Jet Feedback and the Photon Underproduction Crisis in Simba

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ABSTRACT
We examine the impact of black hole jet feedback on the properties of the low-redshift intergalactic medium (IGM) in the Simba simulation, with a focus on the Ly\(\alpha\) forest mean flux decrement \(D_A\) and the inferred \(\text{H}_2\) photo-ionisation rate \(\Gamma_{\text{HI}}\). Without jet feedback, we confirm the Photon Underproduction Crisis (PUC; Kollmeier et al. 2014) in which \(\Gamma_{\text{HI}}\) at \(z=0\) must be increased by \(\times 6\) over the Haardt & Madau (2012) value in order to match the observed \(D_A\). Turning on jet feedback lowers this discrepancy to \(\sim \times 2.5\), and additionally using the recent Faucher-Giguère (2019) background results in even better agreement, nearly solving the PUC. The PUC becomes apparent at late epochs \((z<\sim 1)\) where the jet and no-jet simulations diverge; at higher redshifts Simba reproduces the observed \(D_A\) with no adjustment, with or without jets. The main impact of jet feedback is to lower the cosmic baryon fraction in the diffuse IGM from 39\% to 16\% at \(z=0\), while increasing the warm-hot intergalactic medium (WHIM) baryon fraction from 30\% to 70\%; the lowering of the diffuse IGM content directly translates into a lowering of \(D_A\) by a similar factor. Comparing to the older Mufasa simulation that employs different quenching feedback but is otherwise similar to Simba, Mufasa matches \(D_A\) less well than Simba, suggesting that low-redshift measurements of \(D_A\) and \(\Gamma_{\text{HI}}\) could provide constraints on feedback mechanisms. Our results suggest that widespread IGM heating at late times is a plausible solution to the PUC, and that Simba’s jet AGN feedback model, constrained to reproduce quenched massive galaxies, approximately yields this required heating.

Key words: galaxies: formation, galaxies: evolution, intergalactic medium, quasars: absorption lines, methods: N-body simulations

1 INTRODUCTION

The intergalactic medium (IGM) contains the vast majority of cosmic baryons at all cosmic epochs (Meiksin 2009). After the epoch of reionisation, the IGM is highly ionised by a cosmic background of ultraviolet photons (UVB) emitted by star forming galaxies and active galactic nuclei (AGN). The trace neutral component is detectable as \(\text{H}_1\) Ly\(\alpha\) absorption in the spectra of background sources such as quasars, which is known as the Lyman alpha forest. The temperature of this gas is set by a balance between local adiabatic expansion and photo-heating from the metagalactic flux, leading to a relatively simple equation of state (Hui & Gnedin 1997). Combined with the fact that absorbing gas mostly tracks gravitationally-driven large-scale structure, this has made the Ly\(\alpha\) forest useful for a wide range of cosmological applications.

The optical depth \(\tau\) of Lyman alpha forest absorbing gas along a given line of sight (LOS) depends on the gas density and the neutral fraction. The neutral fraction is itself proportional to the density and inversely proportional to the \(\text{H}_1\) photo-ionisation rate \(\Gamma_{\text{HI}}\). If we consider the mean optical depth in the Ly\(\alpha\) forest, it thus scales as the square of the mean baryonic density (which is \(\propto \Omega_b\), and inversely with \(\Gamma_{\text{HI}}\); \(\tau \propto \Omega_b^2/\Gamma_{\text{HI}}\), with constants that depend on cosmology (Rauch et al. 1997), and a small correction owing to the temperature dependence of the \(\text{H}_1\) recombination rate. The fluctuations around this mean optical depth can thus be
used to measure the matter power spectrum, assuming that the baryons trace matter (e.g. Weinberg et al. 1998). The mean optical depth, meanwhile, can be used to constrain a combination of \( \Omega_b \) and \( \Gamma_H \).

Rauch et al. (1997) applied this approach to measurements of the mean flux decrement in the Ly\( \alpha \) forest at \( z \sim 2 - 3 \) in order to estimate \( \Omega_b \), assuming \( \Gamma_H \) taken from Haardt & Madau (1996), and obtained \( \Omega_b = 0.021h^2 \). The Haardt & Madau (1996) background was estimated from the number density of observed quasars and star-forming galaxies plus radiative transfer through a clumpy IGM, assuming that all ionising photons from quasars and a small fraction of such photons from star-forming galaxies escaped. Despite substantial uncertainties in source count observations at that time, this value for \( \Omega_b \) turned out to be in good agreement with determinations from the deuterium abundance (Tytler et al. 1996) and subsequently the cosmic microwave background (Planck Collaboration et al. 2016).

At lower redshifts, the growth of the Cosmic Web results in gas shock-heating on filamentary structures as it accretes supersonically (Dave et al. 1999). This generates the so-called Warm Hot Intergalactic Medium (WHIM; Cen & Ostriker 1999; Dave et al. 2001) of gas outside bound halos in the \( T \sim 10^5 - 10^7 \) K temperature range. Owing to the nonlinear processes involved, gas dynamical simulations are required to study the growth of the WHIM, and concomitantly, the reduction in Ly\( \alpha \) forest baryons. Such simulations broadly predict that roughly one-third of cosmic baryons at the present epoch are in the WHIM (Dave et al. 2001; Davé et al. 2010; Smith et al. 2011). It is very challenging to detect such warm-hot gas observationally since the hydrogen is fully ionised, so metal line absorbers must be used instead, which are weaker and more uncertain. Nonetheless, an observational census primarily from O\( \text{vi} \) absorption suggests that such predictions are broadly consistent with current data (Tripp et al. 2000; Shull et al. 2012).

In spite of the increased complexity introduced by the WHIM, it is still possible to use the Ly\( \alpha \) forest mean flux decrement to measure \( \Gamma_H \), given that \( \Omega_b \) is now well-determined from other avenues. Indeed, at \( z \sim 0 \), this is currently the most robust approach to measuring \( \Gamma_H \), because it is impossible to directly detect the 912Å photon background directly given foreground Galactic absorption, and other approaches such as \( \text{H}\alpha \) fluorescence are extremely challenging (though see Fumagalli et al. 2017). Dave & Tripp (2001) used this approach on the Hubble Space Telescope Imaging Spectrograph data to measure \( \Gamma_H(z = 0) = 10^{-13.6 \pm 0.7} \) s\(^{-1} \). In the meantime, Haardt & Madau (2001) had improved upon their estimate of \( \Gamma_H \) evolution from source count modeling, and determined \( \Gamma_H(z = 0) = 10^{-13.08} \) s\(^{-1} \), consistent with the Ly\( \alpha \) forest measurements. Thus it appeared that \( \Gamma_H \) at \( z = 0 \) was now pinned down to within a factor of a couple.

Measurements of cosmic ionising photon sources continued to improve. In particular, it became clear that the assumption in Haardt & Madau (2001) of a constant 10% escape fraction of Lyman continuum photons from galaxies was inconsistent with observations; stacked measures of dwarf galaxies at intermediate redshifts suggested instead values below 2% (Rutkowski et al. 2016). Faucher-Giguère et al. (2009) did a new calculation of \( \Gamma_H(z) \), and estimated \( \Gamma_H(z = 0) = 3.9 \times 10^{-14} \) s\(^{-1} \). Haardt & Madau (2012) further updated their estimate assuming an evolving escape fraction of \( 1.8 \times 10^{-4}(1 + z)^{3.4} \) and found an even lower \( \Gamma_H(z = 0) = 2.3 \times 10^{-14} \) s\(^{-1} \). Hence as these calculations became more precise, they diverged substantially from the original determination by Haardt & Madau (2001) of \( \Gamma_H(z = 0) = 8.3 \times 10^{-14} \) s\(^{-1} \), with the latest determinations lower by nearly a factor of four.

In light of this, Kollmeier et al. (2014) re-investigated constraints on \( \Gamma_H \) at \( z = 0 \) from the Ly\( \alpha \) forest using new simulations that were substantially improved in dynamic range and input physics compared to those in Dave et al. (2001). This study was also enabled by an improved census of Ly\( \alpha \) forest absorbers from Hubble’s Cosmic Origins Spectrograph (COS) by Danforth et al. (2016). Kollmeier et al. (2014) found that, in order to match the amplitude of the observed column density distribution or the mean flux decrement, it was necessary to increase the Haardt & Madau (2012) value of \( \Gamma_H(z = 0) \) by a factor of \( \sim 5 \), i.e. \( \Gamma_H(z = 0) \sim 10^{-13} \) s\(^{-1} \). In other words, if the Ly\( \alpha \) forest is robustly predicted in simulations as expected from the simple physics involved, then there was a gross shortfall of observed photon sources relative to that needed to match the observed IGM ionisation level. Most of the newfound discrepancy owed to the change in the source count estimates of \( \Gamma_H \). What had initially seemed like a solved problem in 2001 was now, with improved measurements and simulations, yielding a substantial discrepancy. Kollmeier et al. (2014) dubbed this the Photon Underproduction Crisis (PUC) – the Universe did not seem to be producing nearly enough photons to explain the ionisation level seen in the Ly\( \alpha \) forest.

Subsequent investigations of the PUC differed on the strength of the PUC, but all confirmed the idea that the Haardt & Madau (2012) estimate seemed to be low compared to what was needed to reproduce the observed Ly\( \alpha \) forest. Shull et al. (2015) compared new measurement of the mean flux decrement from COS versus uniform-mesh ENZO simulations, and determined \( \Gamma_H(z = 0) = 4.6 \times 10^{-14} \) s\(^{-1} \). While still a factor of two off from the Haardt & Madau (2012) value, this could be probably accommodated within systematic uncertainties (Gaikwad et al. 2017). However, there are two significant caveats. First, fixed-mesh simulations are known to overproduce entropy in low-Mach number shocks and hence increase the amount of numerical heating in the IGM; indeed, in the Dave et al. (2001) comparison of the WHIM in various simulations, the fixed mesh code of Cen & Ostriker (1999) yielded ~50% the baryons in the WHIM, while adaptive resolution codes (both Eulerrian and Lagrangian) yielded ~30%. Second, their predicted Ly\( \alpha \) absorber column density distribution was substantially steeper than observed, so while at high column densities (\( N_{\text{HI}} \sim 10^{14} \) cm\(^{-2} \)) the amplitude agreed with Haardt & Madau (2012), at low columns (\( N_{\text{HI}} \sim 10^{13} \) cm\(^{-2} \)), it agreed better with Haardt & Madau (2001). Furthermore, the adaptive mesh simulations of Tonnesen et al. (2017) confirmed the Kollmeier et al. (2014) result, suggesting that the PUC is not sensitive to numerics if one has adaptive resolution. Viel et al. (2017) also found that a UVB with a factor ~1.5 – 3 higher than Haardt & Madau (2012) was necessary to reproduce the low-z Ly\( \alpha \) forest column density distribution in a variety of simulations, and Kulkarni et al. (2019) found that AGN can only account for half the required photons even though they are expected to greatly dominate the low-z ionising photon budget. Additionally, Wakker et al. (2015)
found that in order for the HI column density as a function of filament impact parameter from their simulations to match COS observations, they required the Haardt & Madau (2012) ionizing background at $z = 0$ to be increased by a factor of 4-5, consistent with Kollmeier et al. (2014).

Khaire & Srianand (2015) re-did the UV background calculation using updated QSO emissivities that were $2\times$ higher than those in Haardt & Madau (2012), and suggested that this combined with a 4% escape fraction from galaxies could increase the source count estimate of $\Gamma_{\text{HI}}$ up to the levels required to match Kollmeier et al. (2014). While their assumed QSO emissivity is plausible albeit higher than canonical values, the 4% global escape fraction of ionising photons from galaxies seems less plausible given current measurements (e.g. Rutkowski et al. 2016). An update of the Faucher-Giguère et al. (2009) in Faucher-Giguère et al. (2019) also found a $z = 0$ $\Gamma_{\text{HI}}$ value about twice that in Haardt & Madau (2012). Similarly, a recent determination of $\Gamma_{\text{HI}}(z)$ from Khaire et al. (2019) preferred a higher value for $\Gamma_{\text{HI}}(z) = 0$, but not by more than a factor of two. Hence while there may be a $\sim \times 2$ systematic uncertainty on the determination in Haardt & Madau (2012), a factor of $\sim 5$ seems difficult to accommodate.

If the solution to the PUC cannot be (primarily) obtained by appealing to uncertainties in source population modeling, and the simulations of Kollmeier et al. (2014) are correct in their predictions given their input physics, then the next potential solution is that those simulations are missing some widespread IGM heating mechanism that would lower the Ly$\alpha$ absorption. Indeed, Kollmeier et al. (2014) investigated whether the then-popular blazar heating model of Broderick et al. (2012) could accommodate this, and determined that it could go partway, but like the Shull et al. (2015) simulations, it produced a column density distribution that was shallower than observed. Since the mean flux decrement tends to be dominated by near-saturated lines ($N_{\text{HI}} \sim 10^{13.7} \text{cm}^{-2}$) occurring in mildly overdense regions (Davé et al. 1999), it is not possible to solve the PUC by only heating void gas.

Gurvich et al. (2017) investigated the PUC in the Illustris simulation (Vogelsberger et al. 2014). Unlike previous simulations studying the PUC, Illustris included strong AGN feedback. This was primarily designed to quench star formation in massive galaxies by heating halo gas, but as a by-product it also deposited energy not only in the circumgalactic medium (CGM) of quasars, but also into the more diffuse IGM gas. As a result, Illustris AGN feedback was found to substantially impact both Ly$\alpha$-absorption within the CGM of massive halos (Sorini et al. 2018), and the Ly$\alpha$ forest (Gurvich et al. 2017). The latter effect clearly went towards resolving the PUC in Illustris. In fact, when Gurvich et al. (2017) assume a Faucher-Giguère et al. (2009) UVB, they can match the observed mean flux decrement, although their column density distribution slope did not match COS data. Such a large impact from feedback was somewhat surprising, since it is commonly believed that galactic feedback does not strongly impact the diffuse IGM far from galaxies. Although a promising solution, Illustris at the same time greatly over-evacuates gas from massive halos (Genel et al. 2014), so it is likely that their AGN feedback model is too strong, or adds energy in the wrong manner. Hence while Illustris could solve the PUC, it seems to introduce other problems while doing so. Notably, Viel et al. (2017) found that for the Sherwood simulations (Bolton et al. 2017), which implement AGN feedback differently than in Illustris, there was a minimal impact on the column density distribution function when compared to simulations without AGN feedback. Nonetheless, Gurvich et al. (2017) clearly demonstrated that AGN feedback could potentially be an important aspect to consider in solving the PUC.

AGN feedback is yet to be fully understood. Nevertheless, recent years have seen the development of a number of AGN feedback models within cosmological hydrodynamic simulations, primarily designed to quench massive galaxies as observed. One successful recent model is the Simba simulation. This uses an observationally-motivated two-mode feedback model, where at high Eddington rates it follows observed ionised or molecular gas outflow scalings, while at low Eddington rates it switches to a jet mode with outflow speeds up to $\sim 8000 \text{ km s}^{-1}$. The two-mode approach is qualitatively similar to the model in Illustris-TNG (Weinberger et al. 2018), although Simba uses stably bipolar outflows and significantly less total energy which is more consistent with observations of the kinetic power in radio jets (e.g. Whittam et al. 2018). Such jet feedback can potentially carry matter and hence energy far away from its host galaxy into the diffuse IGM (Borrow et al. 2019). Simba is able to quench galaxies in good agreement with observations over cosmic time, and more relevantly for this work, yields a hot baryon fraction in massive halos that is consistent with observations (Davé et al. 2019), so is not over- or under-evacuating halo baryons. Hence it provides a plausible AGN feedback model that can be used to investigate the PUC.

In this paper we examine the PUC in the Simba simulation. To do so, we generate simulated lines of sight in Ly$\alpha$ absorption, and quantify the variation needed in the strength of the assumed photo-ionising background in order to match observations of the mean flux decrement $D_A$. We focus on $D_A$ and not the column density distribution of absorbers in order to avoid uncertainties associated with line identification and fitting, which can be quite sensitive to spectral resolution and signal to noise (e.g. Dave et al. 2001). In particular, we investigate the role of the jet mode of AGN feedback in Simba. We show that this type of AGN feedback has a large impact on the PUC, while other AGN feedback modes in Simba (cf. radiative and X-ray) have minimal impact. We also compare to the MUFASA simulation results, which assumed a different halo-based quenching model that did not employ jets, though still matched massive galaxy properties. We find that Simba’s AGN jet feedback model is crucial for obtaining agreement between the $\Gamma_{\text{HI}}$ required to match the $D_A$ observations and modern determinations of $\Gamma_{\text{HI}}$ from source population modeling, suggesting that widespread IGM heating from AGN is a key factor in solving the PUC.

This paper is organised as follows. In §2 we review the Simba simulations used in this work. In §3 we present some global IGM physical characteristics in the Simba runs with and without AGN jets. In §4 we present our main results in examining the PUC in Simba in runs with and without jets. In §5 we discuss the PUC in other AGN feedback tests in Simba, and in MUFASA. In §6 we summarise our results.
2 THE SIMBA SIMULATIONS

2.1 Input physics and cosmology

SIMBA (Davé et al. 2019) is a cosmological hydrodynamic simulation that uses a Meshless Finite Mass (MFM) hydrodynamics solver (Hopkins 2015), which can be classified as an Arbitrary Lagrangian Eulerian (ALE) code. MFM employs a Riemann solver that is able to handle strong shocks and shear flows accurately, without introducing an artificial viscosity (Hopkins 2015). This is particularly beneficial in situations where high Mach number flows and strong shocks are an important physical aspect in the problem, which is the case here in studying the impact of high-velocity jet outflows (described below) on diffuse IGM gas.

SIMBA further employs a number of state of the art sub-grid physical processes to form realistic galaxies. Photoionisation heating and radiative cooling are implemented using the CRACKLE-3.1 library (Smith et al. 2017) assuming ionisation but not thermal equilibrium, and a Haardt & Madau (2012) ionising background modified to account for self-shielding based on the Rahmati et al. (2013) prescription (A. Emerick, priv. comm.). The strength of the ionising background has a very weak impact on the gas dynamics during the simulation, hence it is possible to meaningfully vary this assumption in post-processing without introducing significant errors (Katz et al. 1996). The production of 11 different elements (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe) are tracked, from Type II and Ia supernovae and stellar evolution. SIMBA tracks dust growth and destruction on the fly, for each individual element (a detailed investigation of the dust model can be found in Li et al. 2019). Star formation is based on a Kennicutt-Schmidt Law (Kennicutt 1998) scaled by the H2 fraction, which is calculated for each particle using its local column density and metallicity following Krumholz & Gnedin (2011). Galactic outflows are implemented as kinetic decoupled two-phase winds, as in MUFASA (Davé et al. 2016), with an updated mass-loading factor based on particle tracking results from the Feedback in Realistic Environments (FIRE) zoom simulations (Anglés-Alcázar et al. 2017b). For more details on these implementations, see Davé et al. (2019).

2.2 Black hole accretion and feedback

The energy release from black holes, i.e. AGN feedback, has a significant impact on the properties of the galaxy and surrounding matter (Fabian 2012). SIMBA is notably unique in its way of modelling black hole processes. Owing to the importance of SIMBA’s black hole growth and feedback model for this study, we describe it more detail here; further details are available in Davé et al. (2019).

SIMBA employs a unique two-mode black hole accretion model. Cold gas (\(T < 10^5 K\)) is accreted via a “torque-limited” sub-grid model that captures how angular momentum loss via dynamical instabilities limits gas inflows into the region near the black hole (Hopkins & Quataert 2011; Anglés-Alcázar et al. 2017a). Meanwhile, hot gas is accreted following the Bondi (1952) formula. The torque-limited mode is appropriate for when black holes are growing in a cold rotationally-supported disk, while Bondi mode is more appropriate for hot gas since it models gravitational capture from a dispersion-dominated medium. SIMBA’s accretion model thus represents a step up in realism as opposed to simply using Bondi accretion for all forms of gas, as most other current simulations do. This unique black hole accretion model underpins the implementation of AGN feedback in SIMBA.

As material accretes into the central region, SIMBA assumes that 10% of it falls onto the black hole; this accretion efficiency is calibrated to match the amplitude of the black hole mass–galaxy stellar mass relation (Anglés-Alcázar et al. 2013, 2017a) for massive galaxies from Kormendy & Ho (2013). Accreted gas elements are subtracted a fraction of their mass and immediately ejected as AGN feedback such that the desired momentum flux in the wind (20L/c, where \(L = 0.1Mc^2\)) is achieved. This ejection is purely kinetic, and purely bipolar – i.e. it is ejected in the \(\pm L\) direction where \(L\) is the angular momentum vector of the inner disk (i.e. the 256 nearest neighbours to the black hole).

There are two modes for this type of feedback: radiative mode feedback, and jet mode feedback. The radiative mode in SIMBA happens when there is a high relative accretion rate around a black hole, above ~10% of the Eddington rate. In this mode, the ejected material is kicked with speeds typically around 1000 km/s, scaled to follow observations of ionised gas outflows from Perna et al. (2017), and its temperature is not changed in order to represent a multi-phase outflows as observed. At lower Eddington ratios, the jet feedback mode begins to switch on, with full jets achieved below 2%. The jet mode ejects gas at much higher velocities than the radiative mode, reaching a maximum of ~8000 km s\(^{-1}\). The jet mode also raises the temperature of the ejected particles, based on observations indicating that jets are mostly made of hot plasma (Fabian 2012). At all times, the amount of matter ejected is mass-loaded from the inner disk in order to have the momentum flux of the outflow be \(\approx 20L/c\).

Besides radiative and jet mode feedback, SIMBA includes also X-ray radiation pressure feedback broadly following Choi et al. (2012). This has the effect of pushing outwards on the gas surrounding the accretion disc based on the high-energy photon momentum flux generated in the black hole accretion disk. It is only activated in low-cold gas content galaxies and when the jet mode is active, because jets tend to be accompanied by strong X-rays and cold dense gas will tend to absorb X-ray energy and radiate it away quickly.

These three forms of AGN feedback – radiative mode, jet mode, and X-ray – combine to create a quenched massive galaxy population in good agreement with observations (Davé et al. 2019), as well as populating them with black holes as observed (Thomas et al. 2019). The jet mode is primarily responsible for quenching, although the X-ray feedback has a non-negligible impact. Radiative mode, meanwhile, has a minimal effect on the galaxy population.

2.3 SIMBA runs

The SIMBA simulations analyzed in this paper are run in a cubic box with length 50h\(^{-1}\)Mpc, with 2\(\times\)512\(^3\) elements. We employ these runs and not the full-size 100h\(^{-1}\)Mpc run with 2\(\times\)1024\(^3\) from Davé et al. (2019) because we have variants at this box size that enable direct tests of the impact of assumed input physics, particularly AGN feedback. Owing to computational cost, we do not have such variants for the
full SIMBA run. Nonetheless, for all checked properties, the 50h$^{-1}$Mpc and 100h$^{-1}$Mpc SIMBA runs agree very well. SIMBA assumes a cosmology consistent with Planck Collaboration et al. (2016) results: $\Omega_m = 0.3, \Omega_A = 0.7, \Omega_b = 0.048, H_0 = 68$ km s$^{-1}$Mpc$^{-1}, \sigma_8 = 0.82$, and $n_s = 0.97$. The resulting mass resolution is $1.82 \times 10^3$ $M_\odot$ for gas elements and $9.6 \times 10^3$ $M_\odot$ for dark matter particles.

We run several variants of AGN feedback, turning off one input physics quantity at a time, denoted as follows:

- “SIMBA” denotes a run with all forms of AGN feedback on.
- “No-X” denotes a run turning off only X-ray AGN feedback.
- “No-jet” denotes a run turning off both jet and X-ray feedback.

We also have a run where all AGN feedback is turned off (“No-AGN”), but it turns out the results are indistinguishable from the No-jet case, hence for simplicity we do not show it here. Apparently, the radiative portion of AGN feedback has little impact on the Ly$\alpha$ forest. The other three runs allow a direct quantification of the effects of the jet and x-ray AGN feedback modes in SIMBA. All these runs are started with identical initial conditions.

We will also compare to the Mufasa simulation, the predecessor to SIMBA which does not contain black holes or an explicit AGN feedback model, but rather utilised a heuristic model in which hot halo gas was prevented to cool in order to quench galaxies as observed (Davé et al. 2016, 2017). This also employed a 50h$^{-1}$Mpc box size with $2 \times 512^3$ elements, with identical initial conditions to the SIMBA runs.

2.4 Generating spectra

To generate spectra, we employ PyGAD\footnote{https://bitbucket.org/broett/pygad} (Röttgers et al., in prep). This is a full-featured toolkit for analysing particle-based simulations, including creating mock spectra in any desired ion. To generate H$\alpha$ spectra, PyGAD computes the neutral hydrogen fraction for each gas element based on an input (spatially-uniform) UVB, puts that gas element into velocity space, smooths its neutral component into velocity bins along a chosen line of sight, and computes the resulting optical depth in each bin. It further computes the optical depth-weighted density and temperature of H$\alpha$ gas. For these spectra, we use a velocity-space pixel size of 6 km s$^{-1}$. Since we do not do line fitting and only consider the Ly$\alpha$ mean flux decrement $D_A$ in this work, it is not necessary to smooth the spectrum with an instrumental line spread function or to add noise, since these would not change $D_A$. Note that we do not apply any continuum-fitting to our simulated spectra, which could in principle affect $D_A$. However, at the low redshifts we consider, continuum fitting in observations is usually very accurate owing to the sparse nature of Ly$\alpha$ forest absorbers, so we assume this has been done accurately in the data that we will compare to.

We generate 1000 spectra for each simulation snapshot through the entire box accounting for periodic boundary conditions. From these spectra, the mean flux decrement $D_A$ was calculated using

$$D_A = \left( \sum_i [1 - \exp(-\tau_i)] \right),$$

where $\tau_i$ is the optical depth in velocity bin $i$ of a given spectrum, and the average is taken over all 1000 generated spectra.

Since Ly$\alpha$ forest gas is optically-thin, the optical depth of any pixel to good approximation scales as $\tau \propto \rho_i \times c \sigma_T / \bar{\rho}$. This means any adjustment to $\rho_i$ can be related to an adjustment in $\tau$. This then gives us a way to constrain $\rho_i$ using the observed value of $D_A$. To do this, we multiply $\rho_i$ (e.g. from Haardt & Madau 2012) by a value we denote $F_{\text{UVB}}$, which corresponds to multiplying each value of $\tau_i$ by $1/F_{\text{UVB}}$; in practice, we do the latter, since optically thick absorption is extremely rare and does not contribute significantly to $D_A$.

The value of $F_{\text{UVB}}$ was then adjusted iteratively until the value of $D_A$ computed via equation 1 matched the observational determination from Danforth et al. (2016) to within 0.0001, at each snapshot redshift. $F_{\text{UVB}}$ can be regarded as the “photon underproduction factor” – i.e., the amount by which $\rho_i$ must be increased in the simulations (assuming a given photo-ionising background) in order to match the observed $D_A$. This will be the primary metric by which we quantify the PUC in this work.

2.5 Sample mock spectra

Figure 1 shows some example $z = 0$ mock spectra generated using PyGAD. These spectra were all generated down the same line of sight, from our three SIMBA variants: one from the SIMBA simulation with jet feedback enabled (green), one from the No-jet simulation with jet and X-ray feedback turned off (blue), and one from the No-X simulation with jets enabled but with X-ray feedback disabled (red). The top panel shows the flux, the middle panel shows the baryonic overdensity ($\rho/\bar{\rho}$), and the bottom panel shows the temperature in Kelvin; these quantities are all plotted versus wavelength, and the latter two are weighted by the H$\alpha$ optical depth.

At $z = 0$, the top panel shows that the Ly$\alpha$ forest is quite sparse compared with higher redshifts, but a number of absorption lines are still visible. Not all of these features are strong enough to be detectable with existing instruments, but this gives an impression of what the underlying HI distribution is within the variants of the SIMBA simulation, without any noise or instrumental broadening.

The middle panel shows that the temperatures are much higher in some parts of the simulations with the jets turned on (SIMBA and No-X) than when they are turned off (No-jet). This illustrates how AGN jet feedback provides an extra source of heating that permeates a significant fraction of the IGM. The additional heating means that the fraction of neutral hydrogen in those regions will be dramatically reduced, and hence that there will be much less Ly$\alpha$ absorption. The densities are also significantly impacted, as the higher temperatures result in smoothing the density distribution.

The top panel shows that in some regions, the spectra appear to be almost identical for all feedback variants. These regions are probing portions of the simulation that have not been affected by jets. The regions that are affected also usually seem to be relatively denser, which owes to the fact
that AGN (and hence AGN feedback) are in galaxies that are biased towards the denser regions. However, the lowest density regions e.g. towards the right of the spectrum are also unaffected, presumably because they are too far away for jet feedback to have reached there.

Comparing the green and red lines that differ by the inclusion of X-ray feedback, we see that this form of feedback has a small but non-negligible impact on IGM gas heating. Turning on X-ray feedback (green line) tends to create a slightly more widespread temperature increase around the densest regions, which are presumably closest to galaxies. The stronger absorption feature around 1219˚A in particular is set by pure photo-ionisation heating. These images are used to understand the implications for the PUC.

### 3 IGM PHYSICAL PROPERTIES

We begin by examining some global properties of the IGM in SIMBA, particularly related to the evolution of the diffuse IGM gas that predominantly gives rise to the Lyα forest.

#### 3.1 Visualising IGM jet heating

Figure 2 shows 50 × 50h⁻¹Mpch temperature maps from our simulations at z = 2, 1, 0. The left panels show the full SIMBA run, while the right panels show the No-jet run. The brightness regions represent T ≥ 10⁷K, and the darkest regions down to temperatures approaching a few times 10⁸K that is set by pure photo-ionisation heating. These images are obtained by computing the mean temperature in each pixel on the $y-z$ plane through the middle of the simulation volume (i.e. at $x = 25h⁻¹$Mpc), using yt’s slice function.

Large-scale filamentary structures are clearly visible in both simulations. These structures stand out as being somewhat hotter than the voids owing to the density-temperature relation in the diffuse photo-ionised IGM (Hui & Gnedin 1997). Around denser structures, there is additional shock heating caused by gravitational collapse onto filamentary structures, which raises temperatures to $T ≥ 10⁸$ K. As the simulations evolve to lower redshifts, many of the smaller filamentary structures drain into the larger ones owing to the hierarchical growth of structure, and the IGM is generally cooler owing to its lower physical density and the lower $\Gamma_{HI}$.

Comparing the left and right panels with and without jets, it can be seen that there is only slightly more heating at $z = 2$ for simulations with the jets included. In the jet run, individual bipolar jets are visible around the largest objects, as these generally have the largest black holes and hence low Eddington ratios that transition into jet mode (Thomas et al. 2019). The No-jet simulation also has some heating owing to gravitational shock heating in large halos as well as weak feedback. In general, there are not large differences in the large-scale thermal structure at $z = 2$ with the inclusion of jets.

The differences become more drastic at lower redshifts. The No-jet simulation shows heating close to the filamentary structures owing to accretion shocks around large halos, but this heating does not extend very far out. In contrast, the full SIMBA simulation including jets shows heating at $\gg$Mpc scales away from galaxies, which is consistent with the very high velocities at which these wind particles are ejected. For instance, an unimpeded 8000 km s⁻¹ jet will travel $\sim 8$ Mpc in a Gyr. While gravity and interactions with surrounding gas will retard this, it is still plausible that such jets will impact gas out to many Mpc over cosmic time (Bowyer et al. 2019). At $z = 0$, many of the locations where the No-jet simulation has cold, diffuse IGM, SIMBA has very hot gas typically in the $T ∼ 10⁶-10⁷$K range. This clearly demonstrates that jet feedback in SIMBA can have widespread impact in the IGM.

#### 3.2 Cosmic phase diagram

An illustrative global diagnostic for understanding IGM evolution is the cosmic phase diagram, i.e. gas temperature versus density of all baryons. In phase space, gas broadly divides into four regimes (Dave et al. 2010): Condensed gas that is cool and dense gas within galaxies and the circumgalactic medium, typically seen neutral and molecular gas; Hot halo gas that has been shock heated typically to near the halo virial temperature, typically observable via X-ray emission; Diffuse gas that is mostly photo-ionisation heated in the IGM, which gives rise to the Lyα forest; and Warm-Hot Intergalactic Medium (WHIM) gas that has been shock heated to higher temperatures, and which hosts the so-called missing baryons (Dave et al. 2001).

Figure 3 shows the $z = 0$ cosmic phase diagram for SIMBA (top panel) and the No-jet (bottom) simulations. The density has been scaled by the cosmic mean baryonic density. The black points show a randomly selected 0.1% of the gas (to avoid saturation). Cyan points show gas that is currently star-forming. Magenta points show gas elements that have recently been ejected in a galactic outflow, and are currently decoupled from hydrodynamics; note that the temperatures of these particles are arbitrary, as they do not currently experience pressure forces. Finally, the red points show gas elements that have been ejected by either radiative and/or jet AGN feedback at some point in their history.

We divide the phase diagram into four regions, demarcated by the horizontal and vertical dotted lines. The temperature cut is set at $T = 10⁷$K, which is a temperature that cannot be obtained without shock heating or feedback, and the traditional definition of the WHIM (Cen & Ostriker 1999). The density threshold follows Davé et al. (2010) as an estimate of a typical overdensity relative to $\Omega_m$ at the virial radius (based on Kitayama & Suto 1996), given by:

$$\delta_{th} = 6\pi^2(1 + 0.4093(1/f_3)^{-1})^{0.9052} - 1,$$

where $f_3$ is given by

$$f_3 = \frac{\Omega_m(1+z)^3}{\Omega_m(1+z)^3 + (1 - \Omega_m - \Omega_{\Lambda})(1+z)^3 + \Omega_{\Lambda}}.$$  

At $z = 0$, this results in $\delta_{th} ≈ 105$. We list the mass fraction
of baryons in each of these phases on Figure 3, along with the baryon fraction in stars that is not included in any of these gas phases but tends to live in dense regions.

The overall phase diagrams in the two cases are generally similar. The condensed phase consists mostly of photo-ionised gas at $\sim 10^4$ K, along with dense gas forming stars that in SIMBA is forced to lie along a density–temperature relation that explicitly resolves the Jeans mass. The wind particles are artificially set to $10^3$ K, but as they do not interact hydrodynamically, their temperature has no impact on their dynamics. The hot halo gas extends up to $T \gtrsim 10^7$ K and generally lies near the virial temperature of its host halo (e.g. Davé et al. 2008). The most massive halo in this box is somewhat anomalously large, giving rise to a distinct clump of high-$T$ gas. The diffuse phase shows the tight density–temperature relation characteristic of photo-heated gas expanding with Hubble flow. Finally, the WHIM phase shows gas that has been shock heated by filamentary accretion as well as feedback processes.

The most notable difference between the SIMBA and No-jet runs is the large decrease in the baryon fraction in the diffuse phase, and a corresponding increase in the baryon fraction contained in the WHIM, when jet feedback is on. The WHIM increase mostly but not entirely comes from the Diffuse phase; the baryon fraction of every other phase is at least halved in the jet simulation compared to the simulation without jets.

The No-jet simulation has baryon phase fractions that are broadly similar to the fiducial model at $z = 0$ in Davé et al. (2010), which had stellar feedback but did not have any AGN feedback. Hence non-jet AGN feedback has a fairly minimal impact on the cosmic phase diagram. We have confirmed this for SIMBA by examining the No-AGN simulation, which is not substantially different than No-jet.

Figure 3 also indicates which gas elements have been ejected by AGN feedback, as red points. In No-jet, we still have radiative AGN feedback up to $\sim 1000$ km s$^{-1}$, which distributes some gas into the diffuse and WHIM phase. However, it does not strongly change the phase of a significant amount of ambient gas; much of it stays at relatively cool temperatures.

In the full SIMBA run with jets, elements touched by AGN feedback can reach well into the diffuse region. In doing so they create a new feature in the cosmic phase diagram at $T \sim 10^6 - 7$ K near the cosmic mean density, that is not present in the No-jet run. This region is actually populated mostly by particles that have not been directly kicked by jet feedback, but rather have been entrained (and heated) by jet-ejected gas (Borrow et al. 2019). Also, in this simulation, very few particles that are ejected by AGN feedback end up in the condensed star-forming gas phases, unlike in the No-jet case. The reason is that the AGN-touched particles are significantly hotter, so do not have a chance to fall back in to bound systems. This is an important factor for suppressing star formation in massive galaxies having jet feedback, and is a key preventive feedback mechanism that keeps galaxies quenched.

Figure 4 quantifies the increase in temperature in unbound gas. It shows histograms of the baryon fraction for low-density phases (i.e. the WHIM and diffuse phases),

Figure 1. An example of three spectra generated using pygad, down the same line of sight at $z = 0$: one from the SIMBA simulation with jets turned on (green line), one from the No-jet run (blue line), and one from the No-X run (red line). The top panel shows the flux, the middle panel shows the density normalized to the cosmic mean, and the bottom panel shows the temperature. All 3 quantities are plotted in wavelength space. It can be seen that high density gas at low temperatures results in absorption.
Figure 2. Temperature slices from the $50 h^{-1}$Mpc SIMBA simulations with AGN jet feedback (left 3 panels) and from the No-jet run (right 3 panels). The top panels are at $z = 2$, the middle panels are at $z = 1$, and the bottom panels are at $z = 0$. The jet feedback clearly has a dramatic effect on the temperature of the IGM by $z = 0$, with many Mpc-scale regions heated by jet energy.
Jet Feedback and the PUC in Simba

Figure 3. Phase diagrams at $z = 0$ for 50h$^{-1}$Mpc Simba simulations, for the full Simba run including jets (top panel) and for the No-jet run (bottom panel). A randomly-selected 0.1% of gas elements are shown for clarity, as black points. Red points are gas elements that have at some point been ejected via AGN feedback; this includes from non-jet (radiative mode) AGN feedback. Magenta points are elements which are currently in a decoupled wind, owing to star formation feedback. Cyan points show star-forming gas. The dotted lines indicate the boundaries between cosmic phases (cf. Figure 5): The vertical division is the approximate density at the virial radius of dark matter halos, while the horizontal division at $T = 10^{5}$K separates cool from warm/hot phases. Percentages of baryons in each phase are indicated. AGN jet feedback results in AGN-ejected particles reaching much further into voids while entraining diffuse gas, thus generating substantially more hot gas well outside of galaxy halos and causing a strong reduction in the amount of cool diffuse IGM gas.

Figure 4. Temperature histograms of IGM gas ($\rho/\bar{\rho} < \delta_{th}$; i.e. the WHIM and diffuse phases). Results are shown for 50h$^{-1}$Mpc simulations with various runs: the main Simba simulation (blue line), the No-jet run (green line), the No-X run (red line), and the Mufasa simulation (purple line). Including jets (either in Simba or No-X) strongly shifts the distribution of IGM gas temperatures, producing a peak at $T \sim 10^{6.2}$K.

binned in temperature, for various models. The most distinct feature is that the Simba runs with AGN jet feedback enabled (Simba and No-X) have a large peak in their diffuse baryon fractions at $T \sim 10^{6.2}$ K. This shows that jet feedback strongly increases the overall temperature distribution in WHIM gas, compared to the No-jet run (green). The Mufasa simulations also produce a peak in approximately the same location, but not as sharply; we thus expect that the Mufasa simulation will show results intermediate between the No-jet and jet runs.

When looking at Figure 3, remember that the diffuse phase gives rise to Ly$\alpha$ absorption; the WHIM is too highly ionised for any H I absorption to occur. This means that a decrease in the diffuse fraction will correspond to a decrease in Ly$\alpha$ absorption. It is therefore clear that jet feedback will have a significant impact on the amount of H I absorption. This is the primary manner by which AGN jet feedback impacts the Ly$\alpha$ forest. The extra WHIM gas could potentially generate more high ionisation metal absorption, such as O vi, O vii, and O viii. Note however that O vi absorption may not be strongly impacted since O vi absorption is best at tracing the range $T \approx 10^{5} - 10^{5.7}$ K, while Figure 4 shows that most of the jet-heated gas is hotter. Thus O vii which is strong in $T \approx 10^{5.7} - 10^{6.3}$ K gas (Nicastro et al. 2018) may be a better tracer (e.g. Chen et al. 2003).

3.3 Baryonic phase evolution

Jet feedback clearly has a large impact on the cosmic phase of baryons at $z = 0$. At very high redshifts before jet feedback begins, it should obviously have no impact. The question is...
then, when do the SIMBA and No-jet diverge in terms of their baryon fractions in the various phases?

Figure 5 shows the evolution from $z = 3 \rightarrow 0$ of the baryon fraction in each phase as defined in Figure 3: Green is WHIM, cyan is condensed, blue is diffuse, red is hot halo, and magenta is stars. The dashed lines show the predictions for the No-jet simulation, and the solid lines show the results from the SIMBA simulation with jets.

The simulations both with and without jets have identical baryon fractions in each phase at $z \sim 3$, since there are essentially no massive black holes with jets yet at these early epochs. The evolutionary tracks begin to diverge shortly thereafter, with the jet simulation showing more WHIM gas and less in every other phase. By $z = 0$ the jet simulation has almost 2.5x as many baryons in the WHIM as the simulation without jets, and a corresponding reduction in the diffuse phase. At $z \lesssim 1$ the WHIM phase dominates the baryon fraction in SIMBA, which never happens in the No-jet case.

The late onset of these differences is to be expected, as the jet feedback in SIMBA only activates for black holes with masses $M_{BH} \geq 10^{7.5} \, M_\odot$ with low Eddington ratios, and black holes in SIMBA only reach the required typical sizes at late epochs (see Thomas et al. 2019). The No-jet case broadly reproduces the same evolution of the baryon fractions as the fiducial model used in Davé et al. (2010), which did not include any AGN feedback.

The SIMBA results with jets show a significantly higher fraction of baryons in the WHIM than previous simulations (Dave et al. 2001). These predicted fractions are also at the high end of current inferences from observations of O VII absorbers at $z \sim 0.4$, which suggest baryon fractions 20–60% (Nicastro et al. 2018) in IGM gas with $T = 10^5–7 \, K$ (see their Table 1). Our predicted value from the jet simulation is at the top end of this, while from no-jets it is at the bottom end. We will examine predictions for high-ionisation metal lines from SIMBA in future work, which could be a key discriminant between these types of models with future X-ray missions such as Athena and Lynx.

4 THE PUC: MEAN FLUX DECREMENT EVOLUTION

Armed with an understanding of the physical properties of the IGM, we now examine how AGN feedback impacts H I absorption in the IGM, and thereby investigate the PUC. To study this, we will use the metric of $D_A$, the mean flux decrement in the Lyα forest. This avoids the uncertain and non-unique process associated with line identification and fitting, which can depend fairly sensitively on signal-to-noise, spectral resolution, and other specific aspects that would need to be more closely reproduced in the mock spectra when comparing to observations, and impart greater uncertainties. For our purposes, $D_A$ provides a robust and well-defined measure that accurately quantifies the PUC.

Figure 6 encapsulates our main results. Here we show $D_A$ as a function of redshift in the top panels, and the inferred $F_{UVB}$ versus redshift in the bottom panels. In the left panels, $D_A$ and $F_{UVB}$ have been computed from spectra assuming a Haardt & Madau (2012) UVB (henceforth referred to as HM12), while in the right panels a Faucher-Giguère (2019) UVB (henceforth referred to as FG19) has been assumed. We choose these two background since the former is the one in which the PUC was originally found, and the latter is a recent state of the art UVB model. The solid green line represents values measured from spectra from the full SIMBA simulation with jets, and the solid blue line represents the No-jet results. Dotted lines indicate uncertainty due to cosmic variance, which was estimated by splitting the spectra into 4 quadrants based on their LOS down the simulation box, and computing the standard deviation on the value of $D_A$ found in each of the 4 quadrants. This cosmic variance uncertainty is typically ~ 8% for the full SIMBA results, and ~ 20% for the No-jet results. The effect of cosmic variance appears to be somewhat larger in the No-jet case, which may owe to the fact that without jets, Lyα absorbing gas is present in highly overdense regions where the variance in absorption is higher, whereas jet feedback removes this. The estimated effect of cosmic variance is in all cases greater than the statistical uncertainty on $D_A$, which is ~ 0.8% for all samples.

In the top panel, the black data points show the Danforth et al. (2016) measurements from HST/COS data, and the best-fit is shown as the dashed black hole with fit uncertainties indicated by the shading. For comparison, we also show the determination of $D_A(z)$ using HST’s Faint Object Spectrograph (FOS) from Kirkman et al. (2007) as the short dashed grey line. These observational values are the same in the both top panels.

The bottom panels of Figure 6 show $F_{UVB}$ for the SIMBA simulation variants as a function of redshift. The calculation of $F_{UVB}$ is described in §2.4, and can be regarded as the “pho-
Figure 6. Top panels: \( D_A \) versus redshift for simulations versus observations, with the left panels showing the results when simulated spectra are generated using the HM12 background, while right panels show the results when assuming an FG19 background. The solid green line is from the full Simba simulation with jets, while the solid blue line is from the No-jet run; dotted lines indicate estimates of the uncertainty due to cosmic variance. Black points with error bars are the binned observations from COS data by Danforth et al. (2016) and the black dashed line shows their low redshift best-fit with the grey shading indicating the fit uncertainty. The short dashed line shows the observational results from Kirkman et al. (2007) from Faint Objects Spectrograph (FOS) data. Bottom panels: Photon underproduction factor \( F_{\text{UVB}} \), i.e. the factor by which \( \Gamma_{\text{HI}} \) must be multiplied in order for simulated predictions of \( D_A \) (in the top panel) to match observations of \( D_A \) by Danforth et al. (2016). The dashed black line shows the value which indicates no adjustment \( (F_{\text{UVB}} = 1) \), with the gray shading indicating an approximate uncertainty on this from Danforth et al. (2016) when assuming optically thin gas \((\tau \ll 1)\). The dashed blue line shows \( F_{\text{UVB}} = 2 \), which is approximately the amount which Khaire & Srianand (2015) found the UVB might be changed by when using more recent values of QSO emissivities. It can clearly be seen in the top panels that the Simba simulations including jets are much closer to matching observed values of \( D_A \) than the No-jet runs, regardless of the background used. The FG19 background provides a closer match to observation than the HM12 background. By \( z = 0 \), \( F_{\text{UVB}} \approx 1.5 - 2.5 \) for Simba, while \( F_{\text{UVB}} = 4 - 6 \) for the No-jet run, showing that jets strongly mitigate the Photon Underproduction Crisis.

Figure 6, top panels, clearly illustrates the PUC. The No-jet simulation (blue line) shows significantly higher absorption than HST observations, moreso for HM12. Meanwhile, the absorption in Simba simulation with jets is significantly closer to matching the HST data at low redshifts \((z \lesssim 0.5)\), though the HM12 case is still mildly discrepant.
This illustrates our primary result, that including jet feedback and employing a modern determination of the UVB from FG19 essentially solves the PUC in Simba, and allows consistency between source count determined UVB estimates and the estimate obtained from the Lyα forest.

As we have shown that the jets are a source of additional heating, and heating should reduce the amount of Lyα absorption, the reduction in $D_A$ with jets is expected. The discrepancy between jet and no-jet results is also expected to be greater going towards lower redshifts, as this is when the jets have had more time to affect the IGM gas in the simulation. At $z > 1$, the jet and no-jet simulations do not show strong differences in $D_A$ for either HM12 or FG19, which is expected because there are only minor differences in the diffuse baryon fraction above this redshift (cf. Figure 5). Thus the PUC is only present at $z < 1$, and increases strongly to lower redshift.

The predicted $D_A$ generally follows a power-law slope in $(1 + z)$, but that slope is different depending on whether the HM12 or FG19 UVB is adopted. The slopes when using the FG19 background match the slope of the Danforth et al. (2016) data better than they match the Kirkman et al. (2007) data, while the converse is the case when using the HM12 background. The contrast between the two backgrounds is particularly stark at $z > 0$. Fitting a power law with $D_A \propto (1 + z)^\alpha$, we obtain slopes of $\alpha = [1.4, 0.62]$ for the jet and no-jet cases respectively for HM12, and $\alpha = [2.0, 1.5]$ for FG19. This can be compared to the Danforth et al. (2016) slope of $\alpha = 2.2 \pm 0.2$, showing that the full Simba case with FG19 produces a $D_A(1+z)$ slope in very good agreement with observations, and as a result a non-evolving $F_{UVB}$. At higher redshifts ($z > 1$), the predicted values of $D_A$ match fairly well with expectations from either HM12 or FG19, which nicely demonstrates that prior to the impact of AGN jet feedback, the UVB amplitude determined from source count modeling is in good agreement with that inferred from the Lyα forest. To more precisely quantify this excess of absorption shown in the top panels, we show $F_{UVB}$ as a function of redshift in the bottom panels of Figure 6. For the No-jet case and the HM12 UVB, the photon underproduction factor reaches --6 at $z = 0$, and is already --3 at $z = 0.5$. This confirms the PUC found by Kollmeier et al. (2014) in the case with no AGN feedback and HM12. In fact, even though the No-jet run has some AGN feedback, the underproduction factor is higher compared to the $x5$ discrepancy found by Kollmeier et al. (2014). This may owe to the lower star formation-driven wind speeds in Simba relative to the Davé et al. (2013) simulations used in Kollmeier et al. (2014), and/or the use of MFM rather than SPH for the hydrodynamics. In any case, the overall results are very similar, and confirm that the PUC is present in state of the art simulations when no feedback is included that heats the IGM.

With jets on, the green line shows that the PUC is not completely eradicated -- at $z = 0$, with HM12, the photon underproduction factor is still 2.5 (lower left panel). However, this is clearly much closer to unity, which would be the value if the predicted $D_A$ exactly matched the Danforth et al. (2016) measurements. Given that there are ~$x2$ uncertainties in the source count modeling determinations of $N_{HI}$ (Khaire & Srianand 2015), as roughly indicated by the green dashed line, such a discrepancy may not be considered severe.

Looking at the lower right panel which assumed FG19 instead of HM12, the PUC is essentially gone. The No-jet case still has a factor of 3 discrepancy in $F_{UVB}$, while the jet simulations reduces this to ~ 1.2, which is now likely well within current uncertainties. Interestingly, the evolution of $D_A(z)$ predicted in the Simba simulation is in very good agreement when assuming FG19, but with HM12 we predict a fairly strongly increasing PUC to lower redshifts. Thus the Simba simulations with jet feedback and using the FG19 background are in quite good agreement with the low-redshift Lyα forest data from Danforth et al. (2016).

It is interesting to note that $F_{UVB}$ is actually somewhat larger than the discrepancy in $D_A$ from the top panel. For instance, at $z = 0$ for the No-jet case, the ratio of the predicted $D_A$ (blue line) and the Danforth et al. (2016) value is about a factor of 4. However, when one goes through the exercise of iteratively adjusting the ionising background to match $D_A$, this indicates that a factor of 6 is needed to match the observations. The reason is that saturated lines provide a sub-dominant but non-negligible contribution to $D_A$. Saturated lines move into the logarithmic portion of the curve of growth, so their flux decrement no longer scales linearly with optical depth and $F_{UVB}^{-1}$. Hence it is important to do the exercise of iteratively fitting to the observed $D_A$ as we have done, since the PUC is actually worse that it appears simply by examining the discrepancy in $D_A$.

The impact on $D_A$ at lower redshifts owes not only to the increasing filling factor of hot gas as evident from Figure 2, but also to the fact that the largest contribution to $D_A$ comes from marginally saturated lines ($N_{HI} \approx 10^{13.5-14} \text{cm}^{-2}$), since below this the column density distribution has a slope shallower than --2 (Danforth et al. 2016), and above this the increase in absorbers’ column densities no longer contribute linearly to $D_A$. At $z \sim 2-3$, marginally saturated lines correspond to gas at moderate overdensities of a few, but by $z = 0$, these lines arise in diffuse gas of overdensities of ~ 20 – 50 (Davé et al. 1999). As a result, they move into the regions nearer to galaxies that are most dramatically impacted by the jet heating. This exacerbates the effect on $D_A(z)$.

As mentioned in §3, the diffuse phase of matter at low densities and temperatures is responsible for Lyα absorption. The $x2.5$ reduction in $D_A$ when jets are turned on as seen in Figure 6 is consistent with the $x2.5$ reduction in the fraction of baryons in the diffuse Lyα-absorbing phase, as seen in Figures 3 and 5. In light of this, a straightforward physical interpretation of the impact of AGN feedback on the low-redshift IGM is that it serves to heat a sufficient fraction of diffuse gas into the WHIM phase in order to provide a potential resolution to the PUC.

### 5 AGN FEEDBACK VARIANTS

In the previous section, we focused on comparing the full Simba simulation with the No-jet run, because these provide the greatest differences illustrating the impact of AGN feedback. In this section, we further consider two additional model variants, to gain insights into how well these PUC measurements might be able to discriminate between AGN feedback models. In the No-X case, we have left jets on but turned off X-ray AGN feedback; if jets are the dominant
mechanism impacting the IGM, we expect this model to be similar to the full SIMBA run, as opposed to the No-jet run which turns off both jet and X-ray feedback. We will also consider MUFASA, which used a completely different method for quenching galaxies in which hot gas in halos above an (evolving) mass threshold was prevented to cool (Davé et al. 2016). The No-X model produces mostly quenched galaxies but with insufficiently low specific star formation rates compared to observations (Davé et al. 2019), while MUFASA produces a quenched population in very good agreement with observations (Davé et al. 2017), in some ways even better than SIMBA, but it uses a less physical approach that does not directly model black holes. Here we examine $D_A(z)$ and $F_{\text{UVB}}(z)$ in these two variants.

Figure 7 shows $D_A$ (top panel) and $F_{\text{UVB}}$ (bottom) as a function of redshift for various SIMBA simulations using the FG19 background, similar to Figure 6. The red line shows results from the No-X simulation with jets but without X-ray feedback, and the purple line shows results from the MUFASA simulation. Green and blue lines are reproduced from Figure 6 showing the SIMBA and No-jet runs for comparison. Observations are also reproduced from Figure 6, as indicated. The No-X simulation is quite similar to the SIMBA run with X-ray feedback, showing that X-ray feedback has negligible impact on the diffuse IGM, and thus the impact comes from the jets. MUFASA matches observational data better than the No-jet case, but not as well as with jets, indicating that these observations could potentially discriminate between otherwise successful AGN feedback models.

jet and X-ray feedback off) for lowering $D_A$ in SIMBA. For MUFASA, it is interesting to note that there is still a substantial reduction in $F_{\text{UVB}}$, moving $D_A$ closer to the observed values, though not as strongly as in SIMBA. This was anticipated from Figure 4, which showed that MUFASA generates a substantial shift in the IGM temperature distribution from that expected with no or weak AGN feedback. This is somewhat surprising because the direct impact of the feedback is confined to halo gas (by adding heat to offset cooling), yet it appears to have a wider impact on IGM gas. Nonetheless, by $z = 0$, the photon underproduction factor is still $\approx 2$, so significantly higher than in SIMBA, though well lower than in the No-jet case. We do not show the HM12 results here, but the corresponding factor for MUFASA in this case is $\approx 4$. Hence one might envision, with improved measurements of $\Gamma_{\text{HI}}$ in the local universe such as from fluorescence (Fumagalli et al. 2017), it may be possible to discriminate between variants of AGN feedback based on their impact on the diffuse IGM.

6 SUMMARY AND DISCUSSION

We have examined the evolution of the mean flux decrement in the Ly$\alpha$ forest $D_A$ predicted in various simulations from the SIMBA suite, and used this to infer the H$\text{i}$ photo-ionisation rate as a function of redshift from $z = 2 \rightarrow 0$ by iteratively matching it to observations of $D_A$. We consider the full SIMBA simulation that includes various forms of AGN feedback (jet, X-ray, and radiative), and compare it to identical simulations with either X-ray feedback or X-ray and jet feedback turned off. We find greatest sensitivity to the inclusion of jet feedback: With jet feedback turned off, we recover the so-called Photon Underproduction Crisis (Kollmeier et al. 2014) in which the Ly$\alpha$ forest observations require $\Gamma_{\text{HI}}$ values at $z = 0$ that are $\approx 10$ higher than inferred from source count modeling by Haardt & Madau (2012). Including jets (regardless of X-rays or radiative feedback), reduces this discrepancy to $\approx 2.5$, and further using an updated ionising background from Faucher-Giguère
The large increase in WHIM baryon fraction should be testable with future observations, such as with high-ionisation oxygen absorption lines. The impact on O\textsc{vi} absorption may be modest because in \textsc{Simba} the jet heating does not strongly increase the amount of \( \sim 10^{5.5} \text{ K} \) gas (Figure 4) where such absorption is strong, but rather moves gas to higher temperatures that would give rise to e.g. O\textsc{vii} absorption in the soft X-rays. Current constraints are insufficient to discriminate between our jet vs. no-jet predictions, but upcoming facilities such as \textit{Athena} and \textit{Lyman} would be ideal for this. Another potential avenue for constraints is examining Sunyaev-Zel’dovich integrated IGM pressure measurements (e.g. Lim et al. 2018; de Graaff et al. 2019), which could provide constraints on the phase space distribution of IGM baryons. We plan to investigate whether \textsc{Simba} satisfies these constraints in future work.

The shape of the H\textsc{i} column density distribution is also an important constraint for solving the PUC. We have sidestepped this issue here, even though it was an important consideration in previous works (Kollmeier et al. 2014; Shull et al. 2015; Gurvich et al. 2017). Any solution to the PUC must also impact the column density distribution in a way that remains concordant with observations. A proper comparison of this, however, requires carefully mimicking the observational signal to noise, line spread function, wavelength coverage, and profile fitting algorithm used for the data. It is worth noting that in Dave & Tripp (2001), the observed column density distribution using high-resolution HST/STIS data was found to be significantly steeper than that found by Danforth et al. (2016) using lower resolution HST/COS data, illustrating this sensitivity. We plan to conduct side-by-side Voigt profile fitting comparisons of absorber statistics in the future, but the PUC is already evident even when considering the first order statistic of the mean flux decrement.

Broadly, our conclusions highlight the point that the ionisation level of the low-redshift IGM as traced by Ly\textsc{a} absorption can potentially be strongly impacted by AGN feedback originating deep within massive galaxies. While current uncertainties around determining the low-z meta-galactic photo-ionisation rate complicate the interpretation, this nonetheless provides new avenues to constrain AGN feedback models in a regime far removed from where it is typically constrained, via the properties of quenched galaxies and their black holes.

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REFERENCES

Anglés-Alcázar D., Özsel F., Davé R., 2013, ApJ, 770, 5
Anglés-Alcázar D., Davé R., Faucher-Giguère C.-A., Özsel F., Hopkins P. F., 2017a, MNRAS, 468, 2840
Anglés-Alcázar D., Faucher-Giguère C.-A., Kereš D., Hopkins P. F., Quataert E., Murray N., 2017b, Monthly Notices of the Royal Astronomical Society, 470, 4698
Bolton J. S., Puchwein E., Sijacki D., Haehnelt M. G., Kim T.-S., Meiksin A., Regan J. A., Viehmann B., 2017, MNRAS, 464, 897
Bondi H., 1952, MNRAS, 112, 195
Borrow J., Anglés-Alcazar D., Dave R., 2019, arXiv e-prints, p. arXiv:1910.00594
Broderick A. E., Chang P., Pfrommer C., 2012, ApJ, 752, 22
Cen R., Ostriker J. P., 1999, ApJ, 514, 1
Chen X., Weinberg D. H., Katz N., Davé R., 2003, ApJ, 594, 42
Choi E., Ostriker J. P., Naab T., Johansson P. H., 2012, ApJ, 754, 125
Danforth C. W., et al., 2016, The Astrophysical Journal, 817, 111
Dave R., Tripp T. M., 2001, The Astrophysical Journal, 553, 528
Dave R., Hernquist L., Katz N., Weinberg D. H., 1999, ApJ, 511, 521
Dave R., et al., 2001, The Astrophysical Journal, 552, 473
Dave R., Oppenheimer B. D., Srianand R., 2008, MNRAS, 391, 110
Dave R., Oppenheimer B. D., Katz N., Kollmeier J. A., Weinberg D. H., 2010, MNRAS, 408, 2051
Dave R., Katz N., Oppenheimer B. D., Kollmeier J. A., Weinberg D. H., 2013, MNRAS, 434, 2645
Dave R., Thompson R., Hopkins P. F., 2016, MNRAS, 462, 3265
Dave R., Rafieferantssoa M. H., Thompson R. J., 2017, MNRAS, 471, 1671
Dave R., Anglés-Alcázar D., Narayanan D., Li Q., Rafieferantssoa M. H., Appleby S., 2019, MNRAS, 486, 2827
Fabian A. C., 2012, ARA&A, 50, 455
Faucher-Giguère C.-A., 2019, arXiv e-prints, p. arXiv:1903.08657
Faucher-Giguère C.-A., Lidz A., Zaldarriaga M., Hernquist L., 2009, ApJ, 703, 1416
Fumagalli M., Haardt F., Theuns T., Morris S. L., Cantalupo S., Madau P., Fossati M., 2017, MNRAS, 467, 4802
Gaikwad P., Khaire V., Choudhury T. R., Srianand R., 2017, MNRAS, 466, 838
Genel S., et al., 2014, MNRAS, 445, 175
Gurvich A., Burkhardt B., Bird S., 2017, The Astrophysical Journal, 835, 175
Haaft D., Madau P., 1996, ApJ, 461, 20
Haaft D., Madau P., 2001, in Neumann D. M., Tran J. T. V., eds., Clusters of Galaxies and the High Redshift Universe Observed in X-rays. p. 64 (arXiv:astro-ph/0106018)
Haardt F., Madau P., 2012, ApJ, 746, 125
Hopkins P. F., 2015, MNRAS, 458, 13
Hopkins P. F., Quataert E., 2011, MNRAS, 415, 1027
Hui L., Gnedin N. Y., 1997, MNRAS, 292, 2
Katz N., Weinberg D. H., Hernquist L., 1996, ApJS, 105, 19
Kennicutt Robert C. J., 1998, ARA&A, 36, 189
Khaire V., Srianand R., 2015, Monthly Notices of the Royal Astronomical Society: Letters, 451, L30
Khaire V., et al., 2019, MNRAS, 486, 769
Kirkman D., Tytler D., Lubin D., Charlton J., 2007, MNRAS, 376, 1227
Kitayama T., Suto Y., 1996, ApJ, 469, 480
Kollmeier J. A., et al., 2014, ApJ, 789, L32
Kormendy J., Ho L. C., 2013, ARA&A, 51, 511
Krumholz M. R., Gnedin N. Y., 2011, ApJ, 729, 36
Kulkarni G., Worseck G., Hennawi J. F., 2019, MNRAS, 488, 1035
Li Q., Narayanan D., Davé R., 2019, MNRAS, p. 2365
Lim S. H., Mo H. J., Wang H., Yang X., 2018, MNRAS, 480, 4017
Meiksin A. A., 2009, Rev. Mod. Phys., 81, 1405
Nicastro F., et al., 2018, Nature, 558, 406
Perna M., Lanzuisi G., Brusa M., Mignoli M., Cresci G., 2017, A&A, 603, 499
Planck Collaboration et al., 2016, A&A, 594, A13
Rahmati A., Pawlik A. H., Raicic M., Schaye J., 2013, Monthly Notices of the Royal Astronomical Society, 430, 2427
Rausch M., et al., 1997, The Astrophysical Journal, 489, 7
Rutkowski M. J., et al., 2016, ApJ, 819, 81
Shull J. M., Smith B. D., Danforth C. W., 2012, The Astrophysical Journal, 759, 23
Shull J. M., Moloney J., Danforth C. W., Tilton E. M., 2015, The Astrophysical Journal, 811, 3
Smith B. D., Hallman E. J., Shull J. M., O'Shea B. W., 2011, ApJ, 731, 6
Smith B. D., et al., 2017, MNRAS, 466, 2217
Sorini D., O'lohere J., Hennawi J. F., Lukić Z., 2018, ApJ, 850, 125
Thomas N., Davé R., Anglés-Alcázar D., Jarvis M., 2019, MNRAS, 487, 5764
Tonnesen S., Smith B. D., Kollmeier J. A., Cen R., 2017, ApJ, 845, 47
Tripp T. M., Savage B. D., Jenkins E. B., 2000, ApJ, 534, L1
Tytlr D., Fan X.-M., Bulbul S., 1996, Nature, 381, 207
Viel M., Haehnelt M. G., Bolton J. S., Kim T.-S., Puchwein E., Nasir F., Wakker B. P., 2017, MNRAS, 467, L86
Vogelsberger M., et al., 2014, MNRAS, 444, 1518
Wakker B. P., Hernandez A. K., French D. M., Kim T.-S., 2017a, MNRAS, 468, 2558
Wakker B. P., Hernandez A. K., French D. M., Kim T.-S., 2017b, MNRAS, 468, 2558
Weinberg D. H., Katz N., Wehliqué P., Blecha M., 2015, MNRAS, 448, 1035
Weinberg D. H., Katz N., Hernquist L., 1998, in Woodward C. E., et al., eds., The Pacific Conference Series Vol. 148, Origins. p. 21 (arXiv:astro-ph/97070281)
Weinberger R., et al., 2018, MNRAS, 479, 4056
Whittam I. H., Prescott M., Mclvanine K., Jarvis M. J., Heywood I., 2018, Monthly Notices of the Royal Astronomical Society, 480, 358
de Graaff A., Cal Y.-C., Heymans C., Peacock J. A., 2019, A&A, 624, A48

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