Forecast for weighing neutrinos in cosmology with SKA

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We investigate what role the SKA neutral hydrogen sky survey observation will play in weighing neutrinos in cosmology. We use the simulated data of the baryon acoustic oscillation (BAO) measurements from the neutral hydrogen survey based on SKA1 and SKA2 to do the analysis. For the current observations, we use the Planck 2015 cosmic microwave background (CMB) anisotropies observation, the BAO measurements, the type Ia supernovae (SN) observation (Pantheon compilation), and the latest \( H_0 \) measurement. We consider three mass ordering cases for massive neutrinos, i.e., the normal hierarchy (NH), inverted hierarchy (IH), and degenerate hierarchy (DH) cases. It is found that the SKA observation can significantly improve the constraints on \( \Omega_m \) and \( H_0 \). Compared to the current observation, the SKA1 data can improve the constraints on \( \Omega_m \) by about 33%, and on \( H_0 \) by about 36%; the SKA2 data can improve the constraints on \( \Omega_m \) by about 58%, and on \( H_0 \) by about 66%. It is also found that the SKA observation can only slightly improve the constraints on \( \sum m_\nu \). Compared to the current observation, the SKA1 data can improve the constraints on \( \sum m_\nu \) by about 4%, 3%, and 10%, for the NH, IH, and DH cases, respectively; the SKA2 data can improve the constraints on \( \sum m_\nu \) by about 7%, 7%, and 16%, for the NH, IH, and DH cases, respectively.

I. INTRODUCTION

Precise measurement of cosmological parameters is one of the core tasks of cosmology research. The answers to almost all important scientific questions in cosmology depend on precise measurements of cosmological parameters. The measurement of cosmological parameters is closely related to the cosmological model because the determination of cosmological parameters is usually done by fitting observational data under the assumption of a specific cosmological model.

After decades of development, the study of cosmology has entered the era of precision cosmology. At present, a standard model of cosmology has been basically established, of which the prototype is the so-called Λ cold dark matter (ΛCDM) model. The basic version of the ΛCDM model has only 6 base parameters, and this base ΛCDM model is favored by the Planck observation of cosmic microwave background (CMB) anisotropies [1]. However, the base ΛCDM cosmology has also encountered some serious challenges in the aspect of observation. Some significant tensions occur between different observations based on the base ΛCDM cosmology, such as the Hubble constant tension and the matter density fluctuation amplitude tension [2, 3]. This actually indicates that the standard ΛCDM model needs to be extended. Of course, extra parameters need to be introduced in extended cosmological models.

The current mainstream cosmological probes mainly include the following several ones: the CMB anisotropy (temperature and polarization) power spectra measurement, the baryon acoustic oscillation (BAO) measurement, the type Ia supernova (SN) observation, the direct measurement of the Hubble constant \( H_0 \), the shear measurement of weak gravitational lensing, the galaxy cluster counts, the redshift space distortion (RSD) measurement, and the lensing measurement of CMB. These cosmological probes make precise measurements of the expansion history of the universe (the first four) and the structural growth of the universe (the last four). These probes are all based on the optical measurements, and will be further greatly developed in the future. However, in the future we also need to develop new cosmological probes other than those sky surveys based on the optical measurements. Actually, the gravitational-wave standard siren observation and the radio 21 centimeter observation are thought to be the most important new cosmological probes in the forthcoming years. Undoubtedly, the Square Kilometre Array (SKA) radio telescope [4] will definitely play a crucial role in the studies of astronomy and cosmology.

SKA is the largest synthetic aperture radio telescope all over the world the international astronomy community plans to build, with the receiving area of one square kilometer. It is an international science project driven by ambitious scientific goals. Actually, SKA has devoted itself to answering some of the most fundamental questions about the universe, such as how it moves from darkness to light, which will open up a new era in our understanding of the universe. Research on neutral hydrogen 21 cm cosmology is one of the important breakthroughs that we are committed to making. We will take full advantage of the extremely high sensitivity and large area of the sky survey of SKA to conduct 21-centimeter cosmological studies of neutral hydrogen, to reveal the secrets from black holes and galaxy dynamics to the large-scale structure of the universe, and to examine the properties

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of dark matter and dark energy.

The SKA neutral hydrogen sky survey can be used to measure neutral hydrogen power spectrum, BAO, and RSD, and its accuracy can reach or exceed that of future large optical sky survey projects, which will play an important role in the measurement of cosmological parameters and the exploration of the nature of dark energy. For constraints on the EoS of dark energy using the simulated data based on SKA observation, see Refs. [5–8]. (For an investigation on precise measurements of inflationary features with 21 cm simulated observations from Tianlai and SKA, see Ref. [9].) As a next step, we wish to know if the SKA observation could play a significant role in helping improve the constraints on the neutrino mass in cosmology.

Neutrino oscillation experiments have revealed the fact that neutrinos have masses, but the neutrino oscillation experiments cannot measure the absolute masses of neutrinos. Neutrino masses play an important role in the cosmic evolution, which not only affect the expansion history of the universe, but also affect the structural growth of the universe. The Planck observations, combined with other astrophysical observations, have so far constrained the total mass of neutrinos to be less than about 0.12 eV [1]. In recent years, a series of studies have revealed that the properties of dark energy actually play an important role in cosmological measurement of neutrino mass [10–30]. Moreover, the properties of dark energy also influence the cosmological search for sterile neutrinos [31–36]. It should also be mentioned that recent research has shown that the 10-year observation of gravitational-wave standard sirens from the Einstein Telescope (ET) can help improve the constraints on the total neutrino mass by about 10% [37] (see also Refs. [38–40] for relevant studies). In this work, we will use the simulated data of the neutral hydrogen survey observation of SKA to perform constraints on the total neutrino mass, of which the purpose is to see whether the SKA observation could help improve the cosmological measurement of the neutrino mass.

This paper is organized as follows. In Sec. II, we introduce the analysis method and the observational data used in this work. We will consider some current actual observational data, and use these data to constrain the cosmological model with massive neutrinos considered in it. Then, we will further consider the simulated data of the neutral hydrogen survey observation of SKA in the cosmological fit. The neutrino mass splittings measured in the neutrino oscillation experiments are considered in this work. In Sec. III, we report the constraint results and make some relevant discussions. The conclusion of this work is given in Sec. IV.

II. METHOD AND DATA

In this work, we consider massive neutrinos in a flat ΛCDM model. With the increasing accuracy of the observational data, the effects from the mass splittings of the neutrinos can gradually be sensitive to the observational data, and thus we also consider the mass splittings of the neutrinos in this work. In the neutrino oscillation experiments, the solar and reactor experiments have measured $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV$^2$, and the atmospheric and accelerator beam experiments have measured $\Delta m^2_{31} \approx 2.5 \times 10^{-3}$ eV$^2$ [41], indicating that there are two possible mass orders, i.e., the normal hierarchy (NH) with $m_1 < m_2 \ll m_3$ and the inverted hierarchy (IH) with $m_3 \ll m_1 < m_2$. Thus, in this paper, we follow Refs. [16, 19, 20, 22, 25, 42] to use these two mass splittings as an input to parameterize the total mass of neutrinos, in terms of $m_1$ as a free parameter for the NH case and in terms of $m_3$ as a free parameter for the IH case.

We will first use the current observations to constrain the cosmological model involving massive neutrinos. Then, we will use the simulated data of the neutral hydrogen survey observation of SKA to constrain the same model, and we will directly see how the SKA observation would help improve the constraints on the neutrino mass.

The current observations we use in this paper are the CMB, BAO, SN, and $H_0$ data. For the CMB data, we use the Planck temperature and polarization power spectra at the full range of multipoles [43], which can be denoted as “Planck TT,TE,EE+lowTEB”. For the BAO data, we use the measurements from the six-degree-field galaxy survey (6dFGS) at $z_{e\!f\!f} = 0.106$ [44], the SDSS main galaxy sample (MGS) at $z_{e\!f\!f} = 0.15$ [45], the SDSS DR12 galaxy sample at $z_{e\!f\!f} = 0.38$, $z_{e\!f\!f} = 0.51$, and $z_{e\!f\!f} = 0.61$ [46]. For the SN data, we use the latest sample consisting of 1048 data from the Pantheon compilation [47]. For the $H_0$ data, we use the latest measurement given by Ref. [48], with the result $H_0 = 73.52 \pm 1.62$ km s$^{-1}$ Mpc$^{-1}$. The basic data combination used in this work is from the current observation, i.e., CMB+BAO+SN+$H_0$, denoted as “data0” for convenience in the following discussions.

We consider the simulated data of the neutral hydrogen survey observation from the SKA Phase 1 (denoted as SKA1) and the SKA Phase 2 (denoted as SKA2). The concrete simulation has been made in Ref. [5]. The simulated data of the BAO measurements from the neutral hydrogen survey based on SKA1 and SKA2 have been given in Ref. [5]. We thus directly use these simulated data in this work. The relative errors of the expansion rate, $\sigma_H/H$, and the angular diameter distance, $\sigma_{D_A}/D_A$, can be directly gained from the simulation in Ref. [5]. In this work, we use the SKA1-MID B1 data including 11 data points of $\sigma_H/H$ and 6 data points of $\sigma_{D_A}/D_A$, and use
SKA1-MID B2 data including 7 data points of $\sigma_H/H$ and 8 data points of $\sigma_{D_A}/D_A$, and we combine these data to establish likelihood function of SKA1. For the SKA2 simulated data, we use the sample including 17 data points of $\sigma_H/H$ and 17 data points of $\sigma_{D_A}/D_A$ to establish its likelihood function. We thus consider another two data combinations in this work: CMB+BAO+SN+ data combination CMB+BAO+SN+ to perform constraints and to estimate their best-fit values and errors. For each neutrino mass ordering case of the cosmological model, we use the three data combinations to perform constraints and to estimate parameters.

### III. RESULTS AND DISCUSSION

In this section, we report the constraint results and make some relevant discussions. Our main results are shown in Tables I–III and Figs. 1–3. The results of the NH case are shown in Table I and Fig. 1, the results of the IH case are shown in Table II and Fig. 2, and the results of the DH case are shown in Table III and Fig. 3. Note also that here we use $data0$ to denote the data combination CMB+BAO+SN+ and $data1$ to denote the data combination CMB+BAO+SN+ +SKA1, and use $data2$ to denote the data combination CMB+BAO+SN+ +SKA2.

From these results, we can clearly see that the SKA observations can significantly improve the constraints on all the parameters, in particular for the parameters $\Omega_m$ and $H_0$. Compared to the SKA1 data, the SKA2 data have a much more powerful constraint capability. In the following, we will first report the constraint results of $\Omega_m$ and $H_0$, and then discuss the constraints results of $\sum m_\nu$.

For the NH case, using $data0$ we have $\Omega_m = 0.3054 \pm 0.0061$ and $H_0 = 67.99 \pm 0.47$ km s$^{-1}$ Mpc$^{-1}$; using $data1$ we have $\Omega_m = 0.3052 \pm 0.0041$ and $H_0 = 68.00 \pm 0.30$ km s$^{-1}$ Mpc$^{-1}$; and using $data2$ we have $\Omega_m = 0.3052 \pm 0.0025$ and $H_0 = 68.00 \pm 0.16$ km s$^{-1}$ Mpc$^{-1}$.

For the IH case, using $data0$ we have $\Omega_m = 0.3075 \pm 0.0061$ and $H_0 = 67.78 \pm 0.46$ km s$^{-1}$ Mpc$^{-1}$; using $data1$ we have $\Omega_m = 0.3072 \pm 0.0041$ and $H_0 = 67.80 \pm 0.30$ km s$^{-1}$ Mpc$^{-1}$; and using $data2$ we have $\Omega_m = 0.3073 \pm 0.0025$ and $H_0 = 67.80 \pm 0.16$ km s$^{-1}$ Mpc$^{-1}$.

For the DH case, using $data0$ we have $\Omega_m = 0.3029 \pm 0.0060$ and $H_0 = 68.24 \pm 0.47$ km s$^{-1}$ Mpc$^{-1}$; using $data1$ we have $\Omega_m = 0.3025 \pm 0.0040$ and $H_0 = 68.27 \pm 0.30$ km s$^{-1}$ Mpc$^{-1}$; and using $data2$ we have $\Omega_m = 0.3025 \pm 0.0024$ and $H_0 = 68.27 \pm 0.16$ km s$^{-1}$ Mpc$^{-1}$.

We find that using the same data combination, the constraints on $\Omega_m$ and $H_0$ are similar for all the mass ordering cases. For the parameter $\Omega_m$, the current observation CMB+BAO+SN+ gives its error around 0.0060; when the SKA1 observation is added, the error becomes around 0.0040, and the constraint is improved by 33.3%; and when the SKA2 observation is added, the error becomes around 0.0025, and the constraint is improved by 58.3%. For the parameter $H_0$, the current observation CMB+BAO+SN+ gives its error around 0.47 km s$^{-1}$ Mpc$^{-1}$; when the SKA1 observation is added, the error becomes around 0.30 km s$^{-1}$ Mpc$^{-1}$, and the constraint is improved by 36.2%; and when the SKA2 observation is added, the error becomes around 0.16 km s$^{-1}$ Mpc$^{-1}$, and the constraint is improved by 66.0%.

Now we discuss the constraints on the neutrino mass. For the NH case, we have $\sum m_\nu < 0.148$ eV, $\sum m_\nu < 0.142$ eV, and $\sum m_\nu < 0.137$ eV by using $data0$, $data1$, and $data2$, respectively. For the IH case, we have $\sum m_\nu < 0.182$ eV, $\sum m_\nu < 0.176$ eV, and $\sum m_\nu < 0.170$ eV by using $data0$, $data1$, and $data2$, respectively. For the DH case, we have $\sum m_\nu < 0.109$ eV, $\sum m_\nu < 0.0983$ eV, and $\sum m_\nu < 0.0911$ eV by using $data0$, $data1$, and $data2$, respectively. Here, as usual, the upper limit values of the neutrino mass refer to the $95.4\%$ (2$\sigma$) confidence level. Note also that the lower bounds of the total neutrino mass have been set for the NH case and the IH case, which are 0.06 eV and 0.10 eV, respectively, as shown in Figs. 1 and 2. For the DH case, there is no a lower bound of the total neutrino mass; see also Fig. 3.

We find that, for the constraints on the neutrino mass $\sum m_\nu$, when the SKA1 observation is added, the upper limit values are reduced by 4.1%, 3.3%, and 9.8% for the NH, IH, and DH cases, respectively; when the SKA2 observation is added, the upper limit values are reduced by 7.4%, 6.5%, and 16.4% for the NH, IH, and DH cases, respectively. Therefore, it is found by this investigation that the SKA observations can also improve the constraints on the total neutrino mass to some extent.

### IV. CONCLUSION

In this work, we investigate how the SKA neutral hydrogen sky survey observation can be used to improve the constraints on the total neutrino mass. We use the simulated data of the BAO measurements from the neutral hydrogen survey based on SKA1 and SKA2 to do the analysis. We wish to see, compared to the current observations, what role the SKA observations...
TABLE I: The constraint results for the NH case of the neutrino mass ordering. Here, data0 denotes CMB+BAO+SN+H0, data1 denotes CMB+BAO+SN+H0+SKA1, and data2 denotes CMB+BAO+SN+H0+SKA2. Note that \( \sum m_\nu \) is in units of eV and \( H_0 \) is in units of km s\(^{-1}\) Mpc\(^{-1}\).

|          | data0               | data1               | data2               |
|----------|---------------------|---------------------|---------------------|
| \( \Omega_b h^2 \) | 0.02241 ± 0.00014   | 0.02241 ± 0.00012   | 0.02241 ± 0.00011   |
| \( \Omega_c h^2 \) | 0.1177 ± 0.0010     | 0.11772 ± 0.00082   | 0.11773 ± 0.00058   |
| 1000\(\theta_{MC}\) | 1.04102 ± 0.00030   | 1.04101 ± 0.00028   | 1.04101 ± 0.00026   |
| \( \tau \)         | 0.091 ± 0.017       | 0.091 ± 0.016       | 0.091 ± 0.016       |
| \( \ln(10^{10}A_s) \) | 3.113 ± 0.033       | 3.113 ± 0.032       | 3.112 ± 0.032       |
| \( n_s \)          | 0.9700 ± 0.0040     | 0.9700 ± 0.0036     | 0.9699 ± 0.0035     |
| \( \Omega_m \)     | 0.3054 ± 0.0061     | 0.3052 ± 0.0041     | 0.3052 ± 0.0025     |
| \( H_0 \)          | 67.99 ± 0.47        | 68.00 ± 0.30        | 68.00 ± 0.16        |
| \( \sum m_\nu \)   | < 0.148             | < 0.142             | < 0.137             |

FIG. 1: The constraint results for the NH case of the neutrino mass ordering. Marginalized one- and two-dimensional posterior distributions of \( \sum m_\nu \), \( \Omega_m \), and \( H_0 \) using data0, data1, and data2. Here, data0 denotes CMB+BAO+SN+H0, data1 denotes CMB+BAO+SN+H0+SKA1, and data2 denotes CMB+BAO+SN+H0+SKA2. Note that \( \sum m_\nu \) is in units of eV and \( H_0 \) is in units of km s\(^{-1}\) Mpc\(^{-1}\).

can play in the cosmological parameter estimation in a cosmological model involving massive neutrinos. For the current observations, we use the Planck 2015 CMB data, the BAO data, the SN data (Pantheon compilation), and the \( H_0 \) measurement. We use three data combinations, CMB+BAO+SN+H0, CMB+BAO+SN+H0+SKA1, and CMB+BAO+SN+H0+SKA2, to perform constraints, and to further make a comparison. We consider three mass ordering cases for massive neutrinos, i.e., the NH, IH, and DH cases.
TABLE II: The constraint results for the IH case of the neutrino mass ordering. Here, data0 denotes CMB+BAO+SN+$H_0$, data1 denotes CMB+BAO+SN+$H_0$+SKA1, and data2 denotes CMB+BAO+SN+$H_0$+SKA2. Note that $\sum m_\nu$ is in units of eV and $H_0$ is in units of km s$^{-1}$ Mpc$^{-1}$.

|                | data0                      | data1                      | data2                      |
|----------------|----------------------------|----------------------------|----------------------------|
| $\Omega_b h^2$ | 0.02242 ± 0.00014          | 0.02243 ± 0.00012          | 0.02242 ± 0.00011          |
| $\Omega_c h^2$ | 0.1174 ± 0.0010            | 0.11740 ± 0.00081          | 0.11743 ± 0.00058          |
| $100\theta_{MC}$ | 1.04103 ± 0.00029  | 1.04103 ± 0.00028          | 1.04102 ± 0.00026          |
| $\tau$         | 0.094 ± 0.017              | 0.094 ± 0.016              | 0.094 ± 0.016              |
| $\ln(10^{10} A_s)$ | 3.118 ± 0.032   | 3.118 ± 0.032              | 3.118 ± 0.032              |
| $n_s$          | 0.9707 ± 0.0041            | 0.9708 ± 0.0037            | 0.9707 ± 0.0034            |
| $\Omega_m$     | 0.3075 ± 0.0061            | 0.3072 ± 0.0041            | 0.3073 ± 0.0025            |
| $H_0$          | 67.78 ± 0.46               | 67.80 ± 0.30               | 67.80 ± 0.16               |
| $\sum m_\nu$   | < 0.182                   | < 0.176                   | < 0.170                   |

FIG. 2: The constraint results for the IH case of the neutrino mass ordering. Marginalized one- and two-dimensional posterior distributions of $\sum m_\nu$, $\Omega_m$, and $H_0$ using data0, data1, and data2. Here, data0 denotes CMB+BAO+SN+$H_0$, data1 denotes CMB+BAO+SN+$H_0$+SKA1, and data2 denotes CMB+BAO+SN+$H_0$+SKA2. Note that $\sum m_\nu$ is in units of eV and $H_0$ is in units of km s$^{-1}$ Mpc$^{-1}$.

We find that the SKA observation can significantly improve the constraints on $\Omega_m$ and $H_0$. Compared to the current observation, the SKA1 data can improve the constraints on $\Omega_m$ by about 33%, and on $H_0$ by about 36%; the SKA2 data can improve the constraints on $\Omega_m$ by about 58%, and on $H_0$ by about 66%.

We find that the SKA observation can also slightly improve the constraints on $\sum m_\nu$. Compared to the current observation, the SKA1 data can improve the constraints on $\sum m_\nu$ by about 4%, 3%, and 10%, for the NH, IH,
TABLE III: The constraint results for the DH case of the neutrino mass ordering. Here, \( \text{data0} \) denotes CMB+BAO+SN+\( H_0 \), \( \text{data1} \) denotes CMB+BAO+SN+\( H_0 \)+SKA1, and \( \text{data2} \) denotes CMB+BAO+SN+\( H_0 \)+SKA2. Note that \( \sum m_\nu \) is in units of eV and \( H_0 \) is in units of km s\(^{-1}\) Mpc\(^{-1}\).

| \( \Omega_b h^2 \) | \( \Omega_c h^2 \) | 1000\( \theta_{MC} \) | \( \tau \) | \( \ln(10^{10} A_s) \) | \( \Omega_m \) | \( H_0 \) | \( \sum m_\nu \) |
|----------------|----------------|----------------|---------|----------------|---------|---------|---------|
| 0.02238 ± 0.00014 | 0.1182 ± 0.0010 | 1.04099 ± 0.00030 | 0.086 ± 0.017 | 3.104 ± 0.033 | 0.9688 ± 0.0040 | 0.3029 ± 0.0060 | < 0.109 |
| 0.02238 ± 0.00012 | 0.1181 ± 0.00087 | 1.04069 ± 0.00028 | 0.086 ± 0.016 | 3.104 ± 0.032 | 0.9687 ± 0.0037 | 0.3025 ± 0.0040 | < 0.0983 |
| 0.02238 ± 0.00011 | 0.1182 ± 0.00076 | 1.04099 ± 0.00027 | 0.086 ± 0.016 | 3.104 ± 0.032 | 0.9687 ± 0.0035 | 0.3025 ± 0.0024 | < 0.0911 |

FIG. 3: The constraint results for the DH case of the neutrino mass ordering. Marginalized one- and two-dimensional posterior distributions of \( \sum m_\nu \), \( \Omega_m \), and \( H_0 \) using \( \text{data0} \), \( \text{data1} \), and \( \text{data2} \). Here, \( \text{data0} \) denotes CMB+BAO+SN+\( H_0 \), \( \text{data1} \) denotes CMB+BAO+SN+\( H_0 \)+SKA1, and \( \text{data2} \) denotes CMB+BAO+SN+\( H_0 \)+SKA2. Note that \( \sum m_\nu \) is in units of eV and \( H_0 \) is in units of km s\(^{-1}\) Mpc\(^{-1}\).

and DH cases, respectively; the SKA2 data can improve the constraints on \( \sum m_\nu \) by about 7%, 7%, and 16%, for the NH, IH, and DH cases, respectively.

It is expected that in the future the SKA observation, combined with the future highly accurate optical survey projects, such as LSST, Euclid, and WFIRST, as well as the gravitational-wave standard siren observations from ground-based and space-based detectors, would greatly promote the development of cosmology.
Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grants Nos. 11875102, 11835009, 11690021, and 11522540) and the National Program for Support of Top-Notch Young Professionals.

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