Constraining the reionization history with CMB and spectroscopic observations

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We investigate the constraints on the reionization history of the Universe from a joint analysis of the cosmic microwave background and neutral hydrogen fraction data. The tanh parameterization and principal component analysis methods are applied to the reionization history respectively. The commonly used tanh parameterization is over simplistic when the neutral hydrogen fraction data is taken into account. Using the principal component method, the reconstructed reionization history is consistent with the neutral hydrogen fraction data. With PCA method, we reconstruct the neutral hydrogen fraction at $z = 9.75$ as $x_{\text{HI}} = 0.69^{+0.30}_{-0.20}$ for $6 < z < 20$ range reconstruction, and $x_{\text{HI}} = 0.76^{+0.22}_{-0.20}$ for $6 < z < 30$ range reconstruction. These results suggest that the Universe began to reionize at redshift no later than $z = 10$ at 95% confidence level.

1. INTRODUCTION

The observation of the cosmic microwave background (CMB) radiation has provided the state-of-the-art measurements on cosmological parameters. The measurements from Wilkinson Microwave Anisotropy Probe (WMAP) and Planck satellite have pinned down the precision of the reionization optical depth $\tau$ to unprecedented level, which essentially constrains the reionization process. There are two main effects of the reionization history on the CMB angular power spectra. The first effect is the photon attenuation effect, i.e. the ionized electron re-scatters the CMB photons which leads to a suppression of the acoustic peaks in the CMB angular power spectra. So the amplitude of the $C_{\ell}^{TT}$ is proportional to $A_\tau e^{-2\tau}$. Given the same ionized hydrogen fraction, it contributes more to the optical depth to the extent that the reionization process began earlier and lasted longer. The second effect is the reionization bump in the $C_{\ell}^{TE}$ and $C_{\ell}^{EE}$ power spectra, as the polarization is generated due to the quadrupole seen by electrons after reionization. The angular position of the bump is proportional to the square root of the redshift at which the reionization occurs, while the amplitude of $C_{\ell}^{TE}$ and $C_{\ell}^{EE}$ are proportional to $\tau$ and $\tau^2$ respectively \cite{1} [2]. Therefore, measurements of the large-scale polarization angular power spectra can strongly constrain the reionization history \cite{3} [4]. The 9-year results of WMAP give a estimate of optical depth $\tau = 0.089^{+0.014}_{-0.014}$ \cite{2}. In the Planck 2015 analysis based on the temperature power spectra and low-$\ell$ polarization, the optical depth is found to be $\tau = 0.078 \pm 0.019$ \cite{3}. Using the Planck-HFI E-mode polarization and temperature data, the Planck lollipop likelihood gives $\tau = 0.058 \pm 0.012$ \cite{4}.

However, since the value of $\tau$ is an integral of free electron density, the detailed process of reionization is still a mystery although we have fairly precise measurement of $\tau$. A step-like instantaneous reionization model is proposed by Lewis \cite{5} and used in the Planck 2013 and 2015 cosmological results. Some variants of such a phenomenological model were considered to constrain the reionization history \cite{7} [8] [9]. A semi-analytical reionization model is proposed based on the relevant physics governing these processes, such as the inhomogeneous inter-galactic medium (IGM) density distribution, three different sources of ionizing photons, and radiative feedback \cite{11}.

All of the above models are built based on our current knowledge of the reionization. If the ansatz of the reionization model is not accurate, the evaluated values of cosmological parameters may be biased. Therefore, it is important and necessary to constrain it in a relatively model-independent way. Hu & Holder \cite{12} proposed the principal component analysis (PCA) of the reionization history to quantify the information contained in the large-scale E-mode polarization. This approach has been applied to both the simulated and real CMB data \cite{12} [13]. In our previous work, we applied such a PCA method for the reionization history to Planck 2015 data and found that the Universe is not completely reionized at redshift $z \gtrsim 8.5$ at 95% confidence level (C.L.) \cite{13}. The PCA method has been used to investigate the impacts of the reionization model on the estimates of cosmological parameters \cite{15} [20]. The estimated values of cosmological parameters such as the amplitude of the power spectrum of primordial scalar perturbations and neutrino masses are sensitive to the reionization history.

In addition, the evolution of the inter-galactic Lyman-alpha (Lyα) opacity measured in the spectra of quasars...
can provide valuable information on the reionization history [21]. The recent measurements imply that the reionization of the IGM was nearly completed at redshift $z \approx 6$ [22]. The detection of complete Gunn-Peterson (GP) absorption troughs in the spectra of quasars at $z > 6$ suggests that the neutral fraction of the IGM increases rapidly with redshift [23][27]. The rapid decline in the space density of Lyα emitting galaxies in the region $z = 6 - 8$ implies a low-redshift reionization process [28]. But probing the high-redshift reionization history directly is still a big challenge.

In this paper, we apply two different methods to constrain the reionization history: the widely-used tanh parameterization method proposed by Lewis [8] and the PCA approach proposed by Hu & Holder [4]. Using the Planck 2015 data combined with spectroscopic observations, we investigate the constraints on the reionization history and cosmological parameters.

This paper is organized as follows. In Sect. 2, we describe the tanh parameterization and PCA methods respectively. In Sect. 3 we list the current measurements of the neutral hydrogen fraction. In Sect. 4 we use the Planck 2015 data and the neutral hydrogen fraction data to put constraints on the reionization history. Sect. 5 is devoted to discussions and conclusions.

2. METHODS

Throughout our analysis, we adopt a spatially-flat $\Lambda$CDM model described by a set of cosmological parameters \{$\Omega_b h^2, \Omega_c h^2, \theta_{MC}, A_s, n_s$\}, where $\Omega_b h^2$ and $\Omega_c h^2$ are the physical baryon and cold dark matter densities relative to the critical density, $\theta_{MC}$ is an approximation to the ratio of the sound horizon to the angular diameter distance at the photon decoupling, $A_s$ and $n_s$ are the amplitude and spectral index of the primordial curvature perturbations at the pivot scale $k_0 = 0.05$ Mpc$^{-1}$.

2.1. “tanh” function parametrization

The most widely-used parameterization is a step-like transition of the ionized hydrogen fraction $x_e$, which is parameterized by the median redshift $z_{re}$ and duration $\Delta z$ of the reionization. A tanh function is utilized to fit the reionization history [8]:

$$x_{e}^\text{eff}(z) = f \ast x_e(z) = f \left[ 1 + \tanh \left( \frac{y(z_{re}) - y}{\Delta y} \right) \right],$$  

(1)

where $y = (1+z)^{3/2}$ and $\Delta y = 3/2(1+z)^{1/2}\Delta z$. Since the first ionization energy (24.6 MeV) of helium is not much higher than hydrogen (13.6 MeV), it’s usually assumed that helium first reionizes in the same way as hydrogen. Ignoring the residual electron density from recombination, the efficient reionization fraction is $x_{e}^\text{eff} = f \ast x_e$. The factor $x_e$ is the ratio between number densities of ionized hydrogen to the total hydrogen, and $f \ast x_e$ is the number density ratio between free electrons and total hydrogen. Therefore the factor $f$ is $f = 1 + n_{He}/n_H$, where $n_{He}$ and $n_H$ are the number densities of helium and hydrogen respectively. The typical value of $f$ is roughly 1.08 because the helium mass fraction is around 0.24. Additionally, we assume that hydrogen is fully ionized before the second helium ionization (corresponding to 54.4 MeV) and the helium second reionizes in the same form as Eq. (1) with $f = n_{He}/n_H$, $z_{re} = 3.5$ and $\Delta z = 0.5$. The total efficient reionization fraction is the sum of contributions from hydrogen and helium.

Although spectroscopic observations have given a hint that the IGM ionization is similar to a phase transition, it is argued that the hydrogen in the IGM could have been reionized twice [29][30]. The simple parameterization described by Eq. (1) may bias the reionization history. To eliminate the bias, we can define discrete ionization fractions in a series of small redshift bins, which correlate with each other in practice.

2.2. Principal component analysis (PCA)

The PCA method converts a set of correlated variables into a set of linear uncorrelated variables by an orthogonal transformation. Most information is encoded in the principal components, which are picked out according to their corresponding eigenvalues. Following Refs. [14][31], we consider a binned ionization fraction $x_e(z_i)$, $i \in \{1, 2, \ldots, N_z\}$, with redshift bins of width $\delta z = 0.25$. We take $z_{\text{min}} = 6$ and $z_{\text{max}} = 30$ with the definition $z_1 = z_{\text{min}} + \delta z$ and $z_{N_z} = z_{\text{max}} - \delta z$ so that $N_z + 1 = (z_{\text{max}} - z_{\text{min}})/\delta z$. The principal components of $x_e(z_i)$ are the eigenfunctions of the following Fisher matrix $F_{ij}$,

$$F_{ij} = \sum_{\ell=2}^{\ell_{\text{max}}} \left( \ell + \frac{1}{2} \right) \frac{\partial \ln C_{EE}^{\ell}(\ell)}{\partial x_e(z_i)} \frac{\partial \ln C_{EE}^{\ell}(\ell)}{\partial x_e(z_j)},$$

(2)

which describes the dependence of the polarization spectrum $C_{EE}^{\ell}$ on the ionization fraction $x_e(z_i)$. The Fisher matrix $F_{ij}$ can be decomposed as

$$F_{ij} = (N_z + 1)^{-2} \sum_{\mu=1}^{N_\nu} S_{\mu}(z_i)\sigma_{\mu}^{-2} S_{\mu}(z_j),$$

(3)

where $\sigma_{\mu}^2$ are the inverse eigenvalues and $S_{\mu}(z)$ are the eigenfunctions that satisfy the orthogonality and completeness relations

$$\int_{z_{\text{min}}}^{z_{\text{max}}} dz S_{\mu}(z) S_{\nu}(z) = (z_{\text{max}} - z_{\text{min}})\delta_{\mu\nu},$$

(4)

$$\sum_{\mu=1}^{N_\nu} S_{\mu}(z_i) S_{\mu}(z_j) = (N_z + 1)\delta_{ij}.$$  

(5)
Then, the reionization history is represented in terms of the eigenfunctions as
\[ x_e(z) = x_{e}^{\text{fid}}(z) + \sum_{\mu} m_{\mu} S_{\mu}(z). \] (6)

The $x_e^{\text{fid}}$ is the fiducial value of hydrogen reionization fraction, we set $x_e^{\text{fid}} = 0.1$ in our fiducial models, and $m_{\mu}$ are the amplitudes of principal components. Hu et al. [31] argued that $x_e(z)$ is not necessarily bounded in between 0 and 1 at all redshifts and derived a necessary but not sufficient condition for physicality. Nevertheless, in this paper, we simply assume that the selected principal components reconstruct the reionization history sufficiently well so that $x_e(z) \in [0, 1]$. The reason is that we combine the neutral hydrogen fraction data listed in Sect. 3 with CMB to fit the cosmological parameters and our reionization model has no impacts on the neutral hydrogen fraction data (Physically, $x_{\text{HI}} \in [0, 1]$, defined in Sect. 3).

In what follows, “Instant” denotes the parameterization for the reionization history (Eq. (1)) and “PCA” denotes the PCA method (Eq. (6)). The former is described by the median redshift $z_{\text{m}}$ and reionization duration $\Delta z$, while the latter is described by five parameters $m_{\mu}$, $\mu = 1, ..., 5$. In our analysis we use the publicly available CosmoMC package to explore the parameter space by means of Markov Chains Monte Carlo (MCMC) technique [33]. We modify the Boltzmann CAMB code [33] to appropriately incorporate the reionization history. The reionization parameters and other cosmological parameters are evaluated by performing global fitting in Sect. 4.

3. DATA

We list current constraints on the volume-averaged neutral hydrogen fraction in Table 1. Table 1 summarizes the constraints on the neutral hydrogen fraction or free electron fraction over the redshift range $z = 5$–8 which were derived from 2006 to 2017. These constraints can be summarized into four categories.

- Quasar/GRB Lyα absorption line systems [22] [35] [39] [53].

1. Fan et al. [22] used the GP optical depth and HII region size measurements around luminous quasars to measure that the reionization process finishes between $z = 5.9$ and $z = 6.5$.
2. Gallerani et al. [35] and McGreer et al. [36] used quasar-stellar object (QSO) dark gap statistics and measured the fraction of neutral hydrogen to be very low at redshift $z \sim 5.6$.
3. Schroeder et al. [37] used the GP damping wing of the spectra of three quasars (SDSS J1148+5251 ($z = 6.4189$), J1030+0524 ($z = 6.308$) and J1623+3112 ($z = 6.247$)), to constrain the neutral hydrogen fraction, $x_{\text{HI}} = 1 - x_e$, and found the lower limit of $x_{\text{HI}}$ at $z \sim 6.2$–6.4.

4. Totani et al. [38] used Lyα damping wing of GRB 050914 ($z = 6.3$) spectra to obtain the column density of HI, and derived the upper limit of $x_{\text{HI}}$ to be $x_{\text{HI}} < 0.17$ and 0.60 at 68% and 95% C.L. respectively.

5. Gallerani et al. [39] used the dark portions (gaps) in GRB 050904 absorption spectra to derive the neutral hydrogen fraction $x_{\text{HI}} = (6.4 \pm 0.3) \times 10^{-5}$ at $z = 6.29$.

6. Mortlock et al. [53] reported a quasar (ULAS J112001.48+064124.3) at $z = 7.085$, and used the Lyα damping wing profile to obtain that the neutral fraction of the intergalactic medium in front of ULAS J1120+0641 exceeded 0.1. Using the same quasar, Greig et al. [54] accounted for uncertainties of the intrinsic QSO emission spectrum and the distribution of cosmic HI patches during the epoch of reionization (EoR) from simulation, and reported that the EoR is not yet complete by $z = 7.1$, with the volume-weighted IGM neutral fraction constrained to be $x_{\text{HI}} = 0.40 \pm 0.19 \pm 0.32$ at 1σ and 2σ C.L.

- The number density and clustering of Lyα emitting galaxies [10] [13] [45] [47]. This type of observations is to use Lyα emitting galaxies to measure the Lyα luminosity functions and then by comparing the Lyα luminosity function measurements with reionization models, one can derive the neutral hydrogen fraction of the intergalactic medium $x_{\text{HI}}$. Such studies give the measurement of $x_{\text{HI}}$ in the redshift range of 6.5 to 8.0.

- Gravitational clustering of Lyα emitters [14] [52]. As shown in [44], reionization increases the measured clustering of emitters, which can be computed observationally. By comparing the observational clustering of emitters with the results using radiative transfer simulations, McQuinn et al. [44] and Sobacchi et al. [52] obtained the upper limit of $x_{\text{HI}} \lesssim 0.5$ at $z = 6.8$ and 7.0 respectively.

- Prevalence of Lyα emission in galaxies at redshift 6–8 [49] [51] [55]. This class of observation is to assume that Lyα emission is prevalent in star-forming galaxies at $z \sim 6.5$–8, which is a simple extrapolation of the observed prevalence at $z \sim 4$–6. Then any departure from these trends is due to an increasingly neutral IGM at $z \sim 7$–8. Therefore one can use this technique to quantify the filling factor of ionized hydrogen ($Q_{\text{HI}}$) at $z \sim 6.5$–8. Then one can convert this factor to IGM fractional neutral hydrogen density $x_{\text{HI}}$.

As marked in the last column of Table 1 we divide the $x_{\text{HI}}$ data into different datasets. Only the data with
TABLE I: The current constraints on the neutral hydrogen fraction $x_{\text{HI}}$ from different observations, ranging from low to high redshifts. “LAEs” means Lyα emitters, i.e. Lyα emitting galaxies.

| Redshift $z$ | $x_{\text{HI}}$ data | C.L. | Technique | Observation | Ref. Year | Dataset |
|-------------|----------------------|------|-----------|-------------|-----------|---------|
| 5.03        | $x_{\text{HI}} = (5.5 \times 10^{-5}) + 1.42 \times 10^{-5}$ | 1σ   | GP optical depth of QSOs | SDSS       | 2006      | full    |
| 5.25        | $x_{\text{HI}} = (6.7 \times 10^{-5}) - 2.44 \times 10^{-5}$ | 1σ   | QSO dark gap statistics | SDSS       | 2008      | full    |
| 5.65        | $x_{\text{HI}} = (4.3 \times 10^{-5}) - 2.8 \times 10^{-5}$ | 1σ   | Counts of dark Lyman-alpha pixels | Keck II telescopes | 2015      | full    |
| 5.37        | $x_{\text{HI}} < 0.04 + 0.05$ | 1σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.06 + 0.05$ | 1σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.11 + 0.11$ | 2σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.14 + 0.14$ | 2σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.04 + 0.05$ | 1σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.06 + 0.05$ | 1σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.11 + 0.11$ | 2σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |
| 5.37        | $x_{\text{HI}} < 0.14 + 0.14$ | 2σ   | QSO damping wing J1623+3112 | SDSS       | 2013      | full/ext |

* Converted from ionized fraction. This data is derived from numerical simulation rather than observation.
FIG. 1: The state-of-the-art measurement on $x_{\text{HI}}(z)$, taken from Table I. The black and red dashed lines are two examples of the “tanh” model which cannot fit the data very well.

C.L. is used in our analysis, while the others are plotted in figures for comparison. The error bar is conservatively estimated if it is not given explicitly. For example, since a lower limit is given in Ref. [48] we assume that the mean value is $x_{\text{HI}} = 1$, and the mean value is $x_{\text{HI}} = 0$ for an upper limit given in Ref. [52]. Because the limit derived in Ref. [39] is much tighter than the others, we do not use this data in our analysis. In the “PCA” model, we assume that the reionized fraction $x_e$ is exact unity at $z \leq 6$. The dataset of $x_{\text{HI}}$ used to constrain the reionization history in the “PCA” model is denoted by “ext” in Table I. All data given with confidence level can be used in the “instant” model, which is denoted by “full”. Based on the common “instant” reionization assumption, we obtain a “tanh” model of $x_{\text{HI}}$ increasing with $z$.

4. RESULTS

In our analysis, besides the neutral hydrogen fraction data, we use Planck 2015 likelihood code and data, including the Planck low-$\ell$ likelihood at multipoles $2 \leq \ell \leq 29$ and high-$\ell$ PlikTT likelihood at multipoles $\ell \geq 30$ based on pseudo-$C_\ell$ estimators. The low-$\ell$ likelihood uses the foreground-cleaned LFI 70 GHz polarization maps together with the temperature map obtained from the Planck 30 to 353 GHz channels by the Commander component separation algorithm over $94\%$ of the sky. The high-$\ell$ PlikTT likelihood uses 100 GHz, 143 GHz, and 217 GHz cross-half-mission temperature spectra, avoiding the Galactic plane as well as the brightest point sources and the regions where the CO emission is the strongest. Hereafter, “Planck 2015” denotes the combination of the PlikTT temperature likelihood and the low-$\ell$ temperature-polarization likelihood.

We constrain the “instant” model of the EoR with Planck 2015 data and the “full” $x_{\text{HI}}$ data. We reconstruct the EoR during the redshift interval $5 < z < 20$ in Fig. 2. The transition occurs at the redshift ranging from $z \sim 8$ to 14. The reconstructed figure is not fully consistent with the $x_{\text{HI}}$ data. Meanwhile, in Fig. 3 we see that the posterior distributions of $\tau$, $z_{\tau e}$ and $\Delta z$ are bimodal. This means the “instant” model may bias the EoR. The 2D contours derived from Planck 2015 + “ext” are also plotted in Fig. 3. There is no $x_{\text{HI}}$ data at redshift $z < 6$ in the “ext” dataset, which means we remove the limit that the Universe is fully ionized at $z \sim 6$ in this model. But the estimated median redshift and duration of reionization are $z_{\tau e} \sim 8$ and $\Delta z \gtrsim 8$. This gives an unphysical result that the Universe is still not fully ionized today.

We constrain the “PCA” model of EoR with Planck 2015 + “ext” data, with a reshift interval of $6 < z < 30$. As plotted in Fig. 4, the reconstructed $x_{\text{HI}}(z)$ function covers the $x_{\text{HI}}$ data. The error bar of the optical depth
\[ \Delta z_{\text{re}} \]

\[ \tau \]

\[ x_{\text{e}} \]

\[ z \]

\[ A_{\text{s}} \]

\[ \sigma_8 \]

\[ A_{\text{s}} e^{-2\tau} \]

\[ x_{\text{H}} \]

\[ \Delta \tau \]

\[ \text{Planck 2015 + "ext"} \]

\[ \text{Planck 2015 + "full"} \]

\[ m_{\mu} \]

\[ 6 < z < 20 \]

\[ \text{PCA} \]

\[ x_{\text{e}} \] is smaller than in the “instant” model as shown in Table I. Comparing the confidence regions derived from Planck 2015 + “ext” data (blue) and Planck 2015 (gray) in Fig. 4, we see that constraints on \( x_{\text{e}} \) between \( z \sim 6 \) and \( z \sim 10 \) are strengthened with the help of \( x_{\text{H}} \) data. But the additional data does not have significant impacts on the high-redshift EoR.

We also limit the range of reconstruction to be \( 6 < z < 20 \) in the “PCA” model, and obtain that the mean value of \( \tau \) decreases by about 1σ C.L. The reconstructed EoR is shown in Fig. 5. The confidence regions are stretched with the increase of \( z_{\text{end}} \), because \( \tau \) is an integral \( \int x_{\text{e}} n_{\text{H}} \, dt \) and the Planck data are more sensitive to \( \tau \) than the detailed reionization process [7].

Table II summarizes the constraints on the EoR and other cosmological parameters from the Planck 2015 and \( x_{\text{H}} \) data. Bounds on parameters are nearly unchanged between different models, except the parameters of detailed reionization, the optical depth \( \tau \), the degenerated parameter \( A_{\text{s}} \) and the rms matter fluctuations today in linear theory \( \sigma_8 \). The amplitude of primordial spectrum of scalar perturbations \( A_{\text{s}} \) degenerates with optical depth \( \tau \) in the form \( A_{\text{s}} e^{-2\tau} \) on small scale [56], which means that a large \( \tau \) leads to a large \( A_{\text{s}} \) and \( \sigma_8 \). In the “PCA” model with a redshift interval of \( 6 < z < 30 \), the marginalized 2D contours (68% and 95% C.L.) and posterior distributions for \( m_{\mu} \) derived from Planck 2015...
+ “ext” and Planck 2015 are shown in Fig. 6. The “ext” $x_{\text{HI}}$ dataset is consistent with Planck 2015 data. Constraints on the amplitudes of principal components $m_\mu$ are significantly improved in the joint analysis of Planck 2015 and “ext” data.

## 5. DISCUSSION & CONCLUSIONS

We have derived constraints on the cosmic reionization history using Planck temperature and low-$\ell$ polarization power spectra together with the neutral hydrogen fraction data in the ΛCDM model. We studied the commonly adopted tanh parameterization and the “PCA” reionization model. It gives unphysical results if we use the combined Planck 2015 data and the “ext” $x_{\text{HI}}$ dataset to constrain the “instant” model. Meanwhile, our results show significant tension after adding the “full” $x_{\text{HI}}$ dataset in the “instant” model. We may infer that the assumed “instant” model is over simplified when the neutral hydrogen fraction data is included.

The “PCA” model is introduced to eliminate the model-dependent bias. In the “PCA” model, the reconstructed $x_{\text{HI}}$ is consistent with $x_{\text{HI}}$ data. Constraints on the low-redshift ($z \lesssim 10$) cosmic reionization history are significantly improved with the help of $x_{\text{HI}}$ data; nevertheless, we find that the low-redshift $x_{\text{HI}}$ data is nearly unhelpful for the high-redshift ($z \gtrsim 10$) constraints on $x_{\text{HI}}$ when combined with Planck 2015 data. From the reconstructed reionization history, both in the case of redshift ranging from 6 to 30 and 6 to 20, we find that the Universe began to re-ionize at redshift no later than $z = 10$ at 95\% C.L. Quantitatively, we derive the constraints on $x_{\text{HI}}$ at $z = 9.75$ for both $6 < z < 20$ and $6 < z < 30$ redshift range reconstruction, and find

$$x_{\text{HI}} (z = 9.75) = 0.69^{+0.30}_{-0.32},$$  \hspace{1cm} (7)$$

for $6 < z < 20$ reconstruction, and

$$x_{\text{HI}} (z = 9.75) = 0.76^{+0.22}_{-0.27},$$  \hspace{1cm} (8)$$

for $6 < z < 30$ reconstruction.

In the “PCA” model, the mean value of reionization optical depth is higher than but consistent with that obtained in the “instant” model. As is shown in Fig. 4, lacking of direct measurements on the reionization at high redshift, constraints on the EoR is strengthened at low redshift $z \lesssim 10$ but remains nearly unchanged at high redshift $z \gtrsim 10$ by means of Planck 2015 and the $x_{\text{HI}}$ data. The high-redshift EoR is only constrained by Planck 2015 data, which puts the upper limits on $x_e$ (the lower limits on $x_{\text{HI}}$). The uncertainty of $x_e$ at high-redshift epoch leads to a higher optical depth. The current data are incapable of constraining the high-redshift ($z \gtrsim 10$) cosmic reionization history model independently. Recently, Bowman et al. \cite{57} reported an absorption profile in the sky-averaged radio spectrum of 21-cm signal detected with the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) low-band instruments. Experiments using interferometric arrays (e.g. LOFAR \cite{58}, MWA \cite{59}, PAPER \cite{60, 61}, HERA \cite{62} and SKA \cite{63}) aimed at measuring the 21-cm signal from neutral hydrogen during the EoR have made progress. These future experiments probes the reionization at high redshift directly will determine the reionization process eventually, which will also break the degeneracy between the reionization optical depth and other cosmological parameters such as the amplitude of the power spectrum of primordial scalar perturbations and neutrino masses \cite{64}.

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FIG. 6: Marginalized 2D contours (68% and 95% C.L.) and posterior distributions for $m_\mu$, derived from Planck 2015 (red) and Planck 2015 + “ext” data (blue).

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| Model         | $\text{Planck 2015 + “ext”}$ | $\text{Planck 2015 + “full”}$ |
|--------------|--------------------------------|-------------------------------|
|              | $\text{“PCA” } 6 < z < 30$  | $\text{“PCA” } 6 < z < 20$  |
| $\Omega_m h^2$ | $0.02233 \pm 0.00023$   | $0.02227 \pm 0.00022$   |
| $\Omega_b h^2$ | $0.1187 \pm 0.0021$     | $0.1192 \pm 0.0021$     |
| $100\Omega_{MC}$ | $1.04102 \pm 0.00047$  | $1.04095 \pm 0.00046$  |
| $\tau$       | $0.110 \pm 0.014$       | $0.098 \pm 0.013$       |
| $n_s$        | $0.9691 \pm 0.0062$     | $0.9674 \pm 0.0060$     |
| $\ln(10^{10} A_s)$ | $3.151 \pm 0.026$    | $3.128 \pm 0.024$    |
| $H_0$ (km s$^{-1}$ Mpc$^{-1}$) | $67.82 \pm 0.93$   | $67.58 \pm 0.94$   |
| $\sigma_8$  | $0.852 \pm 0.012$       | $0.844 \pm 0.011$       |
| Age (Gyr)   | $13.79 \pm 0.037$       | $13.802 \pm 0.037$      |
| $\Omega_{\Lambda}$  | $0.692 \pm 0.013$     | $0.689 \pm 0.013$     |
| $\Omega_m$  | $0.308 \pm 0.013$       | $0.311 \pm 0.013$       |
| $m_1$       | $0.070 \pm 0.039$       | $0.204 \pm 0.073$       |
| $m_2$       | $-0.070 \pm 0.056$      | $-0.124 \pm 0.083$      |
| $m_3$       | $0.098 \pm 0.053$       | $0.120 \pm 0.069$       |
| $m_4$       | $-0.052 \pm 0.041$      | $-0.040 \pm 0.068$      |
| $m_5$       | $0.082 \pm 0.042$       | $0.031 \pm 0.061$       |
| $\Delta z$  | N/A                    | N/A                    |

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