, with a special focus on the cosmic dawn (CD) and the epoch of reionization (EoR). Hydrogen is ubiquitous in the universe, and it constitutes about 75% of the gas mass in the intergalactic medium, thus it actually provides a convenient tracer of the properties of the gas before the completion of reionization. The HI 21 cm line is produced by the hyperfine splitting caused by the interaction between the magnetic moments of electron and proton in the hydrogen atom. The 21 cm signals from HI during CD and EoR are redshifted to the low-frequency radio band today.

The SKA seeks to explore the CD and EoR by performing the imaging and power spectrum measurements of the 21 cm brightness field. The SKA1-LOW array can be used for 21 cm signal detection in the frequency range of 50-200 MHz to probe the physics of CD and EoR at the redshifts 6-27. It is expected that the first image of the cosmic reionization in the frequency range of 100-200 MHz could be obtained, which can be used to uncover the mysterious veil of the cosmic reionization, and the HI power spectra of CD and EoR on

the scales 0.02-0.1 Mpc⁻¹ in the frequency range of 50-200 MHz could also be statistically obtained. EoR imaging observations can reveal the formation of the first stars and black holes as well as the complex process of gas reionization.

Actually, by using the 21 cm signal of HI as a tracer of the matter distribution, the 21 cm cosmology is also one of the breakthroughs the SKA is attempting to make. In addition to the SKA-LOW for the early structure formation studies, the design of SKA-MID array has a special focus on the evolution of the late universe and the nature of dark energy. The SKA1-MID will be a mixed dish array consisting of an existing SKA precursor, MeerKAT, of 64 13.5-m diameter dishes, and a newly-built array of 133 15-m dishes, covering the frequency range from 350 MHz to 14 GHz. These dishes are planned to be equipped with receivers sensitive to 5 different frequency ranges (or *bands*), but in the present SKA baseline configuration there are only sufficient funds to deploy Band 1 (0.35-1.05 GHz) and Band 2 (0.95-1.75 GHz), which are most relevant to cosmology, and Band 5 [3].

The SKA-MID array can be used to implement the HI sky survey and study the large-scale structure of neutral hydrogen. An effective way to map the sky called the “intensity mapping” (IM) adopts a low angular resolution approach (in which each pixel contains many galaxies) to perform the sky survey, and thus can get the large-scale distribution of neutral hydrogen with extremely high efficiency. The 21 cm IM survey by the SKA could provide accurate measurements for the HI power spectrum, and the associated signals of BAO and RSD can reach percent-level precision in the expansion rate measurements of the universe, providing effective constraints on the equation of state (EoS) of dark energy up to $z \sim 3$.

It has been shown [4-7] that the SKA-MID HI 21 cm IM survey could play an important role in improving the cosmological parameter estimation in the future, in particular for the constraints on the EoS of dark energy [4], the possible interaction between dark energy and dark matter [5], the total mass of neutrinos [6], and the primordial non-Gaussianity and inflation features [7]. It can be expected that in the future the SKA observation, combined with the future highly accurate optical surveys from the Stage IV dark energy experiments, such as DESI, LSST, and Euclid, as well as the gravitational-wave standard siren observations from ground-based and space-based detectors, would greatly promote the development of cosmology.

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