Limits on non-canonical heating and turbulence in the intergalactic medium from the low redshift Lyman-α forest

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ABSTRACT
We examine the column density distribution function (CDDF) and Doppler parameter distribution from hydrodynamical simulations and Cosmic Origins Spectrograph (COS) observations of the Lyα forest at redshift 0 ≤ z ≤ 0.2. Allowing for a factor of two uncertainty in the metagalactic H1 photoionisation rate, our hydrodynamical simulations are in good agreement (1−1.5σ) with the shape and amplitude of the observed CDDF at H1 column densities 10^{13.3} cm^{-2} ≤ N_{HI} ≤ 10^{14.5} cm^{-2}. However, the Doppler widths of the simulated lines remain too narrow with respect to the COS data. We argue that invoking AGN feedback does not resolve this discrepancy. We also disfavour enhanced photoheating rates as a potential solution, as this requires an unphysically hard UV background spectrum. Instead, we appeal to a non-canonical source of heating, an additional specific heat injection of u ≲ 6.9 eV m_p^{-1} is required at z ≲ 2.5 for gas that has N_{HI} ≳ 10^{13.5} cm^{-2} by z = 0.1. Alternatively, there may be an unresolved line of sight turbulent velocity component of v_{turb} ≲ 8.5 km s^{-1} (N_{HI}/10^{13.5} cm^{-2})^{0.21} for the coldest gas in the diffuse IGM.

Key words: methods: numerical - intergalactic medium - quasars: absorption lines

1 INTRODUCTION

Hydrodynamical simulations of the Lyα forest in a ΛCDM universe are in broad agreement with a range of observational data at redshift 2.5 ≤ z ≤ 4.5 (Hernquist et al. 1996; Lukić et al. 2015; Bolton et al. 2017; Rossi 2020; Villasenor et al. 2021). Allowing for the approximately factor of two uncertainty in the amplitude of the metagalactic UV background (e.g. Bolton et al. 2005; Becker & Bolton 2013), quantities such as the H1 column density distribution (Altay et al. 2011; Rahmati et al. 2013), the Doppler widths of the Lyα absorption lines (Schaye et al. 2000; Hiss et al. 2018), and the distribution and power spectrum of the transmitted flux (Rorai et al. 2017; Walther et al. 2019) can be readily reproduced. While astrophysical processes such as feedback (Theuns et al. 2002b; Viel et al. 2013; Chabanier et al. 2020) and spatial fluctuations in the UV background (Greig et al. 2015; Upton Sanderbeck & Bird 2020; Molaro et al. 2022) can further modify this picture, these effects are typically of secondary importance to the assumed cosmological model and the average photoionisation and photoheating rates (see McQuinn 2016, for a review).

Toward lower redshifts, however, the familiar character of the Lyα forest changes. Observationally, the redshifted Lyα transition shifts from optical to UV wavelengths at z ≃ 1.5, and can therefore only be observed from outside the atmosphere. Physically, the densities probed by the Lyα absorbers also change, from gas that is close to the mean background density, to higher density material that resides at the outskirts of galaxies (Theuns et al. 1998a; Davé et al. 1999, 2010; Nasir et al. 2017; Maitra et al. 2022). Recent progress has been largely driven by results from the Cosmic Origins Spectrograph (COS, Green et al. 2012) on the Hubble Space Telescope (e.g. Wakker et al. 2015; Danforth et al. 2016; Khare et al. 2019; Kim et al. 2021). Intriguingly, the straightforward evolution of successful Lyα forest models at z > 2 to lower redshift does not automatically guarantee a good match to the Lyα forest absorption lines identified with COS. One challenge is correctly reproducing the incidence of Lyα forest absorbers at z ∼ 0. Kollmeier et al. (2014) were the first to highlight a discrepancy between the observed and simulated H1 column density distribution function (CDDF) at z ∼ 0 for column densities 10^{13.6} cm^{-2} ≤ N_{HI} ≤ 10^{14.4} cm^{-2}, finding the
metagalactic H I photoionisation rate, \( \Gamma_{\text{HI}} \), required by the observed CDDF was considerably larger (by factor of \( \sim 5 \)) than predicted in the empirically calibrated Haardt & Madau (2012) UV background model. This implied that either the ionising photon production rate from galaxies and quasars had been significantly underestimated by Haardt & Madau (2012), or that the IGM simulations were missing an important physical ingredient. Subsequent work has revised this apparent discrepancy downward to a more manageable factor of two, either by using independent simulations (Wakker et al. 2015; Shull et al. 2015; Gaikwad et al. 2017; Viel et al. 2017; Nasir et al. 2017), revising the predicted amplitude of the UV background in the empirical models (Khaire & Srianand 2015, 2019; Puchwein et al. 2019; Faucher-Giguère 2020), or by invoking black hole feedback that efficiently heats and ionises the low density IGM (Christiansen et al. 2020). Regardless of any remaining tension between data and theory, however, this work has demonstrated that the Ly\( \alpha \) forest CDDF at \( z \sim 0 \) is a valuable diagnostic of ionising photon production and galactic feedback (Gurvich et al. 2017).

By contrast, the direct comparison of the Doppler parameter distribution of the Ly\( \alpha \) forest absorption lines identified with COS to hydrodynamical simulations has received less attention. The few studies that have attempted this recently have (as for the CDDF) also struggled to reproduce the COS data at \( 0 \leq z \leq 0.2 \), finding line widths that are too narrow compared to the observations (Gaikwad et al. 2017b; Viel et al. 2017; Nasir et al. 2017). The reason for this discrepancy remains unclear, but – assuming there are no unaccounted for instrumental systematics that systematically broaden the absorption lines – it suggests that the gas temperatures associated with the simulated Ly\( \alpha \) absorbers may be too low and/or there is missing non-thermal broadening in the models. It is also not certain whether missing feedback can resolve this discrepancy. Viel et al. (2017) and Nasir et al. (2017) found that the AGN feedback model used in the Sherwood simulations (Bolton et al. 2017) has a very limited impact on the Ly\( \alpha \) line widths; any additional hot gas was in the Warm-Hot IGM (WHIM), and was too highly ionised to detect in Ly\( \alpha \) absorption. On the other hand, more recently Christiansen et al. (2020) have found that hot, highly ionised gas produced by the jet feedback model in the SIMBA simulation (Davé et al. 2019) significantly improves agreement with the mean Ly\( \alpha \) forest transmission at \( z < 0.5 \). However, it is not obvious if this improved agreement also extends to the Doppler parameter distribution.

Hence, the goal of this work is to present a quantitative assessment of the additional heating and/or non-thermal contribution to the line widths required for consistency with the Ly\( \alpha \) forest CDDF and Doppler parameter distribution from COS observations at \( 0 \leq z \leq 0.2 \). We achieve this by forward modelling the COS data, and then fitting Voigt profiles to the simulations in the same manner as the observations. Our joint analysis of the CDDF and Doppler parameter distribution is then used to simultaneously constrain the metagalactic H I photoionisation rate and the effective power-law spectral shape of the UV background close to the Lyman limit. We shall argue that reproducing the Doppler widths of the Ly\( \alpha \) absorbers in the COS data by boosting the thermal line widths requires a UV background with an unphysically hard ionising spectrum. This implies that there is still missing physics in the models, and that either an additional, non-canonical heating mechanism, or a source of non-thermal broadening that is missed by the simulations (e.g., IGM turbulence), is necessary for achieving consistency between hydrodynamical simulations of the Ly\( \alpha \) forest and the COS data.

This paper is organised as follows. In Section 2 we describe the simulations used in this work. We then give an overview of the physical properties of simulated Ly\( \alpha \) forest absorbers at \( z \sim 0.1 \) in Section 3, and perform an initial comparison of our simulated results to the COS data. Section 4 describes the relationship between the UV background spectral shape and the IGM temperature in our models, and outlines the simple model we use for including an unresolved turbulent contribution to the Ly\( \alpha \) forest line widths. We then present and discuss our limits on non-canonical heating and/or the turbulent contribution required by the COS Ly\( \alpha \) absorbers in Section 5, and summarise our conclusions in Section 6. The corrections to the simulated CDDF for box size and mass resolution that we use throughout this work are presented in Appendix A. An examination of the effect that noise and spectral resolution have on the CDDF and Doppler parameter distribution is presented in Appendix B, along with a test of our assumption that photoionisation equilibrium holds in the low redshift Ly\( \alpha \) forest. In Appendix C, we compare the TNG100-1 simulation from the IllustrisTNG project (Nelson et al. 2019) to the COS data. We confirm that the Ly\( \alpha \) forest line widths predicted by TNG100-1 are also narrower than observed at \( z \sim 0.1 \).

Finally, throughout this work, it may be useful to recall that a \( M_{\text{HI}} \sim 10^{13.5} \text{cm}^{-2} \) Ly\( \alpha \) forest absorber at \( z = 0.1 \) is typically associated with a gas overdensity of \( \Delta \sim 10 \) (or equivalently \( n_{\text{HI}} \sim 10^{-5.6} \text{cm}^{-3} \)) within our models. Comoving and proper distance units use the prefixes “c” and “p” respectively.

2 NUMERICAL MODELS

2.1 Hydrodynamical simulations

The 18 cosmological hydrodynamical simulations used in this work are listed in Table 1. The simulations were performed with a version of the Tree-PM SPH code P-GADGET-3 (Springel 2005), modified for the Sherwood simulation project (Bolton et al. 2017; Nasir et al. 2017). Our fiducial box size is \( L = 60h^{-1} \text{Mpc} \) with \( 2 \times 768^3 \) gas dark matter and gas particles, giving a gas (dark matter) particle mass of \( M_{\text{gas}} = 6.38 \times 10^5 h^{-1} \text{M}_\odot \) (\( M_{\text{dm}} = 3.44 \times 10^7 h^{-1} \text{M}_\odot \)). This improves our fiducial mass resolution by a factor of 8 compared to Nasir et al. (2017). The gravitational softening length is set to 0.04 times the mean interparticle separation in all models. The cosmological parameters are \( \Omega_m = 0.308, \Omega_\Lambda = 0.692, h = 0.678, \Omega_b = 0.0482, \sigma_8 = 0.829 \) and \( n = 0.961 \) (Planck Collaboration et al. 2014), with a primordial helium fraction by mass of \( Y_p = 0.24 \) (Hsyu et al. 2020).

Our main simulation (AGN) incorporates energy-driven galactic outflows and AGN feedback using the model described in detail by Puchwein & Springel (2013). Briefly, the star formation model is based on Springel & Hernquist (2003), but for a Chabrier (2003) rather than Salpeter (1955) initial mass function and a galactic wind velocity that is directly proportional to the escape velocity of the galaxy. In the black hole feedback model, for the “quasar” mode when accretion rates are above 0.01 of the Eddington rate, 0.5 per cent of the accreted rest mass energy is thermally coupled to the gas. For lower accretion rates the “radio” mode is used instead. This is triggered for a fractional increase in the black hole mass of \( 10^{-4} \), with 2 per cent of the rest mass energy used for injecting hot AGN bubbles. This is the same star formation and AGN feedback model used in our earlier work on the Ly\( \alpha \) forest at \( z \sim 0.1 \) (Viel et al. 2017; Nasir et al. 2017).

To explore the effect of AGN feedback further, we also now consider a second model (StrongAGN) where the fractional increase in the black hole mass required for triggering the radio mode is increased to \( 10^{-2} \), with 8 per cent of the rest mass energy now used to inject hot AGN bubbles. This is the same as the “stronger radio”
model used by Henden et al. (2018), and it leads to less frequent but more energetic bubble injections and substantially lower gas fractions in the vicinity of haloes. We use this to provide a model that predicts a gas mass in the Warm-Hot IGM (WHIM) at low redshift that mimics the effect of jet-mode heating in the SIMBA simulation used by Christiansen et al. (2020) (see Section 3.1 for further details).

For the remainder of the simulations in Table 1 we ignore star formation and feedback, and instead directly convert gas with temperature $T < 10^5$ K and density $\Delta = \rho/(\rho_{\text{HII}}) > 10^3$ into collisionless particles (Viel et al. 2004). This “Quick-Ly$\alpha$” approach has been shown to be a reasonable approximation for unsaturated absorption lines, $N_{\text{HI}} < 10^{14.5}$ cm$^{-2}$, in the low redshift Ly$\alpha$ forest (Nasir et al. 2017). Importantly, the Quick-Ly$\alpha$ approach is less computationally expensive than the AGN feedback model, and for this reason we use it to create a grid of 11 simulations (H00–H10) with different IGM thermal histories that we use to obtain our UV background constraints in Section 5.

Photoionisation and heating by a spatially uniform UV background is included in all simulations assuming ionisation equilibration. We use the equilibrium equivalent rates from the UV background model of Puchwein et al. (2019, hereafter P19). This has the advantage of correctly incorporating non-equilibrium ionisation effects on the ionised fraction and gas temperature, but without the additional computational overhead of solving a non-equilibrium thermo-chemistry network. At $z = 0.1$, the P19 model has a photoionisation rate $\log(T_{\text{P19}}^\alpha/\text{s}^{-1}) = -13.04$ and predicts a gas temperature at the mean density of $T_0 \approx 4200$ K, and a power-law temperature-density relation, $T = T_0 \Delta^{\alpha}$, where $\alpha \approx 1.58$ for $\Delta = \rho/(\rho_{\text{HII}}) \lesssim 10$. In the 11 Quick-Ly$\alpha$ simulations (H00–H10) we have varied the UV background photoheating rates, $\epsilon_i$, in the P19 UV background model. We scale the hydrogen and helium photoheating rates by a constant $\zeta$, where $\epsilon_i = \zeta \epsilon^\alpha_i$ and $t = \alpha_1, \alpha_2, \alpha_3$ (cf. Becker et al. 2011). Self-shielding of dense gas to ionising photons is included on-the-fly in all simulations following Rahmati et al. (2013). Metal line cooling is not included, although Tepper-García et al. (2012) found this should have a very small effect on the column densities and Doppler parameters of low redshift Ly$\alpha$ forest absorbers (see their fig. C2). We also indirectly test this in Appendix C by performing a Voigt profile analysis on Ly$\alpha$ forest spectra drawn from the Illustris TNG100-1 simulation, which does include metal line cooling.

For comparison with the canonical UV photoheating paradigm, following Kollmeier et al. (2014) we also consider an alternative model (Blazar) where heating in the IGM at $z < 3$ is dominated by TeV emission from blazars. This results in a much higher temperature in the low-density IGM, $T_0 \approx 31,100$ K, compared to UV photoheating models, with a temperature-density relation that is “inverted” (i.e. $\gamma < 1$) due to a volumetric heating rate that is independent of density (Chang et al. 2012). We adopt the intermediate heating model from Puchwein et al. (2012) for this purpose (see their eq. (1) and table 1), and perform the simulation using the Quick-Ly$\alpha$ approximation.

Finally, we perform four more Quick-Ly$\alpha$ simulations to assess the convergence of our results with box size and mass resolution; these models are listed in the lower section of Table 1. We use these models to apply a correction to the simulated CDDF at our fiducial mass resolution and box size. This correction is listed in Table A1 in Appendix A, along with a more detailed discussion of the convergence properties of the Quick-Ly$\alpha$ simulations.

2.2 Simulated and observed Ly$\alpha$ forest spectra

Simulated Ly$\alpha$ forest spectra are extracted using an approach similar to Nasir et al. (2017). We randomly draw 16384 lines of sight parallel to the box axes, where each line of sight has 2048 pixels. The Ly$\alpha$ optical depths are then obtained from the particle data using the interpolation scheme described by Theuns et al. (1998b) combined with the Voigt profile approximation from Tepper-García (2006).

In this work we will compare the simulated spectra to observational measurements of the Ly$\alpha$ forest CDDF and Doppler parameter distribution first described in Viel et al. (2017). These data are obtained from 44 AGN spectra, selected to have a signal-to-noise per resolution element of $S/N > 20$ and an emission redshift of $0.1 < z_{\text{em}} < 0.35$, and form part of the larger data set recently presented by Kim et al. (2021). Further details regarding the COS data reduction and Voigt profile fitting can be found in Wakker et al. (2015) and Kim et al. (2021). The Voigt profile fits to the COS data and simulations have been obtained using the Ly$\alpha$ transition only. The line list we use consists of 704 H1 Ly$\alpha$ lines with mean redshift $\langle z \rangle = 0.09$, mean column density $\langle \log(N_{\text{HI}}/\text{cm}^{-2}) \rangle = 13.29$ and mean Doppler parameter $\langle b \rangle = 36.6$ km s$^{-1}$. The total redshift path length of the data is $\Delta z = 4.991$, covering the Ly$\alpha$ forest at $0 \leq z \leq 0.2$. As already shown in Nasir et al. (2017), the CDDF and Doppler parameter distribution we use are consistent with independent measurements using COS data from Danforth et al. (2016) and Gaikwad et al. (2017b) over the range of interest for this work.

In order to approximately forward model the COS data, all the simulated spectra are convolved with the COS line spread function$^1$ at 1341 Å, for central wavelength G130M/1327 at lifetime position L1. The spectra are then rebinned onto pixels of width $0.02991$ Å (i.e. 3 times the COS binning of 0.00997 Å following Kim et al. (2021)) and Gaussian distributed noise with a flux independent signal-to-noise ratio of $S/N = 30$ per 19 km s$^{-1}$ resolution element (i.e. $S/N \sim 17.7$ per pixel) is added. Voigt profile fitting to the simulated Ly$\alpha$ spectra is then performed with VPFIT version 10 (Carcwell & Webb 2014), which deconvolves the (already convolved) mock spectra with the instrument profile to obtain the intrinsic line widths. We emphasise that, to ensure a fair comparison between observations and simulations, we have considered only the Ly$\alpha$ lines obtained with VPFIT in this work. This minimises any biases that would arise if, e.g., we had used higher order Lyman series information to perform a curve-of-growth analysis on either the observational or simulated data alone.

We assess the role that a different signal-to-noise ratio or line spread function may have on the recovery of the CDDF and Doppler parameter distribution in Appendix B. To summarise those results, we find that absorption lines with $10^{13.3}$ cm$^{-2} \leq N_{\text{HI}} \leq 10^{14.5}$ cm$^{-2}$ and $20$ km s$^{-1} \leq b \leq 90$ km s$^{-1}$ will remain insensitive to the expected variations in the $S/N$ or line spread function. We will only use the absorption lines in these ranges when obtaining UV background constraints from the COS data. This sub-set consists of 297 H1 Ly$\alpha$ lines with mean redshift $\langle z \rangle = 0.09$, mean column density $\langle \log(N_{\text{HI}}/\text{cm}^{-2}) \rangle = 13.70$ and mean Doppler parameter $\langle b \rangle = 39.9$ km s$^{-1}$.

$^1$ https://www.stsci.edu/hst/instrumentation/cos/performance/spectral-resolution
In this work we identify the virial radius, $R_{\text{vir}}$, as the radius of a sphere centered at the halo center of mass that has mean density $\Delta_c$ times the critical density, where $\Delta_c$ is given by eq. (6) of Bryan & Norman (1998).
The physical properties of the Lyα forest absorbers are explored further in Fig. 2, where the Doppler parameters, $b$, and $N_{\text{HI}}$ column densities, $N_{\text{HI}}$, obtained from fitting mock spectra with Voigt profiles are displayed in the $b-N_{\text{HI}}$ plane. In each panel, the colour scale shows the (optical depth weighted) gas density, gas temperature, baryon phase, and the ratio $b/b_{\text{therm}}$ (where $b_{\text{therm}} = (2k_{\text{B}}T/m_{\text{H}})^{1/2}$ is the thermal line width) associated with the absorbers. The baryon phase definitions follow those introduced by Davé et al. (2010) (see Table 2 for details). The absorption lines enclosed by the dashed lines (i.e. for $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$, $20 \text{ km} \text{s}^{-1} \leq b \leq 90 \text{ km} \text{s}^{-1}$) are associated with predominantly photoionised gas with a median gas density $\log \Delta = 1.14$, median temperature $T = 38380 \text{ K}$ and median $b/b_{\text{therm}} = 1.28$. Note that $b/b_{\text{therm}}$ is consistent with curve-of-growth analyses that use higher order Lyman series lines to separate unresolved Lyα components. For example, Danforth et al. (2010) perform a curve-of-growth analysis on 164 Lyα absorbers using HST/STIS data, finding a median ratio $R_{\text{Lyα}}/R_{\text{cog}} = 1.26 \pm 0.49$ (see also Shull et al. 2000; Danforth & Shull 2008). In general, the

Figure 1. Left: A square slice ($60 h^{-1} \text{ cMpc}$ on each side) displaying the logarithm of the gas density, $\log \Delta = \log (\rho/\rho_0)$, in the AGN simulation at $z = 0.1$, projected over a distance of $500 h^{-1} \text{ cMpc}$. The Lyα absorbers in the slice with H1 column densities $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$ are over-plotted as coloured circles. The cyan stars show the location of haloes in the slice with total mass $M_h \geq 10^{12} M_\odot$. Right: The fraction of Lyα absorbers in the full simulation volume at redshift $z = 0.1$, in bins of width $\Delta \log (N_{\text{HI}}/\text{cm}^{-2}) = 0.2$, located within one (cyan bars), two (orange bars) or three (red bars) virial radii, $R_{\text{vir}}$, of haloes with total mass $10^{10} M_\odot \leq M_h < 10^{12} M_\odot$ (upper panel) or $M_h \geq 10^{12} M_\odot$ (lower panel). Note the different scale on the vertical axis of the lower panel. The percentages at the base of each bar give the fraction of absorbers within $r < R_{\text{vir}}$. 

Table 2. The percentage of Lyα absorbers with $20 \text{ km} \text{s}^{-1} \leq b \leq 90 \text{ km} \text{s}^{-1}$ and $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$ in the AGN, StrongAGN, H02 and Blazar simulations that are associated with the four temperature-density phases defined by Davé et al. (2010). For comparison, the number in parentheses gives the baryon mass fraction associated with each phase, where we also include stars in the condensed phase. The mass fraction in the condensed+stars phase is artificially high in the H02 and Blazar models as a result of using the Quick-Lyα scheme for converting gas to star particles. Note also that while the relative fraction of Lyα absorbers in each phase remains similar across all models, the mass fraction in the WHIM (shown in parentheses) increases significantly in the StrongAGN simulation.

| Model                  | Diffuse IGM $T < 10^5 \text{ K}, \Delta < 97.2$ | WHIM $T \geq 10^5 \text{ K}, \Delta < 97.2$ | Hot halo $T \geq 10^5 \text{ K}, \Delta \geq 97.2$ | Condensed+stars $T < 10^5 \text{ K}, \Delta \geq 97.2$ |
|------------------------|-----------------------------------------------|--------------------------------------------|------------------------------------------|-----------------------------------------------|
| AGN                    | 83.4 (36.7)                                  | 15.2 (37.9)                                | 0.7 (16.1)                               | 0.7 (9.3)                                     |
| StrongAGN              | 82.1 (20.1)                                  | 16.8 (68.4)                                | 0.6 (3.0)                                | 0.5 (8.5)                                     |
| H02 (No SF/feedback)   | 87.3 (35.5)                                  | 10.2 (21.2)                                | 2.0 (13.9)                               | 0.5 (29.4)         |
| Blazar (No SF/feedback)| 82.9 (23.2)                                  | 14.9 (34.3)                                | 1.9 (13.5)                               | 0.3 (29.0)         |
larger column densities and Doppler parameters are associated with higher gas densities and temperatures, respectively. The majority of the absorbers (90 per cent) with $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$ exhibit suprathermal line widths and 83 per cent are associated with the diffuse IGM. Only the absorbers close to the lower boundary of the $b-N_{\text{HI}}$ plane have thermal widths; most of the other Lyα lines are also broadened by peculiar motions and the blending of unresolved Lyα components, gas pressure (Jeans) smoothing and expansion with the Hubble flow.

Finally, in Table 2 we summarise the percentage of Lyα absorbers associated with the four gas phases (diffuse IGM, WHIM, hot halo, and condensed) defined by Davé et al. (2010) are listed for the AGN, StrongAGN, H02 (i.e. the Quick-Lyα simulation with no feedback or star formation) and Blazar models. Note that a similar fraction of
the Lyα absorbers are associated with each baryon phase in all four simulations. This may be contrasted with the baryon mass fraction in each phase, shown in the parentheses in Table 2. In particular, the mass fraction associated with the WHIM increases dramatically in the StrongAGN model. However, this has a very limited effect on the fraction of absorbers in each phase, since most of this gas is too hot and/or low density to produce Lyα absorption lines (Viel et al. 2017).

3.2 Comparison of the models to COS data

We now perform an initial comparison of the simulated spectra to measurements of the column density distribution function (CDDF) and Doppler parameter distribution. The CDDF and Doppler parameter distribution observations were first presented in Viel et al. (2017). In this work, the 1σ uncertainties on the measurements are obtained using 10^3 bootstrap samples with replacement.

The AGN, StrongAGN, Blazar and H02 simulations are compared directly to the COS data in Fig. 3. Following Viel et al. (2017), the H1 column densities from each model have been rescaled by a constant to match the amplitude of the observed CDDF at 10^{13.3} cm^{-2} \leq N_{\text{HI}} \leq 10^{14.5} cm^{-2}. Assuming the Lyα absorbers are in photoionisation equilibrium, this is equivalent to a rescaling of the H1 photoionisation rate Γ_{\text{HI}}, since N_{\text{HI}} \propto \Gamma_{\text{HI}}^{-1}. We verify in Appendix B that this approximation is a good one for modelling the CDDF at 10^{13.3} cm^{-2} \leq N_{\text{HI}} \leq 10^{14.5} cm^{-2} (although see also Khaire et al. 2019), who find this is not the case for the Lyα forest power spectrum at z < 0.5. We speculate this may be due to including absorbers with N_{\text{HI}} > 10^{14.5} cm^{-2}, and/or the influence of hot gas that produces absorption near the continuum that is too weak and/or broad to be identified reliably with VPFIT). The photoionisation rate required to match the observed CDDF, Γ_{\text{CDDF}}^\text{H1}, is a factor of 0.4–0.6 times the P19 UV background model value at z = 0.1, suggesting that the P19 model may overproduce the UV background at z ∼ 0.1. The simulations with a higher fraction of hot gas, either from additional physics (StrongAGN and Blazar) or from artificially increased photoheating rates (e.g. H10) require the smallest Γ_{\text{CDDF}}^\text{H1} as a result of the reduced recombination rate in the hotter IGM (see the second last column of Table 1).

For comparison to the literature, we also calculate the ratio of Γ_{\text{CDDF}}^\text{H1} to the photoionisation rate at z = 0.1 from the Haardt & Madau (2012, hereafter HM12) UV background model; we list this in the final column of Table 1. For absorbers with 10^{13.6} cm^{-2} \leq N_{\text{HI}} \leq 10^{14.4} cm^{-2}, Kollmeier et al. (2014) found that Γ_{\text{CDDF}}^\text{H1} differed from the HM12 model by a factor of ∼ 5 within their simulations. Christiansen et al. (2020) recently revised this discrepancy downward by a factor of ∼ 2 by invoking IGM heating associated with jet feedback in the SIMBA simulation. This revised estimate is in better agreement with the smaller factor of ∼ 2 discrepancy noted

3 We choose to match the CDDF over a limited range in N_{\text{HI}}, rather than matching the mean or distribution of the Lyα forest transmission, as the CDDF is less susceptible to systematic uncertainties associated with signal-to-noise and the uncertain properties of high density gas in the CGM. Nevertheless, we note the mean transmission associated with the rescaled CDDF – given in Table 1 – is in excellent agreement with ⟨F⟩ = 0.983 ± 0.009 at ⟨z⟩ = 0.08 from Kim et al. (2021) and the flux decrement ΔF_{\text{z}} = 1 - ⟨F⟩ = 0.014(1 + z)^{2.2±0.3} from Shull et al. (2015).
by other independent studies (Wakker et al. 2015; Shull et al. 2015; Gaikwad et al. 2017a; Viel et al. 2017), although for different reasons, as these models did not include jet feedback. In this work we find a difference of at most a factor of \( \sim 1.7 \) compared to HM12 for our fiducial AGN feedback and no feedback models (H02), which is within the factor of \( \sim 2 \) uncertainty expected in UV background models (e.g. Khaire & Srianand 2015; Faucher-Giguère 2020). The additional hot gas in the StrongAGN model decreases the \( \Gamma_{\text{CDDF}} \) by a further factor of \( \sim 2 \) relative to our fiducial AGN and H02 simulations, which is also in good agreement with the relative change found by Christiansen et al. (2020) when comparing the SIMBA jet and no-jet feedback models.\(^4\) Sufficiently potent AGN feedback that heats the low density IGM can therefore relax the requirement on the number of ionising photons that was first pointed out by Kollmeier et al. (2014), although in contrast to Christiansen et al. (2020), we find this additional heating is not necessarily required. Blazar heating has a qualitatively similar effect on the required \( \Gamma_{\text{CDDF}} \) to strong AGN feedback, as was also noted by Kollmeier et al. (2014) (see their fig. 3).

Following the rescaling of the column densities, all four models in the left panel of Fig. 3 are in good agreement (i.e. within \( \sim 1-1.5\sigma \)) with the observed CDDF at \( 10^{13.3}\text{cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5}\text{cm}^{-2} \). Note again that at column densities \( N_{\text{HI}} \lesssim 10^{13.3}\text{cm}^{-2} \) the CDDF is in-complete and is dependent on the assumed signal-to-noise (see Appendix B). Comparing the H02 and StrongAGN models, we find that strong AGN feedback can alter the shape and amplitude of the CDDF. This is in agreement with earlier work by Gurvich et al. (2017), although differences between the models are within \( \sim 1\sigma \) at the column densities, \( N_{\text{HI}} \gtrsim 10^{13.3}\text{cm}^{-2} \), where the COS data are complete. With a higher precision measurement of the CDDF, it may therefore be possible to use the slope of the CDDF around \( N_{\text{HI}} \sim 10^{14}\text{cm}^{-2} \) to distinguish between different feedback models. We note, however, that the differences between H02 (no feedback) and our fiducial AGN model are very small at \( N_{\text{HI}} \gtrsim 10^{13.3}\text{cm}^{-2} \), and are comparable to those found by Nasir et al. (2017) and Viel et al. (2017), reiterating their finding that AGN feedback plays a negligible role in changing the amplitude of the CDDF for our fiducial AGN feedback model. We therefore conclude that the extent to which AGN feedback and galaxy formation impact on the CDDF will depend on the specifics of the (uncertain) sub-grid modelling. In contrast our earlier work (Viel et al. 2017; Nasir et al. 2017), however, we find better agreement between the simulated and observed CDDF at \( 10^{14}\text{cm}^{-2} < N_{\text{HI}} \leq 10^{14.5}\text{cm}^{-2} \), and are comparable to those found by Nasir et al. (2017) and Viel et al. (2017).

4. Note the mass fraction in the diffuse IGM and WHIM for the StrongAGN (AGN) models are very similar to the Jet (No-Jet) models presented by Christiansen et al. (2020) which have 16.4 (38.8) per cent and 70.5 (28.7) per cent of the baryon mass in the diffuse IGM and WHIM, respectively (cf. Table 2 in this work).

**4 THERMAL AND TURBULENT LINE BROADENING**

### 4.1 The thermal asymptote at \( z \leq 0.5 \)

Since we argue that our AGN feedback models fail to explain the observed line widths in the Ly\( \alpha \) forest at \( z \approx 0.1 \), we now turn to consider alternatives. One possible explanation for the discrepancy between the simulated and observed Doppler parameter distribution is increased photoheating associated with a hardening of the UV background spectrum. The resulting enhancement to the IGM temperature produces additional thermal broadening in the Ly\( \alpha \) forest. Indeed, additional photoheating is typically invoked to explain the IGM temperature boost inferred from the Ly\( \alpha \) forest at \( z \approx 3 \) (Schaye et al. 2000; Ricotti et al. 2000; Becker et al. 2011; Walther et al. 2019), when the rising contribution to the ionising emissivity from quasars is thought to harden the UV background spectrum and drive He\( \text{II} \) reionisation (Theuns et al. 2002a; Bolton et al. 2009; Puchwein et al. 2015; Upton Sanderbeck et al. 2016). An interesting question is then: how hard would the UV background spectrum need to be to achieve consistency between the observed COS line widths and theoretical models? More importantly, is the required spectral hardening physically plausible?

In the canonical model, the IGM is expected to follow a power-law temperature-density relation following reionisation, \( T = T_{0}\Delta^{-0.72} \), with some additional scatter around this relation due to shock heating (Hui & Gnedin 1997; McQuinn & Upton Sanderbeck 2016). This arises due to photoheating and adiabatic cooling for densities \( \Delta \lesssim 10 \). At late times the slope of this relation approaches \( T \propto \Delta^{0.58} \), where the exponent \( \gamma - 1 = 0.58 \) arises through the temperature dependence of the case-A recombination coefficient for hydrogen, \( \alpha_{\text{A}} \propto T^{-0.72} \) (see e.g. Miralda-Escudé & Rees 1994; McQuinn & Upton Sanderbeck 2016). The temperature-density relation furthermore retains no memory of its earlier reionisation and heating history \( \Delta \sim 1-2 \) after \( \text{HII} \) reionisation at \( z \approx 6 \) or \( \text{HeII} \) reionisation at \( z \approx 3 \). Once this “thermal asymptote” is reached and the IGM is in photoionisation equilibrium, the IGM temperature is set only by the spectral shape of the UV background (Hui & Haiman 2003), and is independent of the UV background intensity.

This is further illustrated in the Fig. 4, where we perform a non-equilibrium ionisation calculation to obtain the temperature of a hydrogen and helium gas parcel that is ionised by a time indepen-
The results for $\Delta = 1$ in Fig. 4 (left panel) encompass the recent IGM temperature measurements at the mean density, $T_0$, from Gaikwad et al. (2021), who use a variety of different statistical measures of the Ly$\alpha$ forest transmitted flux to obtain joint constraints on $T_0$ and $\gamma$ at $2 \leq z \leq 3.8$. The models are also consistent with the only IGM temperature measurement to date from the Ly$\alpha$ forest at $z \simeq 0$ (Ricotti et al. 2000), although the error bars of this measurement are large (see their fig. 12). Note, however, our aim is not to match these data points; a single zone reionisation model will in any case not correctly capture the volume averaged gas temperature during inhomogeneous He$\textsc{ii}$ reionisation at $z \simeq 3$ (see e.g. Upton Sanderbeck et al. 2016; Upton Sanderbeck & Bird 2020). The important point, as we now discuss below, is that this approach captures the late time behaviour of the IGM temperature when it tracks the thermal asymptote (cf. Hui & Haiman 2003).

First, note that Fig. 4 shows the gas temperatures in the low density IGM at $z < 0.5$ follow a single thermal asymptote, as expected. This implies a temperature sensitive statistic, such as the Doppler parameter distribution, should provide an excellent constraint on the spectral shape of the UV background at $z \simeq 0$ if the low column density Ly$\alpha$ forest is primarily thermally broadened by photo-

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**Figure 4.** Left: Temperature evolution with redshift for a gas parcel at the mean density, $\Delta = 1$, that has been photoionised and heated by a power-law UV spectrum, $J_{\nu} \propto E^{-\alpha_{\text{eff}}}$, Individual panels show the effect of varying different parameters on $T_0$. Clockwise from the top left, these are: the effective power-law spectral index, $\alpha_{\text{eff}}$, the redshift of He$\textsc{ii}$ reionisation, $z_{R,\text{HeII}}$, the specific intensity at the Lyman limit, $J_{22} = J_{13.6 \text{eV}/10^{-22} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}}$, and the redshift of He$\textsc{i}$ reionisation, $z_{R,\text{HeI}}$. The central parameter values, corresponding to the black curves in each sub-panel, are $\alpha_{\text{eff}} = 0.5$, $z_{R,\text{HeI}} = 6.5$, $z_{R,\text{HeII}} = 3.0$ and $J_{22} = 0.1$. Note that the temperature at $z \leq 0.5$ depends only on the spectral index. For comparison, temperature measurements from the Ly$\alpha$ forest at $2 \leq z \leq 3.8$ are shown as open circles (Gaikwad et al. 2021), and at $z = 0.06$ by an open square (Ricotti et al. 2000). Right: As for the left panel, but now for a gas parcel with $\Delta = 10$, similar to the densities typically probed by the $z = 0.1$ Ly$\alpha$ forest. Note the different scale on the vertical axis compared to the left panel.
heating. It is convenient to provide a fit to the temperature at the thermal asymptote at the mean density, Θ₀, as a function of α_eff at 0 ≤ z ≤ 0.5. Our numerical results from the non-equilibrium ionisation calculations are well approximated by

\[ \Theta_0(\alpha_{\text{eff}}, z) = 10^{\alpha_0(z)} K [\alpha_{\text{eff}} + k_1(z)]^{k_2(z)}, \]

where the redshift dependent coefficients \( k_0, k_1, k_2 \) are listed in Table 3. Eq. (3) reproduces the numerical calculation to within 1 per cent for −1.5 ≤ α_{\text{eff}} ≤ 3.0.

We can therefore use Eq. (3) to estimate the effective power-law spectra indices, α_{\text{eff}}, that are equivalent to the spectral shape assumed in different synthesis models for the metagalactic UV background (Haardt & Madau 2012; Khaire & Srianand 2019; Puchwein et al. 2019; Faucher-Giguère 2020). In Fig. 5, the black dotted curves show Eq. (3) at redshifts 0 ≤ z ≤ 0.5 for a power-law UV background spectrum with \( J_\gamma \sim E^{-\alpha_{\text{eff}}} \). The fits reproduce the numerical calculation to within 1 per cent for −1.5 ≤ α_{\text{eff}} ≤ 3.0.

Table 3. Coefficients for the best fit to the thermal asymptote, Θ₀, obtained using Eq. (3) at redshifts 0 ≤ z ≤ 0.5 for a power-law UV background spectrum with \( J_\gamma \sim E^{-\alpha_{\text{eff}}} \). The fits reproduce the numerical calculation to within 1 per cent for −1.5 ≤ α_{\text{eff}} ≤ 3.0.

| Redshift, z | k₀ | k₁ | k₂ |
|------------|----|----|----|
| 0.0        | 3.976 | 2.412 | −0.725 |
| 0.1        | 4.022 | 2.413 | −0.727 |
| 0.2        | 4.063 | 2.414 | −0.729 |
| 0.3        | 4.099 | 2.415 | −0.732 |
| 0.4        | 4.131 | 2.416 | −0.734 |
| 0.5        | 4.161 | 2.417 | −0.737 |

6 Note, however, that in photoionisation equilibrium the gas temperature at densities \( \Delta \gtrsim 10 \) will become increasingly sensitive to the spectral shape and specific intensity of the UV background, as the dominant gas cooling mechanism transitions from adiabatic to radiative cooling. In this regime, lowering \( J_{\gamma_2} \) produces colder gas temperatures, since the H1 collisional excitation cooling rate scales as \( \sim n_{HI} \). For gas with \( \Delta = 100 \) at \( z \sim 0.1 \) (\( N_{HI} \sim 10^{13} \text{cm}^{-2} \)) the range of temperatures that result from \( J_{\gamma_2} = 0.03–0.6 \) in our single zone model becomes comparable to the range of temperatures for \( \alpha_{\text{eff}} = −0.5–1.5 \).

7 This hardening is due to the combined effect of the HeI opacity of the IGM and the rapidly declining UVB emissivity at \( z < 1 \). The mean free path at the HeI ionisation edge (\( E \approx 54.4 \text{eV} \)) is \( \sim 500 \text{pMpc} \) by \( z \sim 1 \) (see fig. 1 in Puchwein et al. 2019), so a non-negligible fraction of the \( z \sim 0 \) UVB at \( E \sim 54.4 \text{eV} \) is produced by redshifted photons emitted at higher energies. The average excess energy per HeI photoionisation is therefore significantly increased above that expected for an optically thin IGM at \( z \sim 0 \) (see fig. 3 in Puchwein et al. 2019). By contrast, the UVB spectrum between 13.6\,eV < E < 54.4\,eV can instead slightly soften as a result of IGM processing (Shull & Danforth 2020).
et al. (2014) (consistent with the $\alpha_{eq} = 1.4$ model from Khaire & Srianand (2019), a plausible hard limit for quasar dominated UV background models is approximately $\alpha_{eff} \approx 1$, yielding $\Theta_0 \approx 4300 \text{K}$ ($\Theta_1 \approx 14050 \text{K}$) for the thermal asymptote at $z = 0.1$. A more extreme case is possible if instead adopting the harder Tilton et al. (2016) composite spectrum and once again assuming some spectral hardening at the Heii edge, such that $\alpha_{eq} - \alpha_{max} \approx -0.5$. If taking the lower bound of the Tilton et al. (2016) 1σ measurement, we obtain $\alpha_{eff} \approx 0$, yielding $\Theta_0 \approx 5550 \text{K}$ ($\Theta_1 \approx 18150 \text{K}$). We caution, however, the Tilton et al. (2016) composite spectrum may be less reliable than Stevens et al. (2014) due their use of low resolution COS/G140L spectra and their small sample size. In either case, as we will demonstrate in Section 5, an IGM heated by a UV background spectrum with $0 < \alpha_{eff} < 1$ would still be too cold to reproduce the COS Ly$\alpha$ line width distribution in our simulations in the absence of any additional non-thermal broadening.

### 4.2 Unresolved non-thermal broadening

An alternative to increasing the thermal widths of the Ly$\alpha$ absorbers is the introduction of unresolved non-thermal broadening in hydrodynamical simulations of the IGM (e.g. Oppenheimer & Davé 2009; Gaikwad et al. 2017b). We can make a crude estimate of the turbulent contribution needed to reproduce the COS Doppler parameter distribution using the approach introduced by Oppenheimer & Davé (2009). Let there be an unresolved (i.e. sub-grid) turbulent component in the simulated Ly$\alpha$ absorbers, where

$$b_{turb}^2 = b_{obs}^2 - b_{noturb}^2. \quad (4)$$

Here $b_{turb}$ is the turbulent contribution to the Doppler parameters, $b_{obs}$ are the observed Doppler parameters in the COS data, and $b_{noturb}$ are the Doppler parameters obtained from our simulated spectra. Defining $\xi = b_{obs}/b_{noturb}$, Eq. (4) then becomes

$$b_{turb} = (\xi^2 - 1)^{1/2} b_{noturb}. \quad (5)$$

We may now estimate the $b_{turb}$ required to match the COS line widths by taking the photovering in our fiducial UVB model ($\alpha_{eff} = 1.17$) as an effective prior on the gas temperature. From the black dashed curve in the right panel of Fig. 3, we will assume a boost to the line widths of $\xi = b_{obs}/b_{noturb} \approx 1.24$ will allow the AGN and H2 simulations to approximately match the COS data. From Eq. (5), this corresponds to a turbulent Doppler parameter contribution of $b_{turb} \approx 0.73 b_{noturb}$.

It is also instructive to have an estimate for $b_{turb}$ as a function of column density, $N_{HI}$. Here we make use of the fact that the narrowest Ly$\alpha$ line widths associated with gas on the temperature-density relation in the diffuse IGM at $z \approx 0.1$ are thermally broadened (see Fig. 2 and associated discussion). Assuming $b_{noturb} \approx b_{therm}$ for these absorbers, Eq. (4) then becomes

$$b_{turb} = (\xi^2 - 1)^{1/2} \left( \frac{2k_B T}{m_{HI}} \right)^{1/2}. \quad (6)$$

Next, assuming the size of Ly$\alpha$ forest absorbers is set by the local Jeans scale in the IGM (Schaey 2001; Garzilli et al. 2015), a power law relationship between $N_{HI}$ and density will hold,

$$N_{HI} = N_{HI,0} \Delta^b. \quad (7)$$

where $\beta = 1.72 - 0.22\gamma$ for $T = T_0 \Delta^{-1}$ and a case-A recombination coefficient $^\dagger\alpha_A \approx 4.06 \times 10^{-13} \text{cm}^3 \text{s}^{-1} (T/10^4 \text{K})^{-0.72}$. For our

- The power-law approximation for $\alpha_A$ given here reproduces the more acc-

### 5 RESULTS

#### 5.1 Best fit $\Gamma_{HI}$ and $\alpha_{eff}$ for the UV background at $z = 0.1$

We now proceed to perform a joint fit of our simulated spectra to the COS measurements of the CDDF and Doppler parameter distribution. We vary two model parameters in our analysis: the metagalactic H1 photoionisation rate, $\Gamma_{HI}$, and the effective power-law spectral index of the UV background, $\alpha_{eff}$. As discussed earlier, $\alpha_{eff}$ is directly related to the thermal asymptote at $z < 0.5$.

A grid of models is used for this fitting procedure. The line fits are obtained by performing a Voigt profile analysis on hydrodynamical simulations with 11 different $\alpha_{eff}$ values (H00-H10 in Table 1). For each of these simulations we also assume 7 different photoionisation rates $0.4 - 1.0 \Gamma_{HI,0}$ in steps of 0.1. This gives a total of 77 separate sets of mock Ly$\alpha$ forest spectra for Voigt profile fitting. The redshift path length of each set is $\Delta z = 210.1$.

We furthermore consider two different cases in our analysis (i.e. we actually fit $2 \times 77$ sets of mocks). These two cases assume $b_{turb} = 0$ (i.e no additional turbulent broadening, $\xi = 1$) and $b_{turb} = 0.73 b_{noturb}$ (i.e. $\xi = 1.24$), where for the latter we have followed the argument in Section 4.2 and assumed a prior limit on the thermal broadening of the Ly$\alpha$ absorbers.9

A $\chi^2$ minimisation is then performed on the COS data, such that

$$\chi^2 = \sum \sum [x_i(\Gamma_{HI}, \alpha_{eff}) - \mu_i]C^{-1}_i[x_j(\Gamma_{HI}, \alpha_{eff}) - \mu_j], \quad (10)$$

where the vector $\hat{x}$ is the Doppler parameter distribution and CDDF from the simulations, the vector $\hat{\mu}$ is the COS data, and $C$ is the COS data covariance matrix. However, the off-diagonal terms in the covariance matrix for the COS data are noisy, making the inversion of the covariance matrix difficult. We therefore assume the

- The best fit from Verner & Ferland (1996) to within 10 per cent at $10^5 \text{K} \leq T \leq 10^9 \text{K}$.

In principle, we could also find a best fit sub-grid turbulent contribution to the line broadening by treating $\xi$ as a free parameter. However, this would require fitting an additional grid of models in $\xi$ for each of the 77 ($\alpha_{eff}, \Gamma_{HI}$) pairs, which would greatly increase the cost of the already time consuming Voigt profile fitting process. We leave this to future work.
σexemplified by the behaviour of temperature decreases for a softer ionising spectrum (this is also the right panel of Fig. 6, and have \( \chi_{\text{min}}^2 / \nu = 1.04 \) \( b_{\text{turb}} = 0 \), \( \beta_{\text{noturb}} = 0.73b_{\text{noturb}} \)).

COS data and the AGN model have similar covariance properties. If the simulated covariance matrix is \( C_{ij} \), the correlation coefficients are \( r_{ij} = C_{ij} / \sqrt{C_{ii}C_{jj}} \). The off-diagonal terms in the covariance matrix for the COS data can then be estimated from the observed diagonal elements and the simulated correlation coefficients, such that \( C_{ij} = r_{ij}C_{ii}^{1/2}C_{jj}^{1/2} \) (Lidz et al. 2006).

The resulting best fit parameters are displayed in the left panel of Fig. 6, where the \( \alpha \) contours are shown for no additional turbulent contribution to the Ly\( \alpha \) forest (blue solid curves) and including our simple estimate for an additional, unresolved turbulent velocity (red dashed curves). For comparison, the grey shaded region shows the asymptote with \( \theta_0 = 6390^{+680}_{-290} \, \text{K} \) (\( \theta_0 = 4030^{+300}_{-220} \, \text{K} \)), or for gas at \( \Delta = 10 \), \( \theta_1 = 20900^{+7220}_{-950} \, \text{K} \) (\( \theta_1 = 13180^{+980}_{-720} \, \text{K} \)).

In Fig. 7, these results are compared to the predictions from UV background models and independent observational constraints on the metagalactic photoionisation rate, \( \Gamma_{\text{HI}} \). Our constraints on \( \Gamma_{\text{HI}} \) in the left panel of Fig. 7 are consistent with the measurements from Gaikwad et al. (2017a) and Khare et al. (2019) at \( z = 0.1 \) from the probability distribution function (PDF) and/or power spectrum of the Ly\( \alpha \) forest transmission. Our best fit values are a factor of 0.6–0.8 times the Puchwein et al. (2019) model and a factor of 1.6–2.0 times larger than Haardt & Madau (2012) (see also the discussion of \( \Gamma_{\text{CDDF}} \) in Section 3.2). However, the 1σ uncertainties in this work are a factor of \( \sim 3–4 \) smaller than the earlier studies. This is partly because we have not included systematic uncertainties from continuum fitting and the assumed cosmology, that may (conservatively) double the size of the error bar on \( \Gamma_{\text{HI}} \) (see e.g. table 8 in Gaikwad et al. 2017a). However, another reason is that the joint analysis of the CDDF and Doppler parameter distribution is effective at breaking the degeneracy between \( \Gamma_{\text{HI}} \) and the thermal state of the IGM.

Our constraints on \( \alpha_{\text{eff}} \) are shown in the right hand panel of Fig. 7, and are compared to various UV background models. By design, the model with turbulent broadening, \( b_{\text{turb}} = 0.73b_{\text{noturb}} \), is in very good agreement with the spectral shape of UV background models close to the Lyman limit. However, the constraint on \( \alpha_{\text{eff}} \) for \( b_{\text{turb}} = 0 \) yields an unphysically hard spectral shape for the UV background and differs from our fiducial \( \alpha_{\text{eff}} = 1.17 \) model (Puchwein et al. 2019) by \( \sim 6–7\sigma \). It is possible that existing UV background models have spectral shapes that are still slightly too soft, although given the wide range of observables at different redshifts these models cali-

**Figure 6.** Left: The projection of \( \chi^2 \) for the joint fit to the CDDF and Doppler parameter distribution including (red dashed curves) and excluding (blue solid curves) an additional turbulent contribution to the line widths (see Section 4.2 for details). The contours show \( \Delta \chi^2 = \chi^2 - \chi_{\text{min}}^2 = 1 \) and 4, corresponding to the 1σ and 2σ confidence intervals for the individual parameters \( \Gamma_{\text{HI}} \) and \( \alpha_{\text{eff}} \). The best fit model parameters (shown by the crosses) and 1σ uncertainties are \( \log (\Gamma_{\text{HI}} / \text{s}^{-1}) = -13.25^{+0.03}_{-0.08} \) (\( \log (\Gamma_{\text{HI}} / \text{s}^{-1}) = -13.14^{+0.02}_{-0.03} \)) and \( \alpha_{\text{eff}} = -0.43^{+0.13}_{-0.26} \) (\( \alpha_{\text{eff}} = 1.33^{+0.30}_{-0.35} \)). From Eq. (3), this is equivalent to a thermal asymptote with \( \theta_0 = 6390^{+680}_{-290} \, \text{K} \) (\( \theta_0 = 4030^{+300}_{-220} \, \text{K} \)), or for gas at \( \Delta = 10 \), \( \theta_1 = 20900^{+7220}_{-950} \, \text{K} \) (\( \theta_1 = 13180^{+980}_{-720} \, \text{K} \)).
brate to, as well as the good agreement between independent groups, we regard this as unlikely. Our statistical error bars may also underestimate the true uncertainty on \(\alpha_{\text{eff}}\). If, as previously discussed, we instead take \(\alpha_{\text{eff}} = 0\) as a conservative limit on the hardness of the UV background spectrum at \(z = 0.1\) (i.e. assuming it is dominated by emission from quasars with extreme UV spectral indices of \(\alpha_{\text{qso}} \approx 0.5\) (Scott et al. 2004; Tilton et al. 2016)), this differs by \(\sim 2\sigma\) from our constraint of \(\alpha_{\text{eff}} = -0.43 \pm 0.13\). This still suggests that photoheating by a hard UV background is disfavoured as the sole explanation for the observed line widths in the Ly\(\alpha\) forest at \(z = 0.1\).

5.2 Discussion

We now discuss the implications of our results. First, if – as we have argued – matching the COS line widths in the Ly\(\alpha\) forest through photoheating by a hard UV background is unlikely, then if assuming a negligible turbulent component, what other (if any) heating processes might provide the requisite injection of energy? Upton Sanderbeck et al. (2016) demonstrated that the IGM thermal history is already well described by the photoheating expected from \(\text{H}^\text{i}\) and \(\text{He}^\text{II}\) reionisation 1. This work (\(b_{\text{turb}}=0\))

\[
\alpha_{\text{eff}} = -0.43 \pm 0.13 \quad (\text{red shading})
\]

\[
\alpha_{\text{eff}} = 1.33 \pm 0.30 \quad (\text{blue square})
\]

This work (\(b_{\text{turb}}=0\))

\[
\alpha_{\text{eff}} = -0.43 \pm 0.13
\]

This work (\(b_{\text{turb}}=0.73b_{\text{noturb}}\))

\[
\alpha_{\text{eff}} = 1.33 \pm 0.30
\]

Khaire & Srianand 19

\[
\alpha_{\text{eff}} = -0.43 \quad (\text{orange circles})
\]

Gaikwad+17a

\[
\alpha_{\text{eff}} = 1.33 \quad (\text{cyan inverted triangle})
\]

Caruso+19

\[
\alpha_{\text{eff}} = 1.33
\]

Haardt & Madau 12

\[
\alpha_{\text{eff}} = 1.33
\]

This work (\(b_{\text{turb}}=0\))

\[
\alpha_{\text{eff}} = -0.43
\]

This work (\(b_{\text{turb}}=0.73b_{\text{noturb}}\))

\[
\alpha_{\text{eff}} = 1.33
\]

Puchwein et al. (2019) (solid curve), Khaire & Srianand (2019) (short dashed curve), Faucher-Giguère (2020) (long dashed curve) and Haardt & Madau (2012) (dotted curve). Independent \(\Gamma_\text{HI}\) measurements are shown from a joint analysis of the power spectrum and PDF of the Ly\(\alpha\) forest transmitted flux (Gaikwad et al. 2017a, purple diamonds), the power spectrum only (Khaire et al. 2019, orange circles), and from \(\text{H}^\alpha\) fluorescence in a galactic disc (Caruso et al. 2019, cyan inverted triangle).

Right: The specific intensity, \(J_{\text{E}}\), of the metagalactic UV background. The black curves show the UV background models displayed in the left panel, while the shaded blue (red) regions show our constraint on \(\alpha_{\text{qso}}\) excluding (including) turbulent broadening. Note that the model with the turbulent contribution (red shading) has been deliberately calibrated for consistency with the spectral shape of the UV background models at the Lyman limit. To facilitate the comparison, all models have been normalised to match the amplitude of the Puchwein et al. (2019) spectrum at \(E = 13.6\text{eV}\). Vertical arrows show the location of the \(\text{H}^\text{i}\) and \(\text{He}^\text{II}\) ionisation edges at 13.6 eV and 54.4 eV.

We therefore take a similar approach to Upton Sanderbeck et al. (2016), where – based on the observed COS line widths – we estimate an upper limit for the additional energy injection into the IGM required at \(z \leq 2.5\). The specific energy deposited into the IGM at \(z_0 \leq z \leq z_{R,\text{HI}}\) from photoheating at overdensity \(\Delta = \rho/\langle \rho \rangle\) is

\[
u = \int_{z = 0}^{\Delta} \frac{\mathcal{H}}{\rho} \frac{dz'}{H(z')} (1+z'),
\]

where \(\rho = \rho_{\text{HI}} \Omega_{\text{b}} \Delta (1+z)^3\), and for photoheating \(\mathcal{H} = \sum n_i \epsilon_i\), where \(n_i\) and \(\epsilon_i\) are respectively the proper number density and photoheating rate for \(i = [\text{H}^\text{i}, \text{He}^\text{I}, \text{He}^\text{II}]\) (e.g. Nasir et al. 2016). Taking the Puchwein et al. (2019) UV background model (which is already calibrated to match existing IGM temperature measurements at \(z > 2\) and has \(\alpha_{\text{eff}} = 1.17\) at \(z = 0.1\)), we find boosting these model photoheating rates by a factor of 2 at \(z \leq 2.5\) gives good agreement with the \(\alpha_{\text{eff}} = -0.43 \pm 0.13\) (or equivalently the thermal asymptote temperature \(\Theta_1 = 20900^{+2250}_{-950}\) K) we infer for \(b_{\text{turb}} = 0\) in Section 5.1. From Eq. (11), this boost corresponds to an additional \(u \approx 6.9\text{eV}\) \(n_p^{-1}\) (\(u \approx 1.6\text{eV}\) \(n_p^{-1}\)) injected into the IGM\(^{10}\) at \(\Delta = 10\) (\(\Delta = 1\)) by \(z_0 = 0.1\), in excess of that already provided by photoheating in the Puchwein et al. (2019) model. Note again, however, that

\(^{10}\) Note this is consistent with a density scaling of \(u = \Delta^{1-0.72(\gamma-1)} \sim \Delta^{0.58}\) for \(\gamma = 1.58\), which is the expectation for photoheating assuming the IGM is in photoionisation equilibrium.
Any non-canonical heating process would therefore need to inject $\lesssim 6.9 \text{eV m}^{-1}$ into $N_{\text{HI}} \simeq 10^{13.5} \text{cm}^{-2}$ absorbers by $\approx 0.1$, while also having a negligible effect on the IGM temperature at $z > 2.5$. We now speculate on which processes are plausible. As already discussed, we find a volumetric heating process like blazar heating (Puchwein et al. 2012) with $u \propto \Delta^{-1}$ will not heat the IGM sufficiently at $\Delta \gtrsim 10$. A similar situation likely holds for Compton heating of the IGM by X-rays (Madau & Etfathiou 1999), where the heating rate $\dot{\mathcal{E}} \propto n_e u$ and $u \propto \Delta^{-2}$. Heating from dark matter annihilations (e.g. Mapelli et al. 2006; Cirelli et al. 2009; Liu et al. 2021) would need to be fine-tuned to avoid a substantial injection of energy into the IGM at $z > 2.5$. Cosmic rays can introduce significant non-thermal pressure in the IGM (Lacki 2015; Butsky et al. 2020), but they are not expected to directly increase the temperature of the low density IGM unless they can efficiently couple to the gas (Nath & Biermann 1993; Samui et al. 2018). Further study will be necessary for confirming or ruling out these possibilities, however.

In this work we instead focus on photoelectric emission by dust grains (Nath et al. 1999; Weingartner & Draine 2001; Inoue & Kamaya 2003), by virtue of the fact this heating rate should naturally increase toward lower redshift as the IGM is enriched with heavy elements. Large, high velocity dust grains with sizes $\gtrsim 0.1 \mu m$ and velocities $v \gtrsim 100 \text{km s}^{-1}$ may be able to escape into the low density IGM (Bianchi & Ferrara 2005), where the destruction timescale due to thermal sputtering will exceed a Hubble time (Draine 2011). Smaller, slower grains are instead more likely to be eroded within hot halo gas where the sputtering timescale is much shorter. Following Inoue & Kamaya (2010), the specific energy from dust heating scales as $u \propto \Delta^{1/3} - 1/T^{1/6} \propto \Delta^{1/3} (\tau - 1)^{-1/6}$, where the heating rate is proportional to the dust-to-gas mass ratio, $\mathcal{D}$, and depends on the uncertain grain size distribution. The density dependence of $u$ also implies that dust heating should flatten the power law temperature-density relation in the low redshift IGM (i.e. $\gamma < 1.6$), in addition to raising the gas temperature. Inoue & Kamaya (2010) provide an approximate expression for the dust heating rate (their eq. 16) assuming the grain size distribution from Mathis et al. (1977). Taking the Puchwein et al. (2019) UV background model and adding the Inoue & Kamaya (2010) heating rate at $z < 2.5$, we find a constant dust-to-gas mass ratio of $\mathcal{D} = 1.5 \times 10^{-3}$ gives an additional $\approx 6.5 \text{eV} (\gtrsim 4.0 \text{eV})$ per proton at $\Delta = 10 (\Delta = 1)$ by $z = 0.1$. For comparison, $\mathcal{D} \sim 10^{-2}$ for the Milky Way (Draine 2011), while observations of nearby galaxies exhibit a large scatter (2–3 dex) in $\mathcal{D}$ at fixed metallicity (Remy-Ruyer et al. 2014; De Vis et al. 2019).

If we adopt a naive extrapolation of the observed dust-to-gas and metallicity relation from local galaxies (e.g. De Vis et al. 2019) to the $z \sim 0$ IGM, $\mathcal{D} \sim 10^{-3}$ is broadly consistent with $Z \gtrsim 0.1Z_{\odot}$. The requisite heating is therefore only possible if the low density IGM is highly enriched by a viable dust transport mechanism (e.g. galactic winds or radiation pressure). Further investigation of the expected heating rates using a more detailed dust model (e.g. Popping et al. 2017; McKinnon et al. 2017; Hou et al. 2019; Li et al. 2019), along with updated assessment of whether or not dust can be effectively transported into the IGM without being eroded by hot halo gas may be of interest.

Alternatively, if non-canonical heating is negligible, how plausible is our crude upper limit on the (density dependent) line of sight turbulent velocity, $v_{\text{turb}} \lesssim 8.5 \text{km s}^{-1} (N_{\text{HI}}/10^{13.5} \text{cm}^{-2})^{0.213}$. Assuming the IGM has kinematic viscosity $v \approx 5 \times 10^{24} \text{cm}^2 \text{s}^{-1}$ (Evoli & Ferrara 2011)\footnote{For comparison, adopting representative values for the temperature and density in the Ly$\alpha$ forest at $z = 0.1$, $T = 10^{4} \text{K}$ and $n_{\text{HI}} = 10^{-3.5} \text{cm}^{-3}$, the kinematic viscosity of fully ionised hydrogen is $v = 2.9 \times 10^{24} \text{cm}^2 \text{s}^{-1}$ (Chapman 1954). The suggests $v \sim 10^{24} \text{cm}^2 \text{s}^{-1}$ provides a reasonable order-of-magnitude estimate for the IGM kinematic viscosity at $z \approx 0.1$.}, if the typical flow speed in the Ly$\alpha$ forest is the speed of sound, $U = c_{s} \sim 25 \text{km s}^{-1}$, and the characteristic length scale of Ly$\alpha$ forest absorbers at $z \approx 0.1$ is the Jeans scale, $L \approx L_{\text{Jeans}} \sim 250 \text{pkpc}$ (Schaye 2001), the Reynolds number for the low redshift Ly$\alpha$ forest is $Re = UL/v \approx 3.9 \times 10^{5}$. Although only an order of magnitude estimate, $Re \gg 10^{3}$ suggests that, if an appropriate mechanism for continuously generating vorticity is present (e.g. feedback, shocks or magnetic fields), the IGM should indeed be turbulent on small scales (Evoli & Ferrara 2011; Gregori et al. 2012; Iapichino et al. 2013; Zhu et al. 2013). However, given that the Doppler widths of the Ly$\alpha$ absorbers in our simulations decrease with increasing mass resolution (see Appendix A), this implies that – if present – any turbulence must be injected below a spatial resolution scale of roughly $L_{\text{res}} \approx L_{\text{box}}(N_{\text{part}}/2)^{-1/3} \Delta^{-1/3}$ in the simulations (i.e. $L_{\text{res}} \sim 40 \text{ckpc}$ at $\Delta = 10$ for the N1024 simulation). Alternatively, it could be that the gas responsible for the bulk of the low column density Ly$\alpha$ absorption is just not sufficiently agitated by the shocks and/or outflows within our models, or there is some other non-thermal broadening missing in the simulated spectra. Regarding the latter possibility, we note again, however, that most of the Ly$\alpha$ absorbers in our fiducial AGN simulation with $10^{13.3} \text{cm}^{-2} \lesssim N_{\text{HI}} \lesssim 10^{14.5} \text{cm}^{-2}$ are already suprathermal with a median $b_{\text{therm}} = 1.28$. If adding a turbulent component by hand, such that $b_{\text{therm}} = 0.73 b_{\text{nonturb}}$, we instead obtain a median $b_{\text{therm}} = 1.48$. Both of these values are consistent with the curve-of-growth analysis presented by Danforth et al. (2010), who find $b_{\text{LyA}} / b_{\text{cool}} = 1.26^{+0.49}_{-0.25}$.

Nevertheless, if taking our turbulent velocity estimate at face value, it is consistent with the results from the galactic outflow driven IGM turbulence model of Evoli & Ferrara (2011) at the higher redshift of $z = 1$, where from their fig. 5, $b_{\text{turb}} = 8 \pm 4 \text{km s}^{-1}$ for $N_{\text{HI}} \approx 10^{13.6} \text{cm}^{-2}$. Observationally, non-thermal broadening can also be constrained by measuring the Doppler parameters of species with different masses in the same gas phase (e.g. Rauch et al. 1996). However, while there is some evidence for turbulence in the low redshift CGM from well aligned OVI, CIV and H1 absorbers at $z < 0.5$ (Tripp et al. 2008; Thom & Chen 2008; Savage et al. 2014; Werk et al. 2016; Manuwal et al. 2021), the picture for the lower density diffuse IGM is arguably less clear. The few existing constraints instead come from observations of the Ly$\alpha$ forest at $z \sim 3$. This has been attempted with H1 and HeII Ly$\alpha$ absorption, where Zheng et al. (2004) found evidence for purely turbulent broadening from the Doppler parameter ratio of aligned H1 and HeII Ly$\alpha$ lines. However, in an independent analysis, Fechner & Reimers (2007) found that just under half of aligned HeII and H1 Ly$\alpha$ absorbers are consistent with purely turbulent broadening. This confusion arises in part because, at $z \sim 3$, the Hubble broadening of Ly$\alpha$ absorbers across the Jeans smoothing scale, $L_{\text{Jeans}} \approx H(z) L_{\text{Jeans}}$, becomes comparable to the thermal widths of the lines (e.g. Peeples et al. 2010; Garzilli et al. 2015). Hence, without a self-consistent hydrodynamical model for the IGM density field, this “Jeans smoothing” can easily be confused with turbulence.

Rauch et al. (2001b) side-stepped this problem by measuring transverse correlations between the Ly$\alpha$ absorption in gravitationally lensed quasar images separated by $\sim 0.3 \text{ckpc}$ at $z \sim 3$. They
found no evidence for turbulence on this scale, although this may not be surprising: the Lyα forest at $z \approx 3$ is sensitive to gas close to the mean density (Becker et al. 2011) and is therefore unlikely to be disturbed by shocks or feedback (Theuns et al. 2002b; Viel et al. 2013; Chabanier et al. 2020). By contrast, in a companion study of C iv absorbers at $z \sim 2$–3 in three lensed quasars (where the typical gas densities probed are more like $\Delta \sim 10$–100, Bolton & Viel (2011)), Rauch et al. (2001a) found that a turbulent velocity component of $v_{\text{turb}} \sim 4.7 \text{km s}^{-1}$ was required at a scale of $\sim 0.3 \text{ckpc}$, which is consistent with our (line of sight) estimate of $\lesssim 8.5 \text{km s}^{-1}$ for $N_{\text{HI}} \sim 10^{13.5} \text{cm}^{-2}$. At a minimum, this suggests that our crude upper limit on the turbulent contribution to the coldest Lyα forest absorbers at $z = 0.1$ is at least plausible. If a suitably lensed background source could be identified for the Lyα forest at $z < 0.5$, repeating the Rauch et al. (2001b) experiment at $z \approx 0.1$ would be valuable for testing this possibility further.

6 CONCLUSIONS

We have performed a Voigt profile analysis of the column density distribution function (CDDF) and Doppler parameter distribution measured from hydrodynamical simulations and Cosmic Origins Spectrograph (COS) observations of the low redshift Lyα forest at $z \approx 0.1$ (Viel et al. 2017; Kim et al. 2021). We re-examine the tension between the observations and theoretical predictions for the widths of the Lyα forest absorption lines, where the Lyα absorber Doppler parameters in hydrodynamical simulations are too narrow with respect to the COS data (Nasir et al. 2017; Gaikwad et al. 2017b). We also assess the level of agreement between the COS Lyα forest CDDF and simulations, a statistic that is sensitive to both the UV background amplitude and (sufficiently strong) AGN feedback (Kollmeier et al. 2014; Shull et al. 2015; Khaire & Srianand 2015; Gurvich et al. 2017; Christiansen et al. 2020). Our primary conclusions are as follows.

- We focus on absorption lines with column densities $10^{13.3} \text{cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{cm}^{-2}$ and Doppler parameters $20 \text{km s}^{-1} \leq b \leq 90 \text{km s}^{-1}$ at $z \approx 0.1$. We show these absorption lines will be minimally impacted by systematic uncertainties in the signal-to-noise and spectral resolution of the data. In this range, the majority of the absorbers (83 percent) we identify in our fiducial simulation (AGN) reside in the diffuse IGM (i.e. gas with $T < 10^5 \text{K}$ and $\Delta < 97.2$). Strong absorbers with $N_{\text{HI}} \geq 10^{14} \text{cm}^{-2}$ are preferentially located close to haloes, with over half of these within $r < 3R_{\text{vir}}$ of haloes of (total) mass $10^{10} M_\odot \leq M_\odot \leq 10^{12} M_\odot$ (cf. Chen & Muralhaey 2009; Tejos et al. 2014; Keeney et al. 2018). By contrast, fewer than 10 percent of $N_{\text{HI}} \geq 10^{14} \text{cm}^{-2}$ absorbers are within $r < 3R_{\text{vir}}$ of haloes of mass $M_\odot \leq 10^{12} M_\odot$. Hot, collisionally ionised gas from shocks and feedback reduces the incidence of strong absorbers around the most massive haloes at $z = 0.1$.

- After applying a small correction for box size and mass resolution, our fiducial AGN and Quick-Lyα (H2) simulations are both in good agreement (within $\sim 1$–1.5σ) with the shape of the CDDF measured from the COS data at $10^{13.3} \text{cm}^{-2} < N_{\text{HI}} < 10^{14.5} \text{cm}^{-2}$. Adopting an H i photoionisation rate, $\Gamma_{\text{HI}}$, that is $\sim 0.6$ times the Puchwein et al. (2019) model (or $\sim 1.7$ times the Haardt & Madau (2012) model) provides a good match to the amplitude of the COS CDDF. We confirm that potent AGN feedback and/or blazar heating models that produce a substantial fraction of the low density, warm-hot IGM (WHIM) further lower the $\Gamma_{\text{HI}}$ required for consistency with the CDDF amplitude (cf. Christiansen et al. 2020), and will also flatten the CDDF at $N_{\text{HI}} \sim 10^{14} \text{cm}^{-2}$ (Gurvich et al. 2017).

- The simulated Doppler width distribution for lines with $10^{13.3} \text{cm}^{-2} < N_{\text{HI}} < 10^{14.5} \text{cm}^{-2}$ is consistent with the COS measurements; the number of narrow lines with $b \approx 22.5 \pm 2.5 \text{km s}^{-1}$ are over-predicted by 4.6σ in our fiducial AGN model. We show that introducing additional hot gas into the low density IGM by invoking strong AGN feedback or blazar heating does not resolve this discrepancy. As already noted by Viel et al. (2017), this is because this hot gas is primarily in the WHIM with temperatures $T \approx 10^7 \text{K}$. While this changes the average ionisation level of the IGM (and hence induces a shift the amplitude and shape of the CDDF), it does not produce additional Lyα absorption at the necessary density and temperature for resolving the discrepancy in the line widths. We argue this implies the presence of additional heating or turbulence in the low density IGM.

- We perform a joint analysis of the CDDF and Doppler parameter distribution to find the best fit values for the metagalactic H i photoionisation rate, $\Gamma_{\text{HI}}$, and the effective power-law spectral index, $\alpha_{\text{eff}}$ (where $E_{\text{L}} \propto E^{-\alpha_{\text{eff}}}$), of the UV background close to the Lyman limit. Assuming there is no missing non-thermal broadening in the simulations (e.g., from turbulence), the best fit values are $\log(\Gamma_{\text{HI}}/\text{s}^{-1}) = -13.25^{+0.03}_{-0.06}$ and $\alpha_{\text{eff}} = -0.43^{+0.13}_{-0.26}$ for $\chi^2/\nu = 1.04$. While this photoionisation rate is consistent with previous constraints (Shull et al. 2015; Gaikwad et al. 2017a; Khaire & Srianand 2019; Caruso et al. 2019), the inferred value of $\alpha_{\text{eff}}$ is unphysically hard and is inconsistent by 6–7σ (statistical) with the much softer spectral shape, $\alpha_{\text{eff}} \sim 1$–1.4, predicted by state-of-the-art UV background synthesis models that use intrinsic power-law spectral indices of $\alpha_{\text{qso}} = 1.4$–2.0 (Haardt & Madau 2012; Khaire & Srianand 2019; Puchwein et al. 2019; Faucher-Giguère 2020). Even if allowing for a rather extreme UV background with $\alpha_{\text{eff}} \approx 0$, as might be expected for intrinsic quasar extreme-UV spectral indices of $\alpha_{\text{qso}} = 0.5$ (Scott et al. 2004; Tilton et al. 2016) combined with some spectral hardening by the IGM at the He ii ionisation edge, this remains a $\sim 2\sigma$ discrepancy. We conclude that enhanced UV background photoheating rates in the low density IGM that increase the thermally broadened line components are disfavoured as the only solution to the discrepancy between the observed and simulated Lyα forest line widths at $z = 0.1$.

- If taking the UV background heating rates from Puchwein et al. (2019) as a prior (with $\alpha_{\text{eff}} = 1.17$), we may instead appeal to a non-canonical source of heating in the IGM (i.e. heating that is not due to photoheating by the UV background). We then find a specific energy injection of $u \lesssim 6.9 \text{eV} M_\odot^{-1}$ in addition to that expected from UV photoheating is required for gas with $\Delta = 10$ at $z < 2.5$. We briefly discuss the likelihood that other physical processes could contribute the additional energy, including heating by dark matter annihilations (Mapelli et al. 2006; Cirelli et al. 2009; Liu et al. 2021), Compton heating by X-rays (Madau & Efstathiou 1999), cosmic rays (Nath & Biermann 1993; Samui et al. 2018) and photoelectric emission by dust grains (Nath et al. 1999; Weingartner & Draine 2001; Inoue & Kamaya 2003). We speculate on the role of dust heating in particular, as the specific energy injected into the IGM scales as $\sim \Delta^{1/3} T^{-1/6}$, and (unlike other mechanisms) the heating rate should naturally increase toward lower redshift as the IGM is enriched with heavy elements. On adopting the dust heating rates from Inoue & Kamaya (2010), an additional $\sim 6.5 \text{eV} M_\odot^{-1}$ at $z < 2.5$ requires a constant dust to gas ratio of $\delta = 1.5 \times 10^{-3}$ for

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mildly overdense IGM gas with $\Delta = 10$. This is broadly consistent with a metallicity of $Z \gtrsim 0.1Z_\odot$, based on a naive extrapolation of the dust-to-gas and metallicity relation in local galaxies, and would therefore imply a highly enriched IGM. However, it remains an open question as to whether or not sufficient quantities of dust can survive passage through hot halo gas (but see Bianchi & Ferrara 2005). A combination of several non-canonical heating mechanisms along with some non-thermal line broadening may also provide a plausible route for reconciling the COS Ly$\alpha$ line widths and the simulations.

- Alternatively, the additional line broadening may be entirely due to non-thermal broadening that is missing in the hydrodynamical simulations. If again adopting a prior limit on the thermal widths of the Ly$\alpha$ absorbers using the Puchwein et al. (2019) UV background model, we obtain a crude upper limit on a possible additional turbulent contribution to the Ly$\alpha$ forest line widths. For an assumed line width ratio of $b_{\text{turb}}/b_{\text{noturb}} = 0.73$, the best fit UV background parameters are instead log($\Gamma_{\text{HI}}/s^{-1}$) = $-13.14 \pm 0.02$ and $\alpha_{\text{eff}} = 1.33^{+0.30}_{-0.35}$, where $\alpha_{\text{eff}}$ is now consistent with Puchwein et al. (2019) by design. For the coldest gas in the diffuse IGM at $z \simeq 0.1$, the ratio $b_{\text{turb}}/b_{\text{noturb}} = 0.73$ translates to an upper limit of $v_{\text{turb}} \lesssim 8.5 \text{km s}^{-1} [\text{N}_\text{II}/10^{13.5} \text{cm}^{-2}]^{0.21}$ for the additional turbulent velocity component along the line of sight. This estimate is comparable to theoretical estimates at $z = 1$ (Evoli & Ferrara 2011) and observational estimates of turbulence from CIV absorbers at $z \sim 3$ (Rauti et al. 2001a), and would suggest that the stirring of the low density IGM is widespread by $z \simeq 0$.

In summary, we reaffirm that the low redshift Ly$\alpha$ forest provides a powerful diagnostic of complex and poorly understood physical processes in low density intergalactic gas. It would be interesting to assess how well numerical models that are anchored to these data reproduce the observed relationship between galaxies and gas at higher densities and on smaller scales at $z < 0.5$.

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**DATA AVAILABILITY**

All data and analysis code used in this work are available from the first author on reasonable request.

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APPENDIX A: BOX SIZE AND MASS RESOLUTION

Numerical convergence tests of the Ly{$\alpha$} forest CDDF and Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively.

The uncertainties on the COS data for our fiducial values of the Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively. The Doppler parameter distribution with simulation box size and gas particle mass are presented in Fig. A1 and Fig. A2, respectively.
\[ f(\log N_{\text{HI}}) = \frac{\partial^2 n}{\partial \log N_{\text{HI}} \partial z} \]

Figure A1. The effect of box size for a fixed gas particle mass. Left: The CDDF measured from COS data for Ly\( \alpha \) absorbers with Doppler parameters 20 km s\(^{-1}\) \( \leq b \leq 90 \) km s\(^{-1}\), compared to the CDDF obtained from the L40 (red dotted), H02 (black solid) and L80 (blue dashed) simulations. The figure is otherwise the same as Figure 3, but excludes the box size and mass resolution correction to the simulated CDDF. Right: The corresponding Doppler parameter probability distribution for Ly\( \alpha \) absorbers with column densities \( 10^{13.3} \) cm\(^{-2}\) \( \leq N_{\text{HI}} \leq 10^{14.5} \) cm\(^{-2}\).

\[ f(\log N_{\text{HI}}, z) = \frac{\partial^2 n}{\partial \log N_{\text{HI}} \partial z} \]

Figure A2. The effect of gas particle mass for fixed box size. Left: The CDDF measured from COS data for Ly\( \alpha \) absorbers with Doppler parameters 20 km s\(^{-1}\) \( \leq b \leq 90 \) km s\(^{-1}\), compared to the CDDF obtained from the N512 (red dotted), H02 (black solid) and N1024 (blue dashed) simulations. Right: The corresponding Doppler parameter probability distribution for Ly\( \alpha \) absorbers with column densities \( 10^{13.3} \) cm\(^{-2}\) \( \leq N_{\text{HI}} \leq 10^{14.5} \) cm\(^{-2}\). The figure is otherwise the same as Figure 3.

\[ L = 60 h^{-1} \text{Mpc} \text{ and } M_{\text{gas}} = 6.38 \times 10^6 h^{-1} \text{M}_\odot. \] However, a \( \sim 10\)–30 per cent correction to the CDDF – particularly for strong Ly\( \alpha \) absorbers with \( N_{\text{HI}} \geq 10^{14} \) cm\(^{-2}\) – is required on comparing our fiducial model to simulations with \( L = 80 h^{-1} \text{Mpc} \) or \( M_{\text{gas}} = 2.69 \times 10^6 h^{-1} \text{M}_\odot \) (the blue dashed curves in Fig. A1 and Fig. A2). This correction is typically comparable to the \( 1 \sigma \) uncertainties on the COS CDDF measurement. The combined correction for box size and mass resolution that we apply to the CDDF is given in Table A1.
APPENDIX B: SYSTEMATICs

The effect of the assumed signal-to-noise ratio and line spread function (LSF) on our Voigt profile fits to simulated spectra are shown in Fig. B1 and Fig. B2, respectively.

Our fiducial, flux independent signal-to-noise ratio of $S/N = 30$ per 19 km s$^{-1}$ resolution element (black curves) is compared to $S/N = 20$ (red dotted curves) and $S/N = 40$ (blue dashed curves) in Fig. B1. The signal-to-noise ratio affects the identification of narrow ($b < 10$ km s$^{-1}$) absorbers, and impacts on the completeness of low column density ($N_{\text{HI}} < 10^{14.5}$ cm$^{-2}$) absorption lines. We have also tested more complicated noise models that use a combina-
Figure B3. The effect of rescaling the Lyα optical depths under the assumption of photoionisation equilibrium. Left: The CDDF measured from COS data for Lyα absorbers with Doppler parameters $20\text{ km s}^{-1} \leq b < 90\text{ km s}^{-1}$, compared to the CDDF obtained from the H2 simulation for no rescaling (i.e. using the native UV background amplitude, red dotted), a linear rescaling of the pixel optical depths (or equivalently, column densities) in post-processing (black solid) and a full recalculation of the ionisation balance including the effect of collisional ionisation and free electrons from ionised helium (red dotted). Right: The corresponding Doppler parameter probability distribution for Lyα absorbers with column densities $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$. The figure is otherwise the same as Figure 3.

Table A1. The correction we apply to each CDDF bin of width $\Delta \log N_{\text{HI}} = 0.2$ to account for the convergence with simulation box size and mass resolution at our fiducial box size and mass resolution of $L = 60h^{-1} \text{ cMpc}$ and $M_{\text{gas}} = 6.38 \times 10^9 h^{-1} M_{\odot}$. The corrected CDDF is given by $\kappa_{\text{sources}} f(\log N_{\text{HI}}, z)$.

| $\log(N_{\text{HI}}/\text{cm}^{-2})$ | $\kappa_{\text{sources}}$ |
|----------------|----------------|
| 13.4            | 1.00           |
| 13.6            | 1.09           |
| 13.8            | 1.01           |
| 14.0            | 1.15           |
| 14.2            | 1.29           |
| 14.4            | 1.42           |

Section of flux independent and flux dependent terms (not shown), but we find very little difference between these and a flux independent noise model for lines with $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$ and $20\text{ km s}^{-1} \leq b < 90\text{ km s}^{-1}$.

In Fig. B2, we show the effect of deconvolving the mock spectra with the COS LSF (G130M/1327 LP1, black curves)

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Lyα forest absorption lines with $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$ and $20\text{ km s}^{-1} \leq b < 90\text{ km s}^{-1}$ should be the least affected by variations in the assumed signal-to-noise or spectral resolution of the COS data.

Finally, as discussed in Section 3.2, the H I column densities in our simulated spectra are rescaled by a constant to match the amplitude of the observed CDDF at $10^{13.3} \text{ cm}^{-2} \leq N_{\text{HI}} \leq 10^{14.5} \text{ cm}^{-2}$ (following Viel et al. 2017). This is equivalent to rescaling the H I photoionisation rate, $\Gamma_{\text{HI}}$, since $N_{\text{HI}} \propto \Gamma_{\text{HI}}^{-1}$ for optically thin gas in photoionisation equilibrium with the UV background. However, as noted by Khaire et al. (2019), it is possible this assumption may break down if the gas responsible for the Lyα forest absorption at $z \approx 0.1$ is hot ($T > 10^4 \text{ K}$) and collisionally ionised. We test this explicitly in Fig. B3 using three cases: no rescaling of the column densities (blue dashed curves), the post-processed linear scaling of the column densities that we use throughout this work (black curves), and a full recalculation of the IGM ionisation balance using a photoionisation rate that is scaled by the same factor used in the post-processed case (red dotted curves). For the column density and Doppler parameter range we consider in this work, the agreement between the approximate (black dotted curves) and full calculation (red dotted curves) is excellent, justifying our assumption.

APPENDIX C: COMPARISON TO ILLUSTRIS-TNG

In Figure C1, we compare the COS CDDF and Doppler parameter distribution to Voigt profile fits obtained from Lyα forest spectra extracted from the publicly available Illustris TNG100-1 simulation at $z = 0.1$ (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Springel et al. 2018; Pillepich et al. 2018; Nelson et al. 2019).

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This provides a test of whether or not the results of this study are peculiar to our numerical implementation.

In contrast to the simulations used in this work, IllustrisTNG includes metal line cooling and magneto-hydrodynamics, as well as different implementations for AGN feedback, galactic winds, metal enrichment and the UV background. IllustrisTNG furthermore uses the AREPO code (Springel 2010), which employs a moving-mesh hydrodynamics scheme instead of smoothed particle hydrodynamics. The cosmological parameters for the TNG100-1 simulation are very similar to those used in this work, with $\Omega_m = 0.3089$, $\Omega_\Lambda = 0.6911$, $h = 0.6774$, $\Omega_b = 0.0486$, $\sigma_8 = 0.8159$ and $n = 0.9667$. The box size of TNG100-1 is $75h^{-1}$cMpc, with a gas particle mass of $M_{\text{gas}} = 9.4 \times 10^5h^{-1}M_\odot$ (i.e. a factor $\sim 2$ larger volume and a factor $\sim 7$ smaller gas particle mass compared to our fiducial AGN simulation). Photoionisation and photoheating is provided by the 2011 update of the Faucher-Giguère et al. (2009) UV background model. At $z = 0.1$, this has $\log(\Gamma_{\text{CDDF}}/s^{-1}) = -13.31$.

Adopting $\log(\Gamma_{\text{HI}}/s^{-1}) = -13.08$ in the TNG100-1 Ly$\alpha$ forest spectra provides a good match (within $1-2 \sigma$) to the amplitude and shape of the CDDF (this corresponds to $\Gamma_{\text{HI}}/\Gamma_{\text{HM12}} = 2.37$). However, the line widths remain systematically narrower than the COS data, with the number of lines at $b = 22.5 \pm 2.5$km s$^{-1}$ over-predicted by $\sim 5.5 \sigma$. This is consistent with the simulations used in this work.

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\footnote{https://galaxies.northwestern.edu/uvb-fg09/}