Physics Letters B 782 (2018) 87–93

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Impacts of gravitational-wave standard siren observation of the Einstein Telescope on weighing neutrinos in cosmology

Ling-Feng Wang [a], Xuan-Neng Zhang [a], Jing-Fei Zhang [a], Xin Zhang [a,b,*]

[a] Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China
[b] Center for High Energy Physics, Peking University, Beijing 100080, China

ARTICLE INFO

Article history:
Received 8 March 2018
Received in revised form 5 May 2018
Accepted 9 May 2018
Available online xxxx
Editor: H. Peiris

ABSTRACT

We investigate the impacts of the gravitational-wave (GW) standard siren observation of the Einstein Telescope (ET) on constraining the total neutrino mass. We simulate 1000 GW events that would be observed by the ET in its 10-year observation by taking the standard ΛCDM cosmology as a fiducial model. We combine the simulated GW data with other cosmological observations including cosmic microwave background (CMB), baryon acoustic oscillations (BAO), and type Ia supernovae (SN). We consider three mass hierarchy cases for the neutrino mass, i.e., normal hierarchy (NH), inverted hierarchy (IH), and degenerate hierarchy (DH). Using Planck+BAO+SN, we obtain $\sum m_\nu < 0.175$ eV for the NH case, $\sum m_\nu < 0.200$ eV for the IH case, and $\sum m_\nu < 0.136$ eV for the DH case. After considering the GW data, i.e., using Planck+BAO+SN+GW, the constraint results become $\sum m_\nu < 0.151$ eV for the NH case, $\sum m_\nu < 0.185$ eV for the IH case, and $\sum m_\nu < 0.122$ eV for the DH case. We find that the GW data can help reduce the upper limits of $\sum m_\nu$ by 13.7%, 7.5%, and 10.3% for the NH, IH, and DH cases, respectively. In addition, we find that the GW data can also help break the degeneracies between $\sum m_\nu$ and other parameters. We show that the GW data of the ET could greatly improve the constraint accuracies of cosmological parameters.

1. Introduction

On 17 August 2017, the signal of a gravitational wave (GW) produced by the merger of a binary neutron-star system (BNS) was detected for the first time [1], and the electromagnetic (EM) signals generated by the same transient source were also observed subsequently, which indicates that the age of gravitational-wave multi-messenger astronomy is coming. The measurement of GWs from the merger of a binary compact-object system involves the information of absolute luminosity distance of the transient source [2], and thus if we can simultaneously accurately measure the GW and EM signals from the same merger event of a BNS or a binary system consisting of a neutron star (NS) and a black hole (BH), then we are able to establish a true luminosity distance–redshift (d_L–z) relation. Therefore, the GW observations can serve as a cosmic "standard siren", which can be developed to be a new cosmological probe if we can accurately observe a large number of merger events of this class.

The current mainstream cosmological probes include the measurements of cosmic microwave background (CMB) anisotropies (temperature and polarization), baryon acoustic oscillations (BAO), type Ia supernovae (SNIa), and the Hubble constant, etc. In addition, there are also some observations for the growth history of large-scale structure (LSS), such as the shear measurement of the weak gravitational lensing, the galaxy clusters number counts in light of Sunyaev–Zeldovich (SZ) effect, and the CMB lensing measurement, etc. When using these observational data to make cosmological parameter estimation, some problems occur including mainly: (i) there are degeneracies between some parameters, and in some of which the correlations are rather strong, and (ii) there are apparent tensions between some observations. The GW standard siren observations have some peculiar advantages in breaking the parameter degeneracies, owing to the fact that the GW observations can directly measure the true luminosity distances, but the SNIa observations actually can only measure the ratios of luminosity distances at different redshifts, but not the true luminosity distances. In addition, compared to the standard candle provided by the SNIa observations [3–5], which needs to cross-calibrate the distance indicators on different scales, the GW observations allow us to directly measure the luminosity distances up to higher red-

* Corresponding author at: Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China.
E-mail address: zhangxin@mail.neu.edu.cn (X. Zhang).

https://doi.org/10.1016/j.physletb.2018.05.027
0370-2693/

shifts [6]. To obtain the information of redshifts, one needs to detect the EM counterparts of the GW sources. In fact, there are some forthcoming large facility observation programs, such as Large Synoptic Survey Telescope (LSST) [7], Square Kilometer Array (SKA) [8], and Extremely Large Telescope (ELT) [9], which can detect the EM counterparts by optically identifying the host galaxies. In this way, in the near future, the d_L–z relation would be obtained by the GW standard siren measurements, and we could use this powerful tool to explore the expansion history of the universe.

Recently, the related issues have been discussed by some authors [10–19] (see also Ref. [20] for a recent review). For example, in Ref. [10], Cai and Yang estimated the ability of using GW data to constrain cosmological parameters. They considered to use the GW detector under planning, the Einstein Telescope (ET), to simulate the GW data, which is a third-generation ground-based detector of GWs [21]. ET is ten times more sensitive than the current advanced ground-based detectors and it covers the frequency range of $1 - 10^4$ Hz. According to their results [10], the errors of cosmological parameters can be constrained to be $\Delta h \sim 5 \times 10^{-3}$ and $\Delta\Omega_m \sim 0.02$ when using 1000 GW events, whose sensitivity is comparable to that of the Planck data [22]. From their study, we can see that the GW data can indeed be used to improve the constraint accuracies of parameters. In Ref. [23], we can see how the parameter degeneracies are broken by the GW observations in an efficient way. In this work, we investigate the issue of measuring the neutrino mass in light of cosmological observations and we will discuss what role the GW observations of the ET will play as a new cosmological probe in this study.

Since the phenomenon of neutrino oscillation was discovered, which proved that the neutrino masses are not zero [24], the determination of neutrino masses has been an important issue in the field of particle physics. Due to the fact that neutrino oscillation experiments are only sensitive to the squared mass differences between the neutrino mass eigenstates, it is a great challenge to determine the absolute masses of neutrinos by particle physics experiments. Although the solar and atmospheric neutrino oscillation experiments can give two squared mass differences between the mass eigenstates: $\Delta m_{21}^2 \simeq 7.5 \times 10^{-5}$ eV^2 and $|\Delta m_{32}^2| \simeq 2.5 \times 10^{-3}$ eV^2, we cannot determine whether the third neutrino is heaviest or lightest. Therefore, these measurements can only give two possible mass orders, i.e., the normal hierarchy (NH) with $m_1 < m_2 \ll m_3$ and the inverted hierarchy (IH) with $m_3 \ll m_1 < m_2$. If the total mass of neutrinos ($\sum m_\nu$) can be measured, then the absolute masses of neutrinos could be solved by combining the total mass and the two squared mass differences.

Massive neutrinos play an significant role in the evolution of the universe, and thus they leave distinct signatures on CMB and LSS at different epochs of the evolution of the universe. These signatures can actually be extracted from the cosmological observations, from which the total mass of neutrinos can be effectively constrained. In recent years, the combinations of various cosmological observations have been providing more and more tight constraint limits for the total mass of neutrinos. For the latest progresses on this aspect, see e.g. Refs. [25–43].

In fact, in a recent paper [44], the constraints on the total neutrino mass have been discussed by considering the inclusion of the actual observation of GW and EM emission produced by the merger of BNS, GW170817. In Ref. [44], the authors considered a 12-parameter extended cosmological model that contains the dark-energy equation-of-state parameter w_0 and w_a, the spatial curvature Ω_k, the total neutrino mass $\sum m_\nu$, the effective number of relativistic species $N_{\rm eff}$, and the running of the scalar spectral index $dn_s/d\ln k$, besides the 6 base parameters, and they made a comparison for the constraint results of Planck and Planck+GW170817. For such a 12-parameter model, using only Planck data gives $\sum m_\nu < 1.11$ eV, and the combination of Planck+GW170817 gives $\sum m_\nu < 0.77$ eV, showing that the inclusion of GW170817 leads to an about 30% improvement for the upper limit of $\sum m_\nu$, compared to the result obtained from the Planck data alone. However, it is clearly known that the 12-parameter model actually cannot be well constrained by the current observations. In the present work, we wish to scrutinize the standard cosmology, i.e., a 7-parameter Λ cold dark matter (ΛCDM) model that contains the 6 base parameters plus $\sum m_\nu$. We aim to see how the future GW observations help improve the constraints on the total neutrino mass in a 7-parameter ΛCDM cosmology.

In this study, our main focus is on the ability of the GW observations of ET to constrain the neutrino mass. We follow Ref. [10] to generate the catalogue of GW events, from which we can get the corresponding d_L–z relation. According to the influences of instruments and weak lensing, we can estimate the uncertainty on the measurement of d_L. We simulate 1,000 GW events that could be observed by the ET in its 10-year observation. Then, we combine these simulated GW data with other current observations to constrain the total mass of neutrinos, $\sum m_\nu$, by using the Markov-chain Monte Carlo (MCMC) [45] approach.

The paper is organized as follows. In Sec. 2, we describe the method to generate simulated GW events and get the luminosity distances with the simulated measurement errors. In addition, the fiducial model and the data processing method are also briefly introduced. In Sec. 3, we report the results of this work. In Sec. 4, we make a conclusion for this work.

2. Methods of simulating data and constraining parameters

2.1. Method of simulating data

The first step for generating GW data is to simulate the redshift distribution of the sources. Following Refs. [10,16], the distribution takes the form

$$P(z) \propto \frac{4\pi d_C^2(z) R(z)}{H(z)(1+z)}, \tag{1}$$

where $d_C(z)$ is the comoving distance at redshift z and $R(z)$ denotes the time evolution of the burst rate and takes the form [10,46,47]

$$R(z) = \begin{cases} 1+2z, & z \le 1, \\ \frac{3}{4}(5-z), & 1 < z < 5, \\ 0, & z \ge 5. \end{cases} \tag{2}$$

According to the prediction of the Advanced LIGO–Virgo network, we take the ratio between BHNS (the binary system of a BH and a NS) and BNS events to be 0.03. For the mass distributions of NS and BH in the simulation, we randomly sample the mass of NS in the interval $[1, 2]$ $M_\odot$ and the mass of BH in the interval $[3, 10]$ $M_\odot$ (here $M_\odot$ is the solar mass), as the same as in Ref. [10].

After the distribution of the sources is known, the second step is to generate the catalogue of the GW sources through the fiducial model, i.e., the ΛCDM model. If we consider a flat Friedmann–Robertson–Walker universe, the Hubble parameter $H(z)$ for the ΛCDM cosmology can be written as

$$H(z)^2 = H_0^2\left[(1-\Omega_m-\Omega_r) + \Omega_m(1+z)^3 + \Omega_r(1+z)^4\right], \tag{3}$$

where Ω_m and Ω_r represent the fractional energy densities of matter and radiation, respectively. In the late universe, Ω_r can be