

Constraints on the Thomson optical depth to the Cosmic Microwave Background from the Lyman- α forest

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(Received 4 October 2025; revised 4 February 2026; accepted 11 May 2026; published 20 July 2026)

We present the first constraints on the electron optical depth to reionization, τ_e , from the Lyman- α forest alone for physically motivated reionization models that match the reionization's end point, z_{end} , required by the same astrophysical probe, and for symmetric reionization models with fixed duration, Δz , commonly adopted in cosmic microwave background (CMB) reionization analyses. Compared to traditional estimates from the latter, the Lyman- α forest traces the ionization state of the Intergalactic medium (IGM) through its coupling with the thermal state. We find an explicit mapping between the two by solving the chemistry and temperature evolution equations for hydrogen and helium. Our results yield $\tau_e = 0.040^{+0.042}_{-0.018}$ (95% C.L.) and $\tau_e = 0.041^{+0.028}_{-0.017}$ for reionization models with z_{end} and Δz fixed, respectively. With mock Lyman- α forest data that mimics the precision of future larger quasar sample datasets, we would potentially obtain tighter τ_e constraints, paving the way for CMB-independent constraints on the epoch of reionization from a large-scale structure probe.

DOI: [10.1103/4hgw-9cqq](https://doi.org/10.1103/4hgw-9cqq)

Introduction. The optical depth to reionization, τ_e , has recently drawn considerable attention due to its potential to significantly weaken the hints for physics beyond Λ CDM suggested by the latest results from the Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2). When combined with *Planck* cosmic microwave background (CMB) measurements and supernovae datasets, baryon acoustic oscillations (BAOs) from DESI DR2 reveal an $\sim 4\sigma$ preference for dynamical dark energy [1]. Primarily driven by a lower value of Ω_m , this in turn implies a preference for neutrino masses below the minimum allowed by neutrino oscillation experiments [2]. These findings have motivated recent work by Sailer *et al.* [3] and Jhaveri *et al.* [4] to consider the implications of larger optical depths than the standard estimate obtained from polarization measurements at low- l multipoles of the CMB, which yields $\tau_e = 0.054 \pm 0.007$ (68% C.L.) [5]. Since the CMB polarization signal is roughly 100 times weaker than the corresponding temperature fluctuations and subject to the same levels of foreground contamination, τ_e is the least well-constrained parameter within the Λ CDM model. In fact, Sailer *et al.* [3] and Jhaveri *et al.* [4] found that a value of $\tau_e \approx 0.09$ restores consistency between *Planck* and DESI,

reducing the statistical tension below $\sim 2\sigma$. Notably, such *high* τ_e values are consistent with early WMAP results [6], and with recent constraints from the combination of small-scale CMB anisotropies and CMB lensing with various low-redshift probes [7].

It is important to highlight that, unlike cosmological parameters such as Ω_m , τ_e is fundamentally astrophysical, encoding information about the integrated ionized electron fraction up to the epoch of decoupling. To interpret different τ_e estimates, it is crucial to revisit our current understanding of the epoch of reionization (EoR), mainly constrained through the Lyman- α forest. Observational evidence, such as the presence of Gunn-Peterson troughs [8,9], large-scale opacity variations [10], and Lyman- α damping wings [11]), at $z < 6$, along with short mean free paths below this redshift (e.g., Ref. [12]), places robust constraints on a *late* end point of reionization, z_{end} . At the same time, recent JWST detections of Lyman- α emitters at high z appear to suggest an *early* onset of reionization (e.g., Ref. [13]), indicating ongoing reionization already by $z = 13$, as discussed by Cohon *et al.* [14]. Taking the Lyman- α constraints for the late reionization stages into account, Cain *et al.* [18] used measurements of the patchy kinetic Sunyaev-Zel'dovich (pkSZ) effect to place limits on the duration of reionization. Their results indicate that reconciling Lyman- α measurements with a *high* τ_e leads to a $\geq 2\sigma$ tension. However, the pkSZ is highly sensitive to foreground subtraction [19] and the measurement depends on the galaxy clustering model assumed [20]. Such *high* values of τ_e have been excluded with even more significance by Elbers [7] using a compilation of astrophysical measurements of x_{HII} from damping wings and dark pixel constraints. These

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allow to reconstruct the reionization history without assuming a particular parametric model, leading to τ_e constraints that are independent of CMB data.

In this Letter, we argue that current postreionization Lyman- α forest data can independently determine the allowed τ_e for a range of physically motivated reionization models, and for symmetric reionization models, extensively studied by CMB analyses. The constraining power comes from the connection between τ_e and the thermal history of the IGM, to which the Lyman- α forest is highly sensitive: During reionization, baryons react to the photoheating of the IGM and the corresponding increase of the gas pressure, suppressing small-scale structure in the Lyman- α forest. Assuming a cold dark matter cosmology, Boera *et al.* [21] provided the first constraints on these two effects using hydrodynamical simulations for a wide range of thermal history models. The results, together with those from subsequent work [22,23], agree remarkably well with the observational evidence for a *late* end to reionization and independent measurements of the thermal evolution of the IGM [24,25]. Using an empirical mapping between the Lyman- α forest thermal parameters and τ_e from our simulations, we constrain the history of the EoR through τ_e , independently of CMB observations.

Thermal and ionization state of the IGM. The ionization state of the IGM is, in this work, constrained through the electron opacity to CMB photons, τ_e , which depends on the line-of-sight integral of the electron fraction, x_e , with its main contribution coming from the redshift range of the EoR. On the other hand, the IGM's thermal history is described by the cumulative energy deposited into the gas per proton by photoheating, u_0 [27]. This quantity is an integral of the total

photoheating rate per unit volume, $\mathcal{H}_i = \sum n_i \epsilon_i$, where n_i and ϵ_i are the number densities and photoheating rates, respectively, for the species $i \in [\text{H I}, \text{He I}, \text{He II}]$. The u_0 integration redshift range is chosen here to match the timescales at which the flux power spectrum is more sensitive to heating (see Sec. 6.3.3 in Ref. [21]). Note that u_0 is only weakly correlated with thermal broadening, parametrized by the gas temperature at mean density, T_0 . The connection between the thermal parameters u_0 – T_0 and τ_e comes from the relation

$$\mathcal{H} = n_{\text{HI}} \epsilon_{\text{HI}} = n_{\text{HI}} E_{\text{ion}} \Gamma_{\text{HI}}, \quad (1)$$

where Γ_{HI} and ϵ_{HI} are the hydrogen photoionization and photoheating rates, respectively, and E_{ion} corresponds to the mean excess energy available to photoheat the IGM [16], typically assumed to be constant [28]. The Lyman- α forest, therefore, probes Γ_{HI} through its coupling with ϵ_{HI} . At the same time, the photoionization rate, Γ_{HI} , enters into the definition of τ_e through the evolution of x_e , or similarly, of the hydrogen ionized fraction, x_{HII} . The latter is given by the well-known “reionization equation” [29], which, written in terms of the fractional abundances [Eq. (2) in Ref. [30]], shows the connection between Γ_{HI} and x_e , and therefore, τ_e . Hence, Eq. (1) implies that the Lyman- α forest contains information on τ_e and that the parameter pair u_0 – T_0 can be mapped to τ_e .

Data. We use the one-dimensional (1D) Lyman- α flux power spectra dataset presented in Ref. [21]. The measurements are from a high-resolution sample of 15 quasars observed by HIRES and UVES at $z_{\text{bin}} = [4.2, 4.6, 5.0]$. For more details on the data, we refer the reader to Refs. [22,23]. Given the moderate number of quasar sightlines in this sample, we further consider a second mock dataset

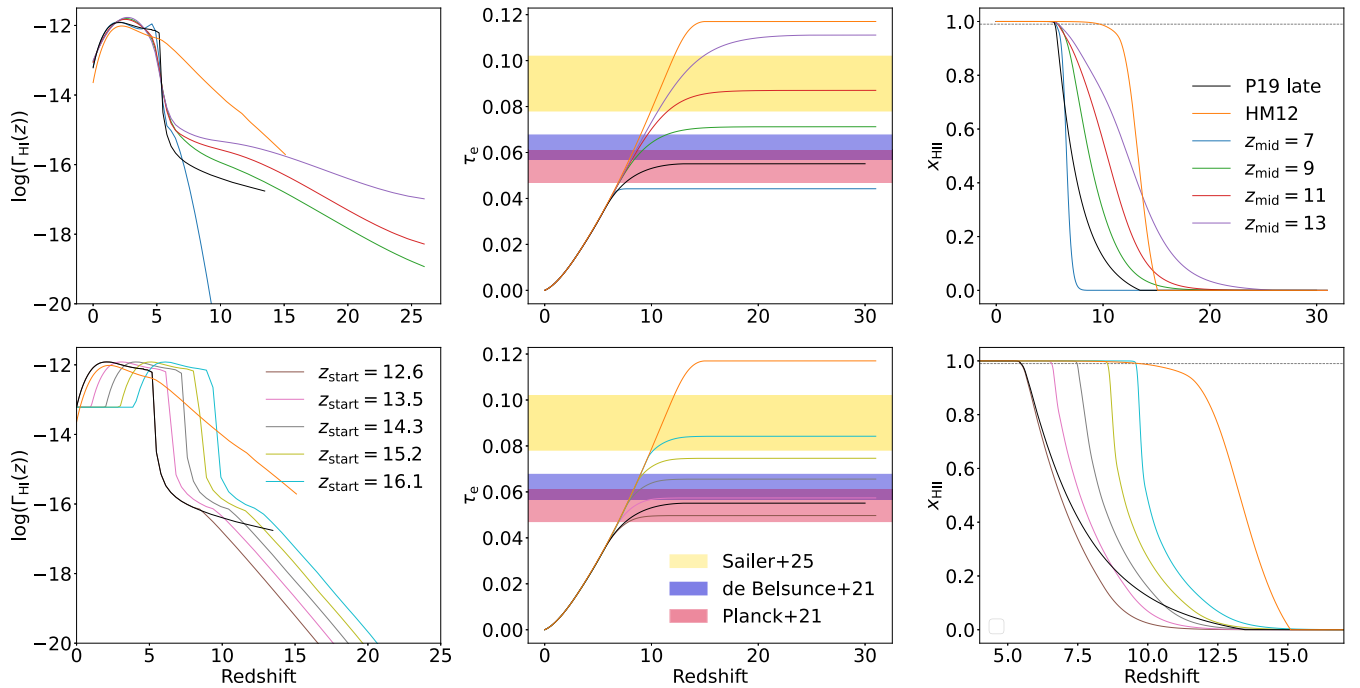


FIG. 1. H I photoionization rate Γ_{HI} (left), electron scattering optical depth τ_e (middle), and H II ionized fraction x_{HII} (right) for reionization models that keep $z_{\text{end}} = z_{\text{end}}^{\text{P19 late}}$ fixed (varying z_{mid}) and $\Delta z \approx 5.5$ fixed (varying z_{start}) in the top and bottom rows, respectively. We highlight in the middle column τ_e inferred by previous works [3,5,15]. We further show Puchwein *et al.*'s [16]'s late and Haardt and Madau's [17]'s reionization models in black and orange, respectively. The gray dashed line on the right column shows the Lyman- α forest end point of reionization requirement from the former: $x_{\text{HII}} \approx 1$.

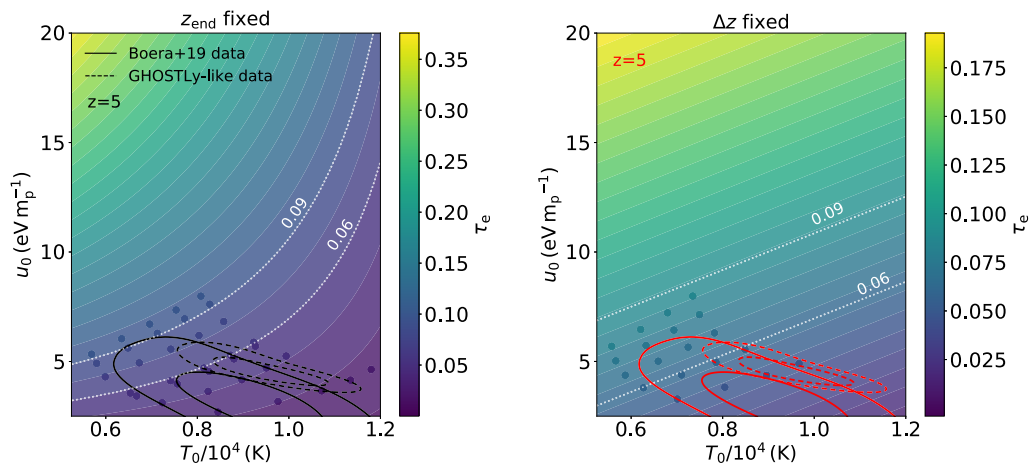


FIG. 2. Posterior in the u_0 - T_0 plane at $z = 5.0$ for the default analysis in Ref. [23] (Gaussian T_0 priors) shown as black and red solid contours. The posteriors resulting from the chains using mock data with smaller relative error bars of 5% are shown as dashed contours also in black and red. The colormap shows isocontours for τ_e . We highlight the $\tau_e = [0.06, 0.09]$ contours in white. The grid points show the simulated reionization models used to infer the extrapolation scheme for τ_e with fixing z_{end} in the *left* and Δz in the *right*. The grid points along the τ_e isocontours are obtained by rescaling the original photoheating rates by $\alpha = [0.5, 0.6, 0.7, 0.8, 0.9]$ [26].

constructed from synthetic Lyman- α forest spectra extracted from Sherwood-Relics simulations' skewers. The mock covariance matrix is rescaled to mimic 5% relative uncertainties. This mock dataset allows us to forecast how sensitive future 1D flux power spectra extracted from a large sample of quasars at the same redshift range ($4 < z < 5$) would be to τ_e . The GHOSTLY (Gemini High Resolution Optical Spectrograph) survey is a program that will target ~ 30 quasars, achieving comparable flux power spectrum error bars to those from our mock data [31,32]. Hereafter, analyses using the mock dataset will be termed GHOSTLY-like.

Hydrodynamic simulations/RT code. The nonlinear physical processes of the IGM to which the Lyman- α forest is sensitive can only be interpreted quantitatively using hydrodynamical simulations. In our previous work [23], we have used the Sherwood-Relics suite of simulations [33] with varying astrophysical parameters, including the mean IGM transmission τ_{eff} and temperature-density power-law index γ along with T_0 and u_0 , to train a neural network emulator. Cosmological parameters (e.g., σ_8) are kept fixed, to which the astrophysical parameters u_0 , T_0 are insensitive [34]. We build on previous work by considering the late reionization model from Ref. [16], with $z_{\text{end}}^{\text{P19 late}} = z(x_{\text{HII}} \approx 1)$. We further consider redshift-symmetric reionization models with fixed duration Δz , corresponding to the usual EoR parametrization employed in CMB analyses. To explore reionization models matching the constraints on z_{end} and Δz separately, we use the nonequilibrium photoionization code developed by Bolton *et al.* [35], and recently used by Šoltinský *et al.* [36]. Given input photoionization rates Γ_i and photoheating rates ϵ_i , the code solves the four coupled first-order differential equations for the abundance of ionized hydrogen and helium (the full “reionization equation” for each species) and for the temperature evolution [see Eqs. (B5)–(B8) in Ref. [37]]. We determine Γ_{HI} and ϵ_{HI} by trial and error, solving the nonequilibrium code until the resulting x_e evolution matches reionization models with $z_{\text{end}} = z_{\text{end}}^{\text{P19 late}}$ fixed and Δz fixed (see tabulated $\Gamma_{\text{HI}}(z)$ in Tables I and II, and corresponding $x_e(z)$

in Fig. S2 in the Supplemental Material [38]). In practice, we use as a starting point a simplified version of Eq. (B5) in Ref. [37], which relates Γ_{HI} and x_e . The photoheating rates are obtained by exploiting their coupling with Γ_{HI} from Eq. (1), with $E_{\text{ion}} = E_{\text{ion}}^{\text{P19 late}}$. The relevant He I quantities are effectively coupled to the H I rates, since both H I and He I reionization are driven by the same sources. The He II rates are left unchanged with respect to the late reionization model of Ref. [16], ensuring that the low-redshift evolution remains consistent with observational constraints.

Our code calculates x_{HII} , x_{HeII} , and x_{HeIII} , from which we compute u_0 . We further integrate over x_e , tied to the evolution of the number density of species i (see the closing conditions in Appendix B3 in Ref. [37]), to compute τ_e . Finally, we extract T_0 at the redshift z_{bin} of the data. In Fig. 1, we show the redshift evolution of Γ_{HI} for these two sets of reionization models, and τ_e and x_{HII} calculated from the output of the photoionization code as described above.

To map the thermal and ionization parameters, (i.e., u_0 - T_0 and τ_e), we first rescale E_{ion} by a factor α_E . This allows us to increase the number of simulated points used in the $u_0(z_{\text{bin}})$ - $T_0(z_{\text{bin}})$ plane, to improve the precision of our inference. This transforms $\mathcal{H}_{\text{HI}}$ following Ref. [26] and leaves τ_e unchanged. In this way, we obtain isocontours of τ_e in the $u_0(z_{\text{bin}})$ - $T_0(z_{\text{bin}})$ plane within the grid points. We further find that $z_{\text{bin}} = 5.0$ is the redshift from the Ref. [21] data most sensitive to τ_e . From the definition of τ_e , $x_e \sim \tau_e$, which depends on Γ_{HI} . From Fig. 1, τ_e is largest at the end of reionization, and therefore the contribution to the cumulative heat peaks at the redshift close to this point [from Eq. (1), one can see that the rate of change of u_0 depends on photoheating rates, and therefore on x_e].

Therefore, we map u_0 - T_0 at $z = 5.0$ ($u_0^{5.0}$, $T_0^{5.0}$) and τ_e by fitting a linear relation using the grid points in Fig. 2 obtained from the photoionization code. Since reionization models with z_{end} fixed exhibit a tighter correlation with u_0 compared to the Δz -fixed models, we include a second-order term in the fit for the former, leading to the isocontours shown in Fig. 2.

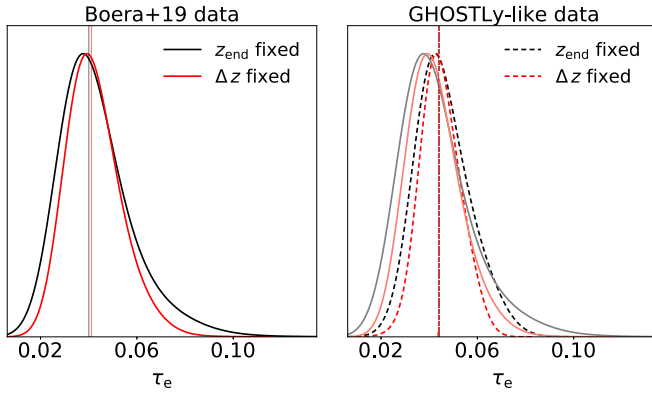


FIG. 3. 1D posterior distribution for τ_e obtained with z_{end} fixed in black and Δz fixed in red reionization models. Solid and dashed lines correspond to the analysis that uses Ref. [21] and GHOSTLy-like data, respectively. Vertical lines indicate the median of each distribution.

Results. The main results are shown in Figs. 2 and 3. The former shows the relation in the $u_0^{5.0}-T_0^{5.0}$ plane between thermal parameters and τ_e . We further show the contours obtained for a CDM cosmology using the emulator from Ref. [23] to check the range of τ_e allowed by the Ref. [21] data. Using the fit for τ_e ($u_0^{5.0}, T_0^{5.0}$) for each set of reionization models yields the following 68% (and 95% C.L.) constraints:

$$\left. \begin{aligned} \tau_e &= 0.040^{+0.017}_{-0.010} \text{ (} +0.042 \text{, } -0.018 \text{)}, & z_{\text{end}} \text{ fixed} \\ \tau_e &= 0.041^{+0.012}_{-0.010} \text{ (} +0.028 \text{, } -0.017 \text{)}, & \Delta z \text{ fixed} \end{aligned} \right\} \text{Boera+19.}$$

From our mock data, we furthermore find

$$\left. \begin{aligned} \tau_e &= 0.044^{+0.014}_{-0.010} \text{ (} +0.027 \text{, } -0.017 \text{)}, & z_{\text{end}} \text{ fixed} \\ \tau_e &= 0.044^{+0.010}_{-0.007} \text{ (} +0.018 \text{, } -0.014 \text{)}, & \Delta z \text{ fixed} \end{aligned} \right\} \text{GHOSTLy-like.}$$

Discussion. The above results indicate that independent constraints of τ_e from Lyman- α forest data are in good agreement with the *Planck* polarization measurements [5]. They are also consistent with other work that has measured τ_e without using CMB data [7], but note that our work does not rely on astrophysical constraints on x_{HII} .

Compared to the τ_e measurement from CMB and DESI BAOs [3,4], we find a mild tension at the 2.4σ and 2.8σ levels with current Lyman- α forest data for the z_{end} and Δz -fixed models, respectively. The tension weakens for $\tau_e = 0.08$, which, as suggested by Sailer *et al.* [3], would be sufficient to reconcile DESI with CMB observations. The panel on the right of Fig. 3 demonstrates the constraining power on τ_e that will be achieved with forthcoming quasar samples. Importantly, the upper uncertainty on τ_e will improve by a factor of ~ 1.6 . Consequently, if GHOSTLy-like data lead to similar constraints on the median of τ_e as current data, a *high* $\tau = 0.09$ will be excluded with 2.5σ and 3σ significance, respectively, for the two reionization models considered. Relating these results to the nature of the reionization history, we find that for *late* reionization models (matching z_{end} inferred from the Lyman- α forest opacity), reionization also needs to be *rapid*, since more extended histories would lead to a higher τ_e . For models with fixed duration Δz , *early* reionization models are strongly ruled out by the flux power

spectrum, since these will also imply a high τ_e . We assume a conservative $\Delta z \approx 5.5$, compared to *Planck* [5], since smaller values require earlier onset/end of reionization to achieve the same levels of τ_e , which is strongly disfavored by Lyman- α forest opacity constraints. Our baseline constraint, $\tau_e = 0.040^{+0.042}_{-0.018}$, suggests that the Lyman- α forest flux power spectrum alone prefers a relatively *rapid* and *late* reionization history. However, the significance of these results depends on the observational uncertainty on the value of z_{end} , as well as on the assumed duration of reionization. Such *high* τ_e values seemed to only be preferred due to the presence of strong degeneracies between the cosmological parameters, mainly with Ω_m and A_s [2]. Thus, we find that, in agreement with Refs. [7,18,20], a large CMB optical depth cannot meet the Lyman- α forest constraints on z_{end} .

We also note from Fig. 3 that the Lyman- α flux power spectrum is more sensitive to τ_e for our second set of reionization models. This highlights that τ_e depends on both the duration and timing of reionization (through the expansion rate $H(z)$ and the scaling of the proper electron number density with redshift). The sensitivity is also greater to the lower bound on τ_e in Fig. 3. However, the lower 1σ bound from the Ref. [21] data depends on the thermal histories considered for the extrapolation in the $u_0^{5.0}-T_0^{5.0}$ plane, since we do not impose any prior on the former parameter. The lowest $u_0^{5.0}$ and highest $T_0^{5.0}$ therefore correspond to the lowest τ_e . These *hotter* models with *lower* pressure smoothing are difficult to explain physically. The 2D contours from the GHOSTLy-like data in Fig. 2, however, become narrower in the direction constrained by the Lyman- α forest. The lower bound for τ_e is therefore not set by the choice of thermal histories, potentially leading to constraints that are as competitive as those from *Planck*.

We have run further an analysis where we impose a prior on $\tau_e \geq 0.034$, which is the lower bound on this parameter assuming instantaneous reionization and $z_{\text{end}} = z_{\text{end}}^{\text{P19 late}}$ [39]. We find $\tau_e = 0.047^{+0.039}_{-0.012}$ (95% C.L.). The corresponding contours in the $u_0^{5.0}-T_0^{5.0}$ plane are shown in the Supplemental Material [38].

The results discussed in this section are subject to a few caveats, mainly introduced by the assumption of Eq. (1). If the spectral energy distribution of the sources driving reionization changes with redshift, E_{ion} will also be redshift dependent. This could occur, for instance, in an Active Galactic Nuclei (AGN)-assisted reionization model, as has been suggested by recent JWST observations of high-redshift faint AGNs (e.g., Refs. [40–42]). However, these sources have been found to contribute at most $\approx 20\%$ to the reionization budget in order to match Lyman- α forest data [43,44]. Exotic sources of heat injection could further lead to an evolving $E_{\text{ion}}(z)$, such as dark matter annihilation or decay [45], or cosmic ray remnants of supernovae [46]. $E_{\text{ion}}(z)$ would modify the coupling between Γ_{HI} and ϵ_{HI} , and therefore the correlation between $u_0(z)-T_0(z)$ and τ_e , potentially leading to weaker τ_e constraints. The mapping between these thermal parameters and τ_e relies on an assumed EoR parametrization, which would change if Pop-III stars drive an early onset of reionization (e.g., Refs. [47,48]). We focus on standard reionization histories, as more complex models come with their own caveats.

Finally, we have checked that even a generously estimated uncertainty of z_{end} of $\sim \pm 0.5$ [49] shifts the τ_e posterior only by $< 1\sigma$. Marginalizing over this parameter would therefore make little difference to our results.

Conclusions. We have used the Lyman- α forest 1D flux power spectrum and its sensitivity to the thermal state of the IGM, through u_0 and T_0 , to constrain τ_e . Given the coupling between photoheating and photoionization rates, there exists a mapping between the thermal and ionization states of the IGM. We fit a relation between the two by solving the temperature and chemistry evolution equations for hydrogen and helium for two sets of reionization models using the nonequilibrium photoionization code from Ref. [35]. We consider z_{end} -fixed and Δz -fixed models, the former motivated by Lyman- α forest opacity bounds and the latter inspired by CMB reionization studies. To find the connection between u_0 - T_0 and τ_e , we use flux power spectrum measurements from Ref. [21] and find that the redshift bin closest to z_{end} is the most sensitive to τ_e , as that is when the pressure smoothing effect on the flux power spectrum is largest. Therefore, we fit a relation for τ_e ($u_0^{5.0}$, $T_0^{5.0}$) and use the same analysis framework as in our previous work [23] to measure τ_e . Our baseline constraints for z_{end} and Δz fixed, respectively, are $\tau_e = 0.040_{-0.018}^{+0.042}$ and $\tau_e = 0.041_{-0.017}^{+0.028}$. The constraints become stronger when using a mock dataset with the characteristics of the forthcoming GHOSTLY survey. In general, our findings are in agreement with a *rapid* and *late* reionization history from CMB data [5,18,20] and independent measurements of the ionized hydrogen fraction [7]. A large optical depth invoked to solve anomalies in DESI BAOs compared to CMB is not supported at the 2.4σ and 2.8σ levels for z_{end} -fixed and redshift-symmetric reionization models, respectively. The statistical significance of this

rejection will likely increase with future Lyman- α forest data. Overall, our findings demonstrate the current constraining power of the Lyman- α forest data on τ_e independently of the CMB, and the level of precision that will be achieved with forthcoming data. Our results, together with observational evidence for a *late* end of reionization from the Lyman- α forest opacity, suggest that z_{end} -fixed type of reionization models provide a more physically motivated framework for future reionization studies than redshift-symmetric reionization histories.

Acknowledgments. The authors thank Laura Keating for useful discussions. V.I. acknowledges partial support by the Kavli Foundation. The simulations used in this work were performed using the Cambridge Service for Data Driven Discovery (CSD3), part of which is operated by the University of Cambridge Research Computing on behalf of the STFC DiRAC HPC Facility [50]. The DiRAC component of CSD3 was funded by BEIS Capital funding via STFC capital Grants No. ST/P002307/1 and No. ST/R002452/1 and STFC Operations Grant No. ST/R00689X/1. DiRAC is part of the National e-Infrastructure. Support by ERC Advanced Grant 320596 “The Emergence of Structure During the Epoch of Reionization” is gratefully acknowledged. O.G.-G. has been supported by STFC Grant No. ST/Y509139/1. M.G.H. has been supported by STFC Consolidated Grants No. ST/N000927/1 and No. ST/S000623/1. J.S.B. was supported by STFC Consolidated Grant No. ST/X000982/1.

Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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