Lyα forest power spectrum as an emerging window into the epoch of reionization and cosmic dawn

Paulo Montero-Camacho,* and Yi Mao†
Department of Astronomy, Tsinghua Center for Astrophysics, Tsinghua University, Beijing 100084, China

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Conventional wisdom was that thermal relics from the epoch of reionization (EOR) would vanish swiftly and hence the usual intergalactic medium (IGM) temperature-density relation would be recovered rapidly. Thus the Lyα forest is one of the primary cosmological probes at the post-reionization epoch. Recently, however, it was shown that the imprint of cosmic reionization can survive to lower redshifts (z ∼ 2) than previously thought. Given the high sensitivities of upcoming Lyα forest surveys, this effect will be a novel broadband systematic that must be tackled for cosmological application. From the astrophysical point of view, however, the imprint of inhomogeneous reionization can shed light on the EOR and cosmic dawn. We utilize a hybrid method — which includes two different simulation codes capable of handling the huge dynamical range — to show the impact of patchy reionization on the Lyα forest and its dependence on different astrophysical scenarios. We found small, but statistically significant, deviations in the 1D Lyα power spectrum that range from a tenth of per cent at z = 2 to a few per cent at z = 4. The deviations in the 3D Lyα power spectrum are considerably large and range from a few per cent at z = 2 up to tens of per cent at z = 4. By exploiting different k-dependence of power spectrum among various astrophysical scenarios, the effect of patchy reionization on the Lyα forest power spectrum can open a new window into the cosmic reionization and possibly even the cosmic dawn.

Key words: methods: numerical — galaxies: intergalactic medium — cosmology: dark ages, reionization, first stars

1 INTRODUCTION
After the surface of last scattering (z_{dec} ∼ 1059) the gas in the Universe became transparent to the cosmic microwave background (CMB) photons. As the Universe expanded and cooled, eventually complex structures, such as stars and galaxies, formed thanks to gravitational instabilities. These objects emit ultraviolet (UV) photons, which ultimately reionize the Universe and heat up the intergalactic medium (IGM) to ∼ 10^4 K (see, e.g., McQuinn 2016; D’Aloisio et al. 2019). After cosmic reionization, which is currently believed to occur halfway around z_{re} = 7.68 (Planck Collaboration et al. 2018), the absorption features of neutral hydrogen regions in quasar spectra, i.e. the Lyα forest, stand as one of the primary probes of the IGM at the redshifts 2 < z < 6.

Among other important probes, the Lyα forest has been used to investigate the H1 and He1 reionization, particularly the end of reionization at z ∼ 6 (Fan et al. 2002, 2006; Cen et al. 2009; McQuinn et al. 2009; Pritchard et al. 2010; Becker et al. 2011; Compostella et al. 2013; Mesinger et al. 2015; Greig et al. 2015; McGreer et al. 2015; Choudhury et al. 2015; Bouwens et al. 2015; Nasir et al. 2016; Oñorbe et al. 2019, 2017; Walther et al. 2019; Wu et al. 2019). The study of the effect of hydrogen and helium reionization in the Lyα forest has traditionally focused on the highest redshifts (e.g. Hui et al. 1997; Trac et al. 2008; Lidz & Malloy 2014), where the IGM has not yet relaxed into the usual temperature-density relation (Furlanetto & Oh 2009) and there are enough sightlines for robust statistics.

At lower redshifts, say 2 < z < 4, conventional wisdom was that thermal relics from the epoch of reionization (EOR) would vanish swiftly and hence the usual IGM temperature-density relation would be recovered rapidly. As such, Lyα forest can probe the cosmological large-scale structure at the post-reionization epoch. However, the sensitivity of the forest to the high redshift IGM can possibly lead to new interesting challenges for current and future Lyα forest sur-

* pmontero@tsinghua.edu.cn (PMC)
† ymao@tsinghua.edu.cn (YM)

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arXiv:2003.10077v1 [astro-ph.CO] 23 Mar 2020
veys. Recent works have shown that the impact of inhomogeneous reionization in the Lyα forest is large at high redshifts (Monsalve et al. 2019; Wu et al. 2019; Oñorbe et al. 2019), and can survive to lower redshifts (z ~ 2) than previously thought and is even comparable to instrumental sensitivities at lower redshifts (Monsalve et al. 2019). This novel low-redshift result is due to the use of high-resolution hydrodynamical simulations capable of resolving the neutral gas below the Jeans mass prior to reionization, and the inclusion of streaming velocities between baryons and dark matter. The effect of inhomogeneous reionization on the Lyα forest power spectrum, as a novel broadband systematic, imposes a serious challenge to the Lyα forest for its promise to do precision cosmology. For this purpose, significant efforts must be made to transform these first studies into holistic precision cosmology programs.

Furthermore, recent developments in the Lyα forest (including large scale fluctuations in its opacity and damping wing studies) and Lyα emission have thrown the status of the redshift of reionization into turmoil (McGreer et al. 2015; Becker et al. 2015; Bosman et al. 2018; Eilers et al. 2018; Hoag et al. 2019; Mason et al. 2019; Keating et al. 2019). Interestingly, a possible emerging consensus points to a later reionization than inferred from the Planck’s optical depth. This is relevant in the context of the imprint of inhomogeneous reionization in the Lyα forest. In particular, if islands of neutral hydrogen are indeed floating around at z < 6 (Kulkarni et al. 2019; Keating et al. 2020), one should expect a stronger impact than that computed in Montero-Camacho et al. (2019) for the later reionization model (their model Λ). In tandem to the theoretical and computational recent discussions, the upcoming observational efforts are coming online. For example, the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2016) will soon start to measure a plethora of Lyα skewers and begin its Lyα science program.

Although the scenario might appear grim, the Lyα forest is not alone. The 21 cm hyperfine transition of hydrogen will ultimately supplement the Lyα forest as yet another rich probe of the EOR and cosmic dawn. Bowman et al. (2018) reported a likely first measurement of the global signal of the 21 cm brightness temperature. Besides, the 21 cm global signal has already been used to rule out some sudden reionization scenarios (Bowman & Rogers 2010; Monsalve et al. 2017; Singh et al. 2018), and to study the astrophysics of high redshift hydrogen gas (Monsalve et al. 2018). Furthermore, as pointed out in Montero-Camacho et al. (2019), in principle the quadrupole of the 21 cm power spectrum can be used to mitigate the effect of patchy reionization in the Lyα forest. For further details in the anticipated fruits of the 21 cm revolution, see, e.g., Mesinger (2019).

From the astrophysical point of view, on the other hand, the imprint of inhomogeneous reionization in the Lyα forest power spectrum can shed light on the EOR and cosmic dawn. This paper has two main goals. First, we shall illustrate how the effect of patchy reionization on the Lyα forest power spectrum, even at low redshift, can become a window into the EOR and cosmic dawn. Secondly, we shall explore the dependence of this effect within the astrophysical parameter space, and investigate different k-dependence of power spectrum which may be exploited to distinguish various astrophysical scenarios. Such a study can help build the connection between the 21 cm cosmology and Lyα forest.

This paper is organized as follows. We outline our simulation strategy for handling the huge dynamical range involved with the effect of inhomogeneous reionization in the Lyα forest and for obtaining the necessary ingredients for our calculations in §2. We describe the key astrophysical parameters used to model the reionization process that were allowed to vary and the different models constructed from them in §3. In §4, we report the impact of inhomogeneous reionization in the Lyα forest, both for the 1D and 3D power spectra, for all our models. We summarize our results and discuss future work in §5.

2 METHODOLOGY

2.1 Simulations

In order to compute the effect of patchy reionization in the Lyα forest, the small-scale physics must be resolved to simulate the behavior of gas, while large box simulations are required to capture the inhomogeneous nature of reionization. Here we follow the approach by Oñorbe et al. (2019); Montero-Camacho et al. (2019) to overcome these obstacles. We split the tasks since the dynamical range is too large with only one simulation. We use the modified GADGET2 code (Springel 2005) from Hirata (2018) to resolve the gas to below the Jeans mass prior to reionization. These small-box simulations have sudden reionization and do not include any prescription to add ionizing sources. From the small-scale simulations, we obtain an optical depth map of how the transmission of the IGM depends on when reionization happens. Meanwhile, we use the 21cmFASTv1.3 code (Mesinger & Furlanetto 2007; Mesinger et al. 2011) with minor modifications from Montero-Camacho et al. (2019) to tackle the patchy nature of reionization on the large scale. We chose this version for simple comparisons with our previous work. The large-scale simulations can extract the effect of patchiness on the matter distribution, specifically the cross-power spectrum of matter and neutral hydrogen fraction, i.e. how matter and bubble spatial structure are correlated. With these ingredients we can calculate the effect of inhomogeneous reionization on the Lyα forest power spectrum.

For small-scale simulations, we describe the key physical ingredients present here, but refer interested readers to Hirata (2018) for a full description of our small box simulations. The simulations used here correspond to the IF simulations from Hirata (2018), which have a box size of 2551 cMpc on each side with the particle number of 2 × (384)3. Furthermore, the dark matter particle mass is 9.72 × 10^4 M⊙ and the gas mass is 1.81 × 10^7 M⊙. We have implemented streaming velocities between baryons and dark matter (Tseliakhovich & Hirata 2010; Givans & Hirata 2020), which modulate the amount of small-scale structure (if baryons are moving faster they might not fall into a specific potential well). In each simulation, reionization happens suddenly at one of the following redshifts: 6, 7, 8, 9, 10, 11 or 12. We ran eight different realizations for each simulation in order to reduce the variance in the inferred transparency of the IGM. The small-scale simulations evolve the neutral gas since recombination up to cosmic reionization. Reionization
is implemented by immediately changing the temperature of all particles to $2 \times 10^4$ K. After reionization the simulation evolves the particles by singly ionized primordial gas physics for H$^+$ and He$^+$. There is no HeII cosmic reionization implemented in the small-scale simulations. We note that this is problematic since the effects of inhomogeneous reionization in the Ly$\alpha$ forest have not relaxed into the usual temperature-density relation by $z \sim 3$ (Montero-Camacho et al. 2019). For large-scale simulations, we use a simulation box size 400 Mpc on each side, larger than the box size of 300 Mpc used in Montero-Camacho et al. (2019), with 256$^3$ (768$^3$) cells for H$\mathrm{I}$ (matter) field. Furthermore, we run four different realizations for each reionization scenario with 21cmFAST in order to reduce the variance in our simulations. As a result, we can compute the sample variance on the mean of our models, and therefore obtain the error associated with the cross-power spectrum.

Throughout this work, we use the cosmological parameters from the full Planck 2015 release (Planck Collaboration et al. 2016), given by $\Omega_m h^2 = 0.14170$, $\Omega_b h^2 = 0.02230$, $\sigma_8 = 0.8159$, $n_s = 0.9667$ and $H_0 = 67.74 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$. 2.2 Ly$\alpha$ forest power spectrum

The formalism for the effect of patchy reionization on the Ly$\alpha$ forest power spectrum is described in detail in §2 of Montero-Camacho et al. (2019). Here we recapitulate the important points of the derivation.

The fluctuations on the transmitted Ly$\alpha$ flux under the effect of patchy reionization can be written as 1

$$\delta F(k, z_{\text{obs}}) = (1 + \beta_T \mu^2) b_T \delta m(k, z_{\text{obs}}) + \beta_T \psi \delta F(k, z_{\text{obs}}, z_{\text{red}}),$$

(1)

where we have explicitly shown the dependence of the different fluctuations involved on the redshift $z_{\text{obs}}$ and wavenumber $k$. Here $b_T$ is the usual flux bias parameter, $\beta_T$ the redshift-space distortion parameter, and $\psi$ is the radiation bias parameter. Its role is here to convert optical depth changes into flux fluctuations. $\delta F$ corresponds to the optical depth needed for the mean flux from a patch of gas with temperature $10^4$ K and density $\Delta_T = 1$ to reproduce the observed transmitted flux. Because we vary the normalization $\Delta_T$ to match the observed flux in our small-scale simulations, the change to the Ly$\alpha$ forest due to reionization happening suddenly at redshift $z_{\text{red}}$ is reported as a change in transparency, and optical depth, of the IGM, which we parametrize as $\Delta m(k, z_{\text{obs}}) = \ln [\tau_F(z_{\text{red}}) / \tau_F(z_{\text{obs}}) ] = \psi(z_{\text{red}}, z_{\text{obs}})$. The results of small-scale simulations are used to compute the transmission $\psi(z_{\text{red}}, z_{\text{obs}})$. Since our simulations are the same as in Montero-Camacho et al. (2019), the function of $\psi(z_{\text{red}}, z_{\text{obs}})$ takes the values listed in their Table 3.

The 3D power spectrum of the transmitted flux of the Ly$\alpha$ forest, ignoring higher order terms in $\psi$ and computed perpendicular to the line of sight, is given by

$$P_F^{3D}(k, z_{\text{obs}}) = b_T^2 P_m(k, z_{\text{obs}}) + 2 \beta_T b_T P_m, \psi(k, z_{\text{obs}}),$$

(2)

where

$$P_m, \psi(k, z_{\text{obs}}) = - \int_{z_{\text{min}}}^{z_{\text{max}}} d\tau \frac{\partial \psi}{\partial \tau}(\tau, z_{\text{obs}}) P_m, \psi(k, \tau) D(\tau_{\text{obs}}) D(\tau).$$

(3)

Here we set the lower limit of integration $z_{\text{min}} = 5.90$ and the upper limit $z_{\text{max}} = 34.7$. Even though we set the integration limits to cover most of the reionization history, the peak of the contribution to the integral roughly comes from when the Universe is half reionized. Interested readers are referred to Montero-Camacho et al. (2019) for more details regarding the derivation and limitations of Eq. (3). The cross-power spectrum of matter and transmission $P_m, \psi(k, z)$ is computed from the results of the large-scale reionization simulations, which are used to compute the cross-power spectrum of matter and the neutral fraction $P_m, \psi(k, z)$, together with the results of small-scale simulations, which are used to compute the transmission $\psi(z_{\text{red}}, z_{\text{obs}})$ and its derivative.

Throughout this work we utilize the same bias parameters used in Montero-Camacho et al. (2019), as summarized in their Table 2. Their radiation bias coefficients were obtained using their simulations and the flux bias coefficients were obtained from McQuinn & White (2011). Also, we follow their choice of setting $b_T = 1$ in the matter-dominated Universe for consistency.

In order to compute the 1D power spectrum of matter and transparency of the IGM, we integrate the second term of Eq. (2) — with the factor of $(1 + \mu^2)$ — over the perpendicular direction. The methodology of converting the map from 3D to 1D is described explicitly in §4.4 of Montero-Camacho et al. (2019). We directly extract the matter power spectrum from the data and then compare with the effect of patchy reionization. In order to estimate the errors due to simulations present herein, we have followed the same procedure described in Montero-Camacho et al. (2019) with the only difference being the smaller amount of the reionization realizations (with the 21cmFAST code) made in this work (four realizations herein compared to eight realizations in the previous work). The main budget of error comes from the small-scale simulations and therefore it is well-justified. Also, we have ignored the error from eBOSS since it is negligible in comparison to the variance in our simulations.

3 MODELS OF REIONIZATION AND COSMIC DAWN

In this paper we allow the variations of five astrophysical parameters used in the 21cmFAST code, as follows.

(1) $T_{\text{min}}$, the minimum virial temperature of haloes that host ionizing sources. For haloes with virial temperatures smaller than this threshold, there is effectively no star formation in them. This temperature threshold plays a role in modulating the sources of ionizing photons and directly affects the properties of the reionization bubbles. If $T_{\text{min}}$ increases (and all other astrophysical parameters are kept fixed), then less haloes of a given mass can have star-forming galaxies, which implies less UV photons available to ionize the Universe.

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1 Throughout this paper, our convention is that fluctuations are defined as $\delta_p = p/p_0 - 1$ for any observable except for the neutral hydrogen fraction, where the fluctuation is given by $\delta_X = X_X - X_0$. Moreover, the auto-power spectrum of $\delta_p$ is written as $P_p$, and the cross-power spectrum of $\delta_p$ with $\delta_p'$ is written as $P_{p,p'}$. Besides, all power spectra are in dimensionless form, $k^3 P(k)/2\pi^2$. | MNRA 000, 1–11 (2020) |
Table 1. Different models explored throughout this work. The symbol "—" herein means that this parameter takes the fiducial value. Here $z_{\text{red}}$ stands for the redshift when the Universe is halfway ionized. The values of optical depth are taken approximately for some of the models (T1, T2, and $\zeta$1 models) wherein the reionization is not completely finished at the end of the large-scale simulations $z_{\text{fin}} = 5.90$.

| Model | $T_{\text{min}}$ [K] | $R_{\text{adj}}$ [Mpc] | $\zeta$ | $E_0$ [eV] | $\zeta_X$ [M$_{\odot}$] | $z_{\text{red}}$ | $\tau$ |
|-------|----------------------|------------------------|--------|------------|------------------------|----------------|------|
| fiducial | $3 \times 10^4$ | $50$ | $25$ | $500$ | $2 \times 10^{10}$ | $7.69$ | $0.0547$ |
| Bubble models | | | | | | | |
| T1 | $5 \times 10^4$ | — | — | — | — | $6.97$ | $0.0477$ |
| T2 | $4 \times 10^4$ | — | — | — | — | $7.28$ | $0.0507$ |
| T3 | $2 \times 10^4$ | — | — | — | — | $8.28$ | $0.0607$ |
| R1 | — | $25$ | — | — | — | $7.68$ | $0.0543$ |
| R2 | — | $15$ | — | — | — | $7.63$ | $0.0536$ |
| $\zeta_1$ | — | — | $20$ | — | — | $7.21$ | $0.0504$ |
| $\zeta_2$ | — | — | $30$ | — | — | $8.08$ | $0.0583$ |
| Heating models | | | | | | | |
| E01 | — | — | — | $100$ | — | $7.68$ | $0.0552$ |
| E02 | — | — | — | $1000$ | — | $7.67$ | $0.0545$ |
| E03 | — | — | — | $1500$ | — | $7.66$ | $0.0544$ |
| $\zeta_X 1$ | — | — | — | — | $1 \times 10^{10}$ | $7.67$ | $0.0546$ |
| $\zeta_X 2$ | — | — | — | — | $4 \times 10^{10}$ | $7.72$ | $0.0550$ |
| $\zeta_X 3$ | — | — | — | — | $8 \times 10^{10}$ | $7.77$ | $0.0556$ |

Table 2. Percentage deviation of the 3D Ly$\alpha$ power spectrum due to patchy reionization, i.e. $2(\delta P_{Ly}/P_{\text{ref}})P_{\text{num}}/P_{\text{ref}} \times 100$% at $k = 0.14$ Mpc$^{-1}$ (a typical scale for Ly$\alpha$ surveys), at various redshifts for the different reionization and thermal models considered herein. The corresponding percentage deviation of the 1D Ly$\alpha$ power spectrum due to patchy reionization is also shown in the lower part of this Table. For the 1D Ly$\alpha$ power spectrum we have used the latest data release by BOSS + eBOSS (Chabanier et al. 2019). For the T1, T2, and $\zeta$1 models with $z_{\text{red}} < 7.30$ wherein reionization is not completely finished at the end of the large-scale simulations $z_{\text{fin}} = 5.90$, the change here represents only a lower limit. The errors in our results correspond to the sample variance in our simulations and are mainly dominated by the variance in our small-scale simulations.

| Model | $z_{\text{obs}} = 2.0$ | $z_{\text{obs}} = 2.5$ | $z_{\text{obs}} = 3.0$ | $z_{\text{obs}} = 3.5$ | $z_{\text{obs}} = 4.0$ |
|-------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 3D Power Spectrum | | | | | |
| Fiducial | $0.20 \pm 0.02$% | $0.31 \pm 0.07$% | $0.61 \pm 0.12$% | $1.35 \pm 0.16$% | $2.76 \pm 0.23$% |
| Bubble models | $T1$ | $0.26 \pm 0.03$% | $0.46 \pm 0.08$% | $0.89 \pm 0.13$% | $1.81 \pm 0.18$% | $3.48 \pm 0.27$% |
| $T2$ | $0.24 \pm 0.02$% | $0.40 \pm 0.08$% | $0.79 \pm 0.13$% | $1.65 \pm 0.17$% | $3.25 \pm 0.26$% |
| $T3$ | $0.14 \pm 0.02$% | $0.18 \pm 0.06$% | $0.35 \pm 0.11$% | $0.92 \pm 0.14$% | $2.05 \pm 0.19$% |
| $R1$ | $0.22 \pm 0.02$% | $0.34 \pm 0.07$% | $0.68 \pm 0.12$% | $1.48 \pm 0.17$% | $2.99 \pm 0.24$% |
| $R2$ | $0.27 \pm 0.03$% | $0.45 \pm 0.08$% | $0.87 \pm 0.14$% | $1.84 \pm 0.19$% | $3.61 \pm 0.29$% |
| $\zeta_1$ | $0.25 \pm 0.03$% | $0.43 \pm 0.08$% | $0.84 \pm 0.13$% | $1.75 \pm 0.18$% | $3.41 \pm 0.27$% |
| $\zeta_2$ | $0.15 \pm 0.02$% | $0.19 \pm 0.06$% | $0.38 \pm 0.10$% | $0.98 \pm 0.14$% | $2.12 \pm 0.19$% |
| Heating models | | | | | |
| E01 | $0.18 \pm 0.02$% | $0.26 \pm 0.06$% | $0.52 \pm 0.11$% | $1.20 \pm 0.15$% | $2.49 \pm 0.21$% |
| E02 | $0.20 \pm 0.02$% | $0.32 \pm 0.07$% | $0.62 \pm 0.12$% | $1.39 \pm 0.16$% | $2.82 \pm 0.23$% |
| E03 | $0.20 \pm 0.02$% | $0.32 \pm 0.07$% | $0.63 \pm 0.12$% | $1.40 \pm 0.16$% | $2.84 \pm 0.24$% |
| $\zeta_X 1$ | $0.20 \pm 0.02$% | $0.31 \pm 0.07$% | $0.62 \pm 0.12$% | $1.38 \pm 0.16$% | $2.80 \pm 0.23$% |
| $\zeta_X 2$ | $0.19 \pm 0.02$% | $0.29 \pm 0.07$% | $0.58 \pm 0.12$% | $1.31 \pm 0.16$% | $2.69 \pm 0.22$% |
| $\zeta_X 3$ | $0.18 \pm 0.02$% | $0.27 \pm 0.06$% | $0.54 \pm 0.11$% | $1.24 \pm 0.15$% | $2.56 \pm 0.22$% |
(2) $R_{\text{mfp}}$, the mean free path of ionizing photons. It dictates the maximum horizon of ionizing photons, and defines the maximum permitted size of the bubbles, and hence a decrease in $R_{\text{mfp}}$ implies more bubbles are needed to percolate the Universe, therefore one should expect a slight delay in the reionization process.

(3) $\zeta$, the ionizing efficiency, i.e., roughly speaking, the number of ionizing photons that can escape from the stars into the IGM per each baryon atom in haloes. This parameter governs the timing of the reionization process in the 21cmFAST code. The ionizing efficiency governs the amount of available UV photons that can ionize the $\text{H}_1$ regions. If $\zeta$ increases, then there will be more UV photons in the IGM, thus reionization will happen sooner.

(4) $E_0$, the energy threshold for the lowest energy X-ray photons not absorbed by galaxies. This parameter mainly affects the heating of the IGM prior to reionization. A larger value corresponds to inefficient X-ray heating of the IGM due to more X-ray photons being absorbed by the host galaxies, i.e. less photons preheat the IGM, and hence there is a slight delay in the reionization process.\footnote{Careful readers may find in Table 1 that $z_{\text{re}}$ for the E01 model is very slightly smaller than that for the fiducial model, which seems to contradict the general trend here. However, the difference $\Delta z_{\text{re}} = 0.01$ between these two models is so small that it is actually due to numerical fluctuations of the different realizations. The comparison of $\tau$ between these two models is indeed consistent with the trend.}

(5) $\zeta_X$, the X-ray efficiency which corresponds to the number of X-ray photons that manage to escape the galaxy per solar mass present in stars. The role of this parameter is to establish the preheating of the IGM. This X-ray efficiency controls the degree of X-ray heating that happens prior to reionization. Higher values would eventually cause reionization to occur earlier.

We chose these parameters inspired by the exploration of the impact of astrophysical parameters on the global 21 cm signal (Monsalve et al. 2018), and the effects on both the 21 cm fluctuations and the neutral hydrogen fraction (Greig & Mesinger 2017; see their Figure 1). For the purpose of comparison, we use a fiducial model: $T_{\text{min}} = 3 \times 10^4 \text{ K}$, $R_{\text{mfp}} = 50 \text{ Mpc}$, $\zeta = 25$, $E_0 = 500 \text{ eV}$, and $\zeta_X = 2 \times 10^{56} \text{ M}_\odot^{-1}$ which corresponds to roughly 0.3 X-ray photons per stellar baryon. The reionization history in our fiducial model reproduces the optical depth of the \textit{Planck} result (Planck Collaboration et al. 2018) quite well.

We list all astrophysical models in Table 1. For clarity, we group different models studied herein into two categories — “bubble models”, and “heating models” — based on the primary role of the parameter allowed to vary. Specifically, the bubble models are those by varying three parameters, $T_{\text{min}}$, $R_{\text{mfp}}$ and $\zeta$, because their variations directly affect the growth or evolution of the ionized bubbles. On the other hand, the heating models correspond to the variations in $E_0$ and $\zeta_X$, because their variations mainly affect the preheating of the IGM. In Table 1, we also list the redshifts of their halfway ionized epoch, $z_{\text{re}}$, and the CMB optical depths $\tau$ corresponding to their global reionization histories. Even though the chosen models have variations of $z_{\text{re}}$ of 1.11, we note that they are all loosely consistent with observational constraints and upper limits (see, e.g., Figure 12 of Mason et al. 2018).
4 RESULTS AND DISCUSSIONS

4.1 The impact of inhomogeneous reionization

In this section we illustrate how strong the impact of patchy reionization in the Lyα forest is. In Table 2, we report the percentage deviation of the 3D Lyα power spectra due to patchy reionization, i.e. the ratio of the second term over the first term of Eq. (2) multiplied by 100% which equals to $2(b_f / b_p)P_{m,\psi}/P_m \times 100\%$, at $k = 0.14$ Mpc$^{-1}$ at various redshifts for the different models included in this study. Furthermore, the 1D Lyα power spectrum has already been measured by observations, and hence we use the latest data release by BOSS+eBOSS (Chabanier et al. 2019) to estimate the degree of contamination.

We observe a decrease of the significance of the effect of patchy reionization in the 1D Lyα forest power spectra overall compared to the results in the previous work. The reason for this lies in the new improved eBOSS measurements. Taking into account the statistical error in the eBOSS measurement and the “reionization-modeling” error, it is currently challenging to use the 1D Lyα power spectrum to extract information from the reionization epoch via the impact of inhomogeneous reionization in the Lyα forest. In particular, for $k = 0.14$ Mpc$^{-1}$, at low redshift ($z_{obs} = 2.0$) the change is in the order of a tenth of per cent (ranging from $\sim 0.14\%$ in our T3 model to $\sim 0.27\%$ in the R2 model). In contrast, at the high redshift ($z_{obs} = 4.0$), the change is in the order of a few per cent (ranging from $\sim 2.05\%$ in the T3 model up to $\sim 3.61\%$ in the R2 model).

On the other hand, the expected effect of patchy reionization in the 3D Lyα forest power spectrum are significantly larger. We find that the percentage deviation is in the order of tens of per cent at $z_{obs} = 4.0$ (e.g. $\sim 41.6\%$ for our model R2), and in the order of a few per cent at $z_{obs} = 2.0$ (e.g. $\sim 2.45\%$ for our model T3).

In Figure 1, we plot the $k$-dependence of both the autocorrelation power spectrum of matter and the cross-correlation power spectrum of matter and the change of transparency of the IGM due to inhomogeneous reionization, at redshift 2.0. In the lower panel, we show the ratio of the contribution to the flux power spectrum from inhomogeneous reionization over the cosmological contribution. Similarly, we illustrate the evolution at $z_{obs} = 3.0$ in Figure 2, and at $z_{obs} = 4.0$ in Figure 3.

Even though the impact of patchy reionization in the Lyα forest is significant — especially at higher redshift — on the large scales, the effect diminishes for the small scales. The different $k$-dependence of the matter power spectrum and that of $P_{m,\psi}$ is a positive sign for modeling and extracting, or marginalizing over, this broadband signal.

For reference, the statistical error per bin of the eBOSS $P_{1D}$ measurement for $k = 0.151$ Mpc$^{-1}$ are 1.05 per cent at $z = 2.6$, 1.23 per cent at $z = 3.0$ and 6.03 per cent at $z = 4.0$. Even in the hypothetical scenario where the statistical error budget of DESI for 1D power spectrum measurements would be only a half of the recent BOSS+eBOSS (Chabanier et al. 2019) measurements, this effect would be comparable to the statistical error at $z = 4$. In fact, DESI is very likely to manage a much better measurement. In that more promising case, this signal would be significant for most of the models in Table 2.

As seen in Eq. (3) this broadband systematic effect for the Lyα forest is fundamentally linked to the astrophysics of reionization, and hence indirectly coupled to the physics of the cosmic dawn. Given the current capabilities of instruments like DESI (DESI Collaboration et al. 2016) and 4MOST (Richard et al. 2019), the 3D Lyα forest will be measured in a time span of a couple of years. In the absence of any mitigation scheme, theoretically, one should be able to use this effect to construct a new avenue for constraining the reionization and thermal histories once DESI has measured the 3D Lyα power spectrum. We will explore this plausible scenario in future work.

4.2 Dependence on astrophysical scenarios

Having shown the effect of patchy reionization in the Lyα forest for our fiducial model and illustrated its significance as a systematic, we now proceed to focus on its potential as a link to the astrophysics of cosmic reionization and cosmic dawn by analyzing the dependence on the different astrophysical parameters, and also strategize how to separate cosmology from astrophysics.

In Figure 4, we show the cross-power spectrum of the matter and transmission of the IGM, $P_{m,\psi}$, as a function of wavenumber for the models that vary the minimum virial temperature of haloes with efficient star formation. Also in these panels we show the dependence of these signals on the redshift of observation. We highlight that it is possible to distinguish between the reionization models because the power spectra in these models show different shapes in wavenumber and different overall amplitudes. The dip of the power spectrum corresponds to the minimum of $T_{\text{min}}$, smoothed by the integration and multiplied by the factors that depend on redshift of observation. We find that the dip of the cross-power spectrum in the T1 model which has the largest $T_{\text{min}}$ has the largest absolute value. Basically, reionization is dominated by more massive haloes in the T1 model because of its higher temperature threshold. This results in the larger fluctuations in neutral fraction field, and therefore larger $|P_{m,\psi}|$.

Furthermore, we show the $P_{m,\psi}$ power spectrum for the models that change the maximum allowed size of the bub-
The cross-power spectra of matter density and the transparency of the IGM, $P_{m,\Psi}$, for the Lyα forest observed at redshift $z_{\rm obs} = 2.0$ (top), $3.0$ (middle), and $4.0$ (bottom), respectively. In each panel, we consider the “T” models wherein the minimum virial temperature of haloes that host ionizing sources takes the value of $T_{\rm min} = 5 \times 10^4$K (T1 model, purple), $4 \times 10^4$K (T2 model, blue), and $2 \times 10^4$K (T3 model, orange), in comparison with our fiducial model wherein $T_{\rm min} = 3 \times 10^4$K (green).

Figure 4. Cross-power spectrum of matter density and the transparency of the IGM, $P_{m,\Psi}$, for the Lyα forest observed at redshift $z_{\rm obs} = 2.0$ (top), $3.0$ (middle), and $4.0$ (bottom), respectively. In each panel, we consider the “T” models wherein the minimum virial temperature of haloes that host ionizing sources takes the value of $T_{\rm min} = 5 \times 10^4$K (T1 model, purple), $4 \times 10^4$K (T2 model, blue), and $2 \times 10^4$K (T3 model, orange), in comparison with our fiducial model wherein $T_{\rm min} = 3 \times 10^4$K (green).

Figure 5. Same as Figure 4 but for the “R” models wherein the mean free path of ionizing photons takes the value of $R_{\rm mfp} = 25$ Mpc (R1 model, purple) and $15$ Mpc (R2 model, blue), in comparison with our fiducial model wherein $R_{\rm mfp} = 50$ Mpc (green).

scales in Figure 5. Generally, the dip of the cross-power spectrum becomes broader for smaller radii. Taking into account the error bars, these models exhibit similar strength in the large-scale, which is due to the similarity of the $P_{m,\Psi}$ for the R models at these scales. However, as we move to smaller scales ($k \gtrsim 0.1$ Mpc$^{-1}$) we see a larger deviation seeded by the difference of how reionization finishes for these three models, i.e. by the process of how many bubbles are needed to evolve and completely percolate the Universe. This deviation is present in the cross-power spectrum of matter and neutral hydrogen fraction, and it is quite small around the mid-point of reionization of these models but becomes slightly stronger as we move to lower redshifts. Moreover, the integration in Eq. (3) enhances the dip resulting in the feature present in the R2 model. While the fiducial model has double the maximum allowed bubble size with respect to the R1 model, the deviation between these cross-power spectra is significantly smaller than that between the R1 and R2 models. Given that this parameter is utilized in the filter radius for the ionized bubbles in the 21cmFAST code, we note that the cross-power in the R2 model might have artificial power given by increased shot-noise due to some isolated regions included into a filter. Therefore, the real behavior of $P_{m,\Psi}$ with maximum bubble size might resemble more the changes between the R1 and the fiducial model.

The cross-power spectra $P_{m,\Psi}$ for the models that vary the ionizing efficiency are shown in Figure 6. The most interesting feature is the difference of $P_{m,\Psi}$ between the models,
i.e. the amplitude of $P_{m,\psi}$ is very sensitive to the value of the ionizing efficiency $\zeta$. We see the expected hierarchical structure due to the $\zeta$ values, i.e. one expects the $\zeta_2$ model to have a less prominent dip than the fiducial model. Naturally, we also observe significant differences of more than 28 per cent between the fiducial model and the $\zeta_1$ model for $P_{m,\psi}$. This deviation is mainly due to the fact that the ionization efficiency dominates the reionization timing in the reionization simulation.

In Figure 7, we illustrate the change of $P_{m,\psi}$ with varying energy threshold for X-ray photons to be not absorbed by galaxies. We see small deviations from the fiducial model, even for the extreme scenario of photon-abundance preheating of the IGM (E01 model); in particular, we see negligible changes for the photon-starved preheating of the IGM (E03 model). Similarly, in Figure 8 where we show the an-

log plots for the efficiency of X-ray photons that manage to escape their host galaxies, the $\zeta_X$ models are effectively indistinguishable in this signal, especially at lower redshifts. Therefore, we conclude that the heating models do not necessarily play a key role in the effect of patchy reionization on the Ly$\alpha$ forest.

We note that all models studied here generically show the similar “smiley face” in the cross-power spectrum $P_{m,\psi}$ as a function of wavenumber. However, the details of the dip of the power spectrum, including the shape information (such as the (a)symmetry and the width) and the amplitude, do depend on the astrophysical parameters, particularly parameters of the bubble models. The difference of $P_{m,\psi}$ is a promising sign of the potential for this systematic signal to

**Figure 6.** Same as Figure 4 but for the “$\zeta$” models wherein the ionizing efficiency takes the value of $\zeta = 20$ ($\zeta_1$, model, purple), and 30 ($\zeta_2$ model, blue), in comparison with our fiducial model wherein $\zeta = 25$ (green).

**Figure 7.** Same as Figure 4 but for the “E0” models wherein the energy threshold for the lowest energy X-ray photons not absorbed by galaxies takes the value of $E_0 = 1000$ eV (E01 model, purple), 1000 eV (E02 model, blue), and 1500 eV (E03 model, orange), in comparison with our fiducial model wherein $E_0 = 500$ eV (green).
Figures 8. Same as Figure 4 but for the “ζX” models wherein the X-ray efficiency takes the value of ζX = 1 × 10^3 M_⊙ (ζX 1 model, purple), 4 × 10^6 M_⊙ (ζX 2 model, blue), and 8 × 10^6 M_⊙ (ζX 3 model, orange), in comparison with our fiducial model wherein ζX = 2 × 10^6 M_⊙ (green).
and from 2.05 to 3.61 per cent at $z_{\text{obs}} = 4.0$. The strength of this effect is smaller than, albeit at $z_{\text{obs}} = 4.0$ comparable to, the observational error bars present in the measurements (Chabanier et al. 2019), so it is not large enough for the attempt to separate the astrophysics of reionization from the cosmological information.

Moreover, we computed the effect of inhomogeneous reionization on the 3D Lyα forest power spectrum for different models of reionization, and found that the effect is generic, i.e. it does not vanish for any model. We found different models of reionization, and found that the effect is reionization on the 3D Lyα power spectrum for the information of cross-power spectrum. Alternatively, one may extract the quadrupole of the 21 cm power spectrum from the astrophysical parameters of cosmic reionization and cosmic dawn, particularly parameters of the bubble models. As such, the Lyα forest power spectrum at the post-reionization epoch has the potential to distinguish between various astrophysical models by exploiting different $k$-dependence of the power spectrum. This is a promising sign for efficient separation of the astrophysical information from cosmological information, and thus opens a new window into the EOR and, if further studies show larger impact due to X-ray preheating, possibly even the cosmic dawn. To achieve this, there are a few possibilities. For example, one may extract the quadrupole of the 21 cm power spectrum for the information of cross-power spectrum. Alternatively, by exploiting the fact that the effect is diminished at lower redshifts, from which cosmology may be extracted, the Lyα forest power spectrum at higher redshifts may be used to constrain the astrophysics of the reionization process. In future work, we will explore the plausible scenario where Lyα forest 3D power spectrum will be measured by instruments like DESI without mitigation scheme implemented, to determine what information could be extracted regarding the reionization and thermal histories.

ACKNOWLEDGEMENTS

This work is supported by the National Key R&D Program of China (Grant No. 2017YFB0203302, 2018YFA0404502), and the National Natural Science Foundation of China (NSFC Grant No.11673014, 11761141012, 11821303). PMC was supported by the Tsinghua Shui Mu Scholarship. YM was supported in part by the Chinese National Thousand Youth Talents Program. We thank Christopher M. Hirata, Xiao Fang, Hayato Shimabukuro and Shifan Zuo for fruitful discussions and valuable feedback, and thank Andrei Mesinger and Jaehong Park for useful suggestions regarding 21cmFAST. The small-scale simulations were done in the Ruby cluster at the Ohio Supercomputer Center, and the large-scale simulations were ran in the Venus and Orion clusters at the Tsinghua University.

REFERENCES

Becker G. D., Bolton J. S., Haehnelt M. G., Sargent W. L. W., 2011, MNRAS, 410, 1096
Becker G. D., Bolton J. S., Madau P., Pettini M., Ryan-Weber E. V., Venemans B. P., 2015, MNRAS, 447, 3402
Blas D., Lesgourgues J., Tram T., 2011, J. Cosmology Astropart. Phys., 2011, 034
Bosman S. E. I., Fan X., Jiang L., Reed S., Matsuoka Y., Becker G., Haehnelt M., 2018, MNRAS, 479, 1055
Bouwens R. J., Illingworth G. D., Oesch P. A., Caruana J., Holwerda B., Smit R., Wilkins S., 2015, ApJ, 811, 140
Bowman J. D., Rogers A. E. E., 2010, Nature, 468, 796
Bowman J. D., Rogers A. E. E., Monsalve R. A., Moudzien T. J., Mahesh N., 2018, Nature, 555, 67
Cen R., McDonald P., Trac H., Loeb A., 2009, ApJ, 706, L164
Chabanier S., et al., 2019, J. Cosmology Astropart. Phys., 2019, 017
Choudhury T. R., Puchwein E., Haehnelt M. G., Bolton J. S., 2015, MNRAS, 452, 261
Compostella M., Cantalupe S., Porciani C., 2013, MNRAS, 435, 3169
D’Aloisio A., McQuinn M., Maupin O., Davies F. B., Trac H., Fuller S., Upton Sandeberk P. R., 2019, ApJ, 874, 154
DESI Collaboration et al., 2016, preprint, (arXiv:1611.00036)
Eilers A.-C., Davies F. B., Hennawi J. F., 2018, ApJ, 864, 53
Fan X., Narayanan V. K., Strauss M. A., White R. L., Becker R. H., Pentericci L., Rix H.-W., 2002, The Astronomical Journal, 123, 1247
Fan X., Carilli C. L., Keating B., 2006, ARA&A, 44, 415
Falkov A., Barkana R., Visbal E., 2014, Nature, 506, 197
Furlanetto S. R., 2020, MNRAS, 499
Givans J. J., Hirata C. M., 2020, arXiv e-prints, p. arXiv:2002.12296
Greig B., Mesinger A., 2017, MNRAS, 472, 2651
Greig B., Bolton J. S., Wyithe J. S. B., 2015, MNRAS, 447, 2503
Hirata C. M., 2018, MNRAS, 474, 2173
Hoag A., et al., 2019, ApJ, 878, 12
Hui L., Guedin N. Y., Zhang Y., 1997, ApJ, 486, 599
Keating L. C., Kulkarni G., Haehnelt M. G., Chardin J., Aubert D., 2019, arXiv e-prints, p. arXiv:1912.05582
Keating L. C., Weinberger L. H., Kulkarni G., Haehnelt M. G., Chardin J., Aubert D., 2020, MNRAS, 491, 1736
Kulkarni G., Keating L. C., Haehnelt M. G., Bosman S. E. I., Puchwein E., Chardin J., Aubert D., 2019, MNRAS, 485, L24
Lidz A., Malloy M., 2014, ApJ, 788, 175
Mason C. A., Treu T., Dijkstra M., Mesinger A., Trenti M., Pentericci L., de Barros S., Vanzella E., 2018, ApJ, 856, 2
Mason C. A., Naidu R. P., Tacchella S., Leja J., 2019, MNRAS, 489, 2669
McGreer I. D., Mesinger A., D’Odorico V., 2015, MNRAS, 447, 499
McQuinn M., 2016, ARA&A, 54, 313
McQuinn M., White M., 2011, MNRAS, 415, 2257
McQuinn M., Lidz A., Zaldarriaga M., Hernquist L., Hopkins P. F., Dutta S., Faucher-Giguère C.-A., 2009, ApJ, 694, 842
Mesinger A., ed. 2019, The Cosmic 21-cm Revolution. 2514-3433, IOP Publishing, doi:10.1088/2514-3433/ab4a73, http://dx.doi.org/10.1088/2514-3433/ab4a73
Mesinger A., Furlanetto S., 2007, ApJ, 669, 663
Mesinger A., Furlanetto S., Cen R., 2011, MNRAS, 411, 955
Mesinger A., Aylutalp A., Vanzella E., Pentericci L., Ferrara A., Dijkstra M., 2015, MNRAS, 446, 566

MNRA 000, 1–11 (2020)
Monsalve R. A., Rogers A. E. E., Bowman J. D., Mozdzen T. J., 2017, ApJ, 847, 64
Monsalve R. A., Greig B., Bowman J. D., Mesinger A., Rogers A. E. E., Mozdzen T. J., Kern N. S., Mahesh N., 2018, ApJ, 863, 11
Montero-Camacho P., Hirata C. M., Martini P., Honscheid K., 2019, MNRAS, 487, 1047
Nasir F., Bolton J. S., Becker G. D., 2016, MNRAS, 463, 2335
Oñorbe J., Hennawi J. F., Lukić Z., Walther M., 2017, ApJ, 847, 63
Oñorbe J., Davies F. B., Lukić Z., Hennawi J. F., Sorini D., 2019, MNRAS, 486, 4075
Planck Collaboration et al., 2016, A&A, 594, A13
Planck Collaboration et al., 2018, arXiv e-prints, p. arXiv:1807.06209
Pritchard J. R., Loeb A., Wyithe J. S. B., 2010, MNRAS, 408, 57
Richard J., et al., 2019, The Messenger, 175, 50
Singh S., et al., 2018, ApJ, 858, 54
Springel V., 2005, MNRAS, 364, 1105
Trac H., Cen R., Loeb A., 2008, ApJ, 689, L81
Tseliakhovich D., Hirata C., 2010, Phys. Rev. D, 82, 083520
Upton Sanderbeck P., Bird S., 2020, arXiv e-prints, p. arXiv:2002.05733
Walther M., Oñorbe J., Hennawi J. F., Lukić Z., 2019, ApJ, 872, 13
Wu X., McQuinn M., Kannan R., D’Aloisio A., Bird S., Marinacci F., Davé R., Hernquist L., 2019, MNRAS, 490, 3177

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