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# First constraints on the local ionization topology in front of two quasars at $z \sim 7.5$

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## ABSTRACT

Thus far, Lyman- $\alpha$  damping wings towards quasars have been used to probe the *global* ionization state of the foreground intergalactic medium (IGM). A new parametrization has demonstrated that the damping wing signature also carries *local* information about the distribution of neutral hydrogen (H I) in front of the quasar before it started shining. Leveraging a recently introduced Bayesian JAX-based Hamiltonian Monte Carlo inference framework, we derive constraints on the Lorentzian-weighted H I column density  $N_{\text{H I}}^{\text{DW}}$ , the quasar’s distance  $r_{\text{patch}}$  to the first neutral patch, and its lifetime  $t_Q$  based on *James Webb Space Telescope* (JWST) Near Infrared Spectrograph (NIRSpec) spectra of the two  $z \sim 7.5$  quasars J1007+2115 and J1342+0928. After folding in model-dependent topology information, we find that J1007+2115 (and J1342+0928) is most likely to reside in a  $\langle x_{\text{H I}} \rangle = 0.32^{+0.22}_{-0.20}$  ( $0.58^{+0.23}_{-0.23}$ ) neutral IGM while shining for a remarkably short lifetime of  $\log_{10} t_Q/\text{yr} = 4.14^{+0.74}_{-0.18}$  (an intermediate lifetime of  $5.64^{+0.25}_{-0.43}$ ) along a sightline with  $\log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2} = 19.70^{+0.35}_{-0.86}$  ( $20.24^{+0.25}_{-0.22}$ ) and  $r_{\text{patch}} = 28.9^{+54.0}_{-14.4}$  cMpc ( $10.9^{+5.6}_{-5.9}$  cMpc). In light of the potential presence of local absorbers in the foreground of J1342+0928 as has been recently suggested, we also demonstrate how the Lorentzian-weighted column density  $N_{\text{H I}}^{\text{DW}}$  provides a natural means for quantifying their contribution to the observed damping wing signal.

**Key words:** methods: statistical – intergalactic medium – quasars: absorption lines – dark ages, reionization, first stars – cosmology: observations – cosmology: theory.

## 1 INTRODUCTION

The highly sensitive Lyman- $\alpha$  transition observed in the spectra of high-redshift sources carries a wealth of information about the epoch of reionization, most particularly when the absorption imprint from the foreground neutral intergalactic medium (IGM) saturates, manifesting in a characteristic *damping wing* signature redward of Lyman- $\alpha$  line centre (J. Miralda-Escudé 1998). Quasars (J. S. Bolton et al. 2011; D. J. Mortlock et al. 2011; B. Greig et al. 2017, 2022, 2024; E. Bañados et al. 2018; F. B. Davies et al. 2018; B. Greig, A. Mesinger & E. Bañados 2019; D. Āurovčíková et al. 2020, 2024; D. M. Reiman et al. 2020; F. Wang et al. 2020; J. Yang et al. 2020)

as well as galaxies (E. Curtis-Lake et al. 2023; T. Y.-Y. Hsiao et al. 2024; L. C. Keating et al. 2024b; H. Umeda et al. 2024, 2025; C. A. Mason et al. 2025; H. Park et al. 2025) have been used as background sources to infer constraints on the global volume-averaged fraction  $\langle x_{\text{H I}} \rangle$  of neutral hydrogen (H I) at the redshift of the source, either by stacking spectra at a similar redshift (e.g. D. Āurovčíková et al. 2024; H. Umeda et al. 2024, 2025) or by statistically combining the inferred  $\langle x_{\text{H I}} \rangle$  constraints (e.g. B. Greig et al. 2024; C. A. Mason et al. 2025). Recently, this has been complemented by claimed detections of damping wings next to individual Gunn–Peterson troughs due to neutral islands persisting until  $5.5 \lesssim z \lesssim 6$  (G. D. Becker et al. 2024; B. Spina et al. 2024; Y. Zhu et al. 2024; F. Sawyer et al. 2025). All these analyses have established IGM damping wings as a natural probe of the timing of reionization. However, recent studies have constructed parametrizations that capture the shape of the IGM

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damping wing significantly more tightly than the global IGM neutral fraction  $\langle x_{\text{H I}} \rangle$ , and even carry information about the *local* ionization topology in front of a given source (H. Chen 2024; L. C. Keating et al. 2024a; T. Kist, J. F. Hennawi & F. B. Davies 2025b; C. A. Mason et al. 2025).

Specifically, T. Kist et al. (2025b) put forward a three-parameter model applicable in the context of quasars, consisting of two summary statistics of the  $x_{\text{H I}}$  field *before* the quasar started shining (which we dub the *pre-quasar*  $x_{\text{H I}}$  field), and the quasar’s lifetime  $t_Q$  encoding the effects of its ionizing radiation. The former two statistics of the pre-quasar ionization topology are (1) the column density  $N_{\text{H I}}^{\text{DW}}$  of neutral material in front of the quasar, weighted by a Lorentzian profile mimicking the frequency dependence of the Lyman- $\alpha$  cross-section  $\sigma_\alpha$  appearing in the optical depth integral and (2) the distance  $r_{\text{patch}}$  from the quasar to the first neutral patch. In a companion paper, T. Kist et al. (in preparation) introduced a fully Bayesian pipeline to infer these two parameters along with the quasar lifetime  $t_Q$  in a reionization model-independent fashion based on observed high-redshift quasar spectra, accounting for all relevant sources of uncertainty such as the unknown intrinsic continuum of the quasar, IGM transmission fluctuations, and spectral noise. Statistical tests on hundreds of mock spectra demonstrated that the pipeline allows them to constrain  $t_Q$  to  $0.58^{+0.13}_{-0.13}$  dex,  $N_{\text{H I}}^{\text{DW}}$  to  $0.72^{+0.08}_{-0.25}$  dex, and  $r_{\text{patch}}$  to  $35.7^{+7.8}_{-31.9}$  cMpc in case a noticeable damping wing is present in the spectrum. Here, we take advantage of this framework to infer the first *local* IGM damping wing constraints from *James Webb Space Telescope* (JWST)/NIRSpec spectra of two of the highest redshift quasars known to date, that is, J1007+2115 at  $z = 7.51$  (J. Yang et al. 2020) and J1342+0928 at  $z = 7.54$  (E. Bañados et al. 2018).

We briefly summarize in Section 2 the underlying theory and our local damping wing analysis framework, and proceed in Section 3 by introducing the data and presenting our analysis results for the two aforementioned objects. We put these measurements into context with existing literature constraints and conclude in Section 4.

## 2 METHODS

We conduct our analysis in the context of the local damping wing parametrization put forward by T. Kist et al. (2025b), harnessing the inference pipeline originally introduced in J. F. Hennawi et al. (2025) and adapted by T. Kist et al. (in preparation) for the use with this parametrization. T. Kist et al. (in preparation) also conceptualized a theoretical framework for tying the inferred local parameter constraints, which are agnostic to the underlying reionization topology to a specific reionization model to obtain a global constraint on the timing of reionization. We restrict this section to a brief but self-contained summary of each of these analysis components and refer the reader to the works above for more comprehensive descriptions of the respective parts.

The first of the two local summary statistics of the pre-quasar ionization topology defined by T. Kist et al. (2025b) that we aim to constrain in this work is the Lorentzian-weighted H I column density

$$N_{\text{H I}}^{\text{DW}} \equiv 5.1 \times 10^{20} \text{ cm}^{-2} \times \left( \frac{r_{\text{T}}}{18 \text{ cMpc}} \right) \times \left( \frac{1 + z_{\text{QSO}}}{1 + 7.54} \right)^2 \int_{r_{\text{min}}/r_{\text{T}}}^{r_{\text{max}}/r_{\text{T}}} \frac{x_{\text{H I}}(r) \Delta(r)}{(r/r_{\text{T}} + 1)^2} d(r/r_{\text{T}}), \quad (1)$$

where  $r$  denotes the comoving distance, and the denominator in the integrand is the Lorentzian weighting kernel, which accounts for the frequency dependence of the Lyman- $\alpha$  cross-section that the neutral

hydrogen field  $x_{\text{H I}}(r)$  and the overdensity field  $\Delta(r)$  are integrated against in the optical depth integral. The three distances  $r_{\text{min}}$ ,  $r_{\text{max}}$ , and  $r_{\text{T}}$  are hyperparameters, which we fix to  $r_{\text{min}} = 4 \text{ cMpc}$ ,  $r_{\text{max}} = r_{\text{min}} + 100 \text{ cMpc}$ , and  $r_{\text{T}} = 18 \text{ cMpc}$  throughout (for details, see T. Kist et al. 2025b). Our second statistic  $r_{\text{patch}}$  can be straightforwardly defined as the (comoving) distance between the source and the first neutral patch. Recall that both  $N_{\text{H I}}^{\text{DW}}$  and  $r_{\text{patch}}$  are summaries of the *pre-quasar* ionization topology  $x_{\text{H I}}$  as this is the cosmological field we are aiming to constrain. Our third parameter, the lifetime  $t_Q$  of the quasar, summarizes the effects of the quasar’s ionizing radiation.

We simulate IGM transmission profiles  $t$  based on a hybrid approach following F. B. Davies et al. (2018) where we combine density, velocity, and temperature skewers from the NYX hydrodynamical simulations (A. S. Almgren et al. 2013; Z. Lukić et al. 2015) and synthetic  $x_{\text{H I}}$  skewers (T. Kist et al. 2025b) generated at 21 column density values in the range  $17.48 \leq \log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2} \leq 21.08$  and 18 different neutral patch distances in the range  $0.3 \text{ cMpc} \leq r_{\text{patch}} \leq 143.0 \text{ cMpc}$ . We then perform one-dimensional radiative transfer (F. B. Davies, S. R. Furlanetto & M. McQuinn 2016) assuming 51 quasar lifetimes in the range  $10^3 \text{ yr} \leq t_Q \leq 10^8 \text{ yr}$ , and forward-model realistic instrumental effects (J. F. Hennawi et al. 2025). All our models are generated assuming  $z_{\text{QSO}} = 7.54$  with an ionizing photon emission rate of  $Q = 10^{57.14} \text{ s}^{-1}$ , explicitly resembling J1342+0928 but also appropriate for J1007+2115. Further, to tie our local constraints to the global IGM neutral fraction  $\langle x_{\text{H I}} \rangle$  in the way described in T. Kist et al. (in preparation), we determine the stochastic mapping  $P_{\text{top}}(\log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2}, r_{\text{patch}} | \langle x_{\text{H I}} \rangle)$ ,<sup>1</sup> by combining the same hydrodynamical NYX sightlines with  $x_{\text{H I}}$  skewers extracted from seminumerical reionization topologies simulated with a modified version of 21CMFAST (A. Mesinger, S. Furlanetto & R. Cen 2011; F. B. Davies & S. R. Furlanetto 2022) at 21 different global IGM neutral fractions in the range  $0 \leq \langle x_{\text{H I}} \rangle \leq 1$ .

In combination with a principal component analysis (PCA) model for the intrinsic quasar continuum  $s$  constructed based on a data set of 44 587 quasar spectra at  $1.878 < z < 3.427$  from the Sloan Digital Sky Survey-III (SDSS-III) Baryon Oscillation Spectroscopic Survey (BOSS) and SDSS-IV Extended BOSS (J. F. Hennawi et al., in preparation; T. Kist et al., in preparation), this allows us to write down the likelihood of an observed spectrum  $f$  given the astrophysical parameters  $\theta$ , the PCA coefficients  $\eta$ , and its observational noise vector  $\sigma$  as the following multivariate Gaussian distribution (J. F. Hennawi et al. 2025):

$$L(f | \sigma, \theta, \eta) = \mathcal{N}(f; \langle t \rangle \circ \langle s \rangle, \Sigma + \langle S \rangle \mathbf{C}_t \langle S \rangle + \langle T \rangle \mathbf{C}_s \langle T \rangle), \quad (2)$$

where  $t \circ s$  is the element-wise (Hadamard) product of the two mean vectors  $\langle t \rangle$  and  $\langle s \rangle$ , and  $\mathbf{C}_t$  and  $\mathbf{C}_s$  are the covariance matrices of  $t$  and  $s$ , and we write  $\Sigma \equiv \text{diag}(\sigma)$ ,  $T \equiv \text{diag}(t)$ , and  $S \equiv \text{diag}(s)$ .

We follow T. Kist et al. (in preparation) and initially infer the local parameters  $\theta \equiv (\log_{10} t_Q/\text{yr}, \log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2}, r_{\text{patch}})$  under the assumption of a logarithmically flat prior on the lifetime in the range  $3 \leq \log_{10} t_Q/\text{yr} \leq 8$ , and a constant two-dimensional topology-agnostic prior on  $(\log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2}, r_{\text{patch}})$  with a non-trivial boundary enclosing all physically permitted regions of parameter space (for details, see T. Kist et al., in preparation). After marginalizing out the nuisance parameters  $\eta$ , we can probabilistically tie these local constraints on  $\theta$  to the aforementioned seminumerical reionization topology via the conditional distribution  $P_{\text{top}}(\log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2}, r_{\text{patch}} | \langle x_{\text{H I}} \rangle)$  and obtain a joint constraint on

<sup>1</sup>Throughout, we use a ‘top’ subscript to denote probability distributions that are defined in the context of a specific reionization model.

the global IGM neutral fraction:

$$P_{\text{top}}(\langle x_{\text{H I}} \rangle, \theta | \mathbf{f}, \sigma) = L(\mathbf{f} | \sigma, \theta) \times P(\langle x_{\text{H I}} \rangle) \times P(\log_{10} t_{\text{Q}} / \text{yr}) \\ \times P_{\text{top}}(\log_{10} N_{\text{H I}}^{\text{DW}} / \text{cm}^{-2}, r_{\text{patch}} | \langle x_{\text{H I}} \rangle) / P(\mathbf{f} | \sigma). \quad (3)$$

For comparison, we also perform the inference following the conventional approach without local summary statistics where  $\theta \equiv (\langle x_{\text{H I}} \rangle, \log_{10} t_{\text{Q}} / \text{yr})$  such that no conversion according to equation (3) is necessary. We henceforth refer to this as the *global* parametrization (as opposed to our *local* one). Here, we assume a flat neutral fraction prior in the range  $0 \leq \langle x_{\text{H I}} \rangle \leq 1$ .

Practically, we sample from the respective posterior distribution via the NUMPYRO Hamiltonian Monte Carlo (HMC) implementation with No U-Turn Sampler. Each inference run consists of 8 HMC chains with 1000 warm-up and 2000 sampling steps per chain (for details, see J. F. Hennawi et al. 2025; T. Kist et al., in preparation). We reweight these samples based on the coverage tests performed in T. Kist et al. (in preparation) to ensure that we are quoting statistically faithful constraints.

### 3 LOCAL IGM DAMPING WING CONSTRAINTS AT $z \sim 7.5$

We now proceed by leveraging the framework summarized in the previous section to infer the first *local* IGM damping wing constraints for two of the highest redshift quasars known to date. That is, J1007+2115 at  $z = 7.51$  (J. Yang et al. 2020) and J1342+0928 at  $z = 7.54$  (E. Bañados et al. 2018) with absolute magnitudes of  $M_{1450} = -26.82$  and  $M_{1450} = -26.34$  at 1450 Å in the rest frame, respectively, determined based on Euclid photometry (Euclid Collaboration, in preparation).

This work presents the first damping wing analysis of *JWST*/NIRSpec spectra of these two objects (*JWST* GO 1764, PI: Fan, and *JWST* GTO 1219, PI: Luetzgendorf; see also L. Christensen et al. 2023; J. F. Hennawi et al., in preparation). The spectra were taken with the NIRSpec Fixed Slits together with the G140H/F070LP and G235H/F170LP grating and filter combinations at a resolution of  $R \simeq 2700$  and have signal-to-noise ratios of  $S/N \simeq 10$ –25 and 50–100, respectively, in the smooth Lyman- $\alpha$  region. The data were reduced via a combination of the *JWST* Science calibration pipeline CALWEBB (version 1.13.4) and the PYTHON-based semi-automated reduction pipeline PyPeIt (J. Prochaska et al. 2020). The full details of the reduction procedure are discussed in J. F. Hennawi et al. (in preparation).

The spectral coverage of these observations allows us to operate on a rest-frame wavelength range of  $1175 \text{ Å} \leq \lambda \leq 3000 \text{ Å}$ . After masking narrow absorbers, we rebin both spectra to a velocity pixel scale of  $dv = 500 \text{ km s}^{-1}$  (and likewise are our forward-modelled IGM transmission profiles) as our current likelihood prescription does not allow us to extract all information from the full resolution data at its native pixel scale in a statistically faithful manner (T. Kist, J. F. Hennawi & F. B. Davies 2025a; T. Kist et al., in preparation), which is pending improvements in our likelihood prescription, for example, through simulation-based inference (H. Chen 2024).

#### 3.1 J1007+2115

We start by analysing the quasar J1007+2115 at  $z = 7.51$ . Previous studies have inferred IGM neutral fractions of  $\langle x_{\text{H I}} \rangle = 0.39^{+0.22}_{-0.13}$  (J. Yang et al. 2020) and  $\langle x_{\text{H I}} \rangle = 0.27^{+0.21}_{-0.17}$  (B. Greig et al. 2022) from ground-based spectra of this object. Note that the former analysis also obtained a constraint of  $\log_{10} t_{\text{Q}} / \text{yr} = 4.89^{+1.15}_{-0.76}$  on its lifetime

(A.-C. Eilers et al. 2021), and used, upon some minor differences, the same simulation models as we do in this work, however, with a significantly different analysis pipeline. Our re-analysis is based on the new *JWST*/NIRSpec spectrum of this object, and we perform the analysis both in the context of the conventional global as well as our local IGM damping wing parametrization. We depict the final rebinned spectrum that forms the input to our pipeline as the black line in Fig. 1 with associated noise vector in yellow. The upper panel depicts our reconstruction in the context of the local parametrization, and the lower panel in the context of the global one. The median reconstructed continua are shown in blue, and the full models including IGM absorption in red. The shading around these lines highlights the associated 16 and 84 per cent percentile variations, reflecting parameter uncertainty, continuum reconstruction errors, and spectral noise (for further details, see J. F. Hennawi et al. 2025).

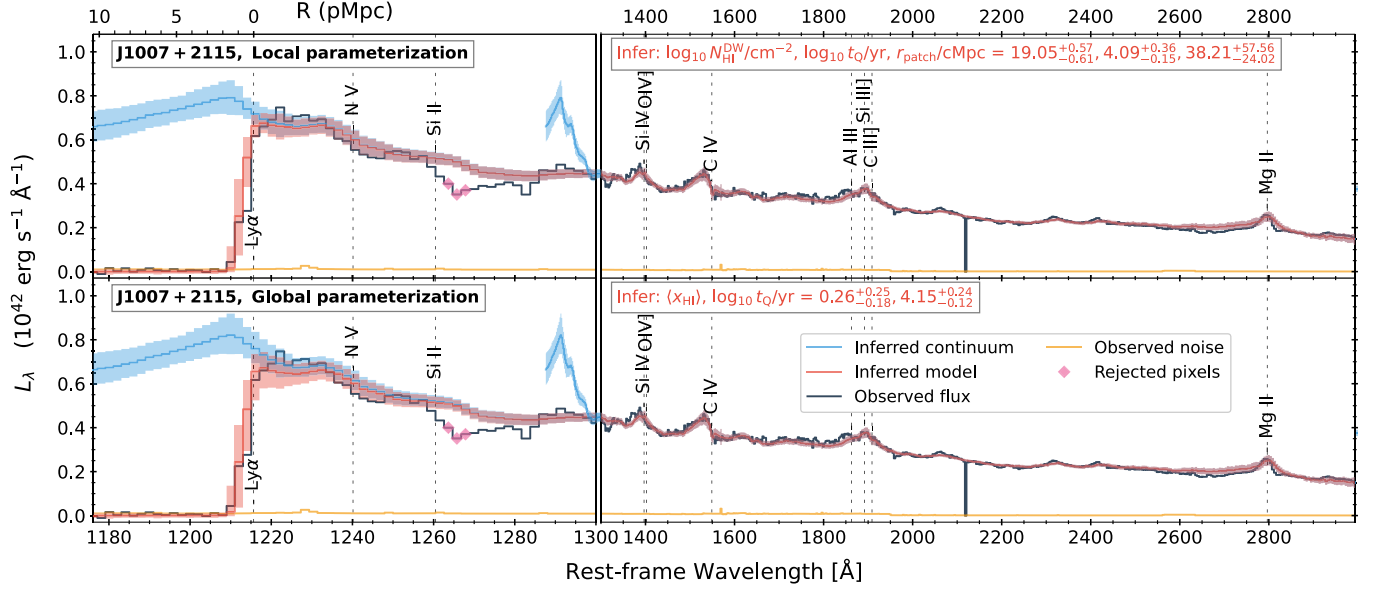
Overall, the models show a remarkable agreement, both providing a good fit to the spectrum across the entire spectral range, not only matching the shape of the proximity zone and the Lyman- $\alpha$  damping wing, but also the smooth emission lines redward of Lyman- $\alpha$ . The median models slightly undershoot the observed spectrum around  $\lambda \approx 1225 \text{ Å}$  (somewhat more pronounced in the global parametrization), and slightly overshoot at  $\lambda \approx 1245 \text{ Å}$ . However, in both regions the observed value is still within the 68 per cent region. Somewhat more redward, at  $\lambda \approx 1265 \text{ Å}$ , three pixels got rejected by the sigma-clipping procedure we apply prior to the inference (see T. Kist et al., in preparation). These pixels are possibly affected by a mild broad absorption line system, but this does not appear to impact our conclusions as we obtain the same results when no clipping is applied.

The only main difference between the global and the local model curves is a reduced degree of scatter in the local parametrization as this parametrization excludes the scatter due to the stochastic distribution of neutral patches along the line of sight from the inference task. Both models only show a very mild damping wing. The black contours in Fig. 2 depict the associated local parameter constraints. The lifetime posterior peaks relatively sharply at  $\log_{10} t_{\text{Q}} / \text{yr} = 4.09^{+0.36}_{-0.15}$ , implying that we are concerned with a comparably young object, as already hinted at by its small proximity zone (see e.g. also the objects in A.-C. Eilers et al. 2020, 2021). The data are not overly constraining with respect to the two local parameters  $N_{\text{H I}}^{\text{DW}}$  and  $r_{\text{patch}}$ . In essence, only the highest H I column densities [and correspondingly short neutral bubble distances that are still located in the physically permitted region of parameter space enclosed by the dashed line in the ( $N_{\text{H I}}^{\text{DW}}, r_{\text{patch}}$ ) panel] are excluded as these would lead to a noticeable damping wing imprint.

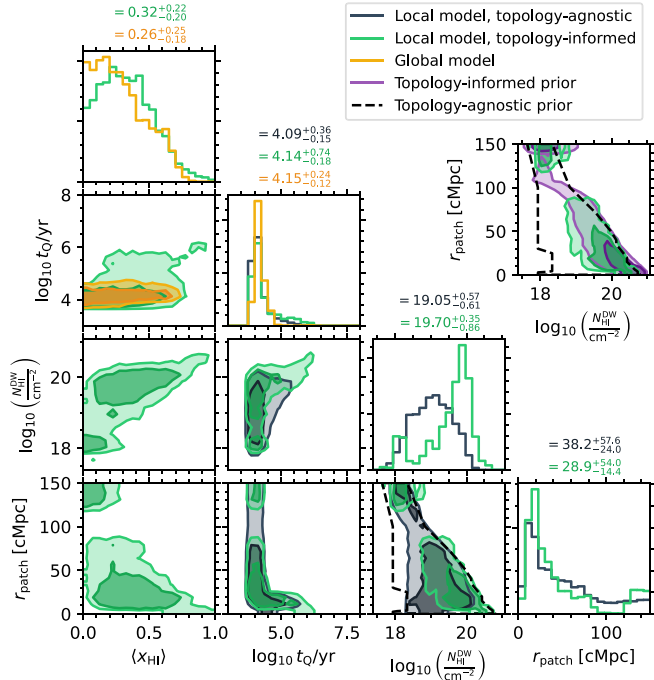
We obtain a global  $\langle x_{\text{H I}} \rangle$  constraint on the timing of reionization based on these local constraints by following the procedure introduced in T. Kist et al. (in preparation) and summarized in Section 2, folding in the distribution of our local parameters within the realistic seminumerical reionization topology as a prior. The green contours in Fig. 2 show the resulting posterior distribution. We see that the prior on  $N_{\text{H I}}^{\text{DW}}$  and  $r_{\text{patch}}$  induced by this topology (shown explicitly in purple in the extra panel of the plot) disfavors the (low- $N_{\text{H I}}^{\text{DW}}$ , low- $r_{\text{patch}}$ ) region of the posterior and therefore gives more weight to the (low- $N_{\text{H I}}^{\text{DW}}$ , high- $r_{\text{patch}}$ ) and (high- $N_{\text{H I}}^{\text{DW}}$ , low- $r_{\text{patch}}$ ) peaks.<sup>2</sup> The

<sup>2</sup>Note that the green converted posterior seemingly has support in regions where the black unconverted one does not. In fact, *both* posteriors have support in these regions, but before performing the conversion, these are not included in the 95 per cent contour shown in the plot. Further, due to smoothing effects and the statistical reweighting procedure we apply, the contours marginally





**Figure 1.** Inferred model for the *JWST*/NIRSpec spectrum of the quasar J1007+2115, fitted in the context of the local IGM damping wing parametrization (upper row) and the global one (lower row). The observed (and rebinned) spectrum of the quasar is depicted in black, with the noise vector shown in yellow. The inferred model spectrum is depicted in red and the unabsorbed inferred continuum in blue, where solid lines represent the median inferred models, and shaded regions the 16 and the 84 per cent percentile variations reflecting parameter uncertainty, continuum reconstruction errors, and spectral noise.



**Figure 2.** Posterior distributions inferred from the *JWST*/NIRSpec spectrum of the quasar J1007+2115 depicted in Fig. 1 in the context of the local IGM damping wing parametrization (black) and the global one (yellow). Both distributions are marginalized over seven nuisance parameters describing the shape of the quasar continuum. Additionally depicted in green is the topology-informed version of the local constraints, entailing the non-trivial prior  $P_{\text{top}}(\log_{10} N_{\text{H}}^{\text{DW}}/\text{cm}^{-2}, r_{\text{patch}})$  (explicitly depicted in purple in the extra panel), and also providing a constraint on the global IGM neutral fraction  $\langle x_{\text{H I}} \rangle$  in good agreement with the directly inferred one.

resulting  $\langle x_{\text{H I}} \rangle$  posterior suggests a comparably low to intermediate neutral fraction of  $\langle x_{\text{H I}} \rangle = 0.32^{+0.22}_{-0.20}$  at this redshift. The lifetime constraint largely remains unaffected by folding in the topology information, still peaking at  $\log_{10} t_{\text{Q}}/\text{yr} = 4.14^{+0.74}_{-0.18}$ , on the lower end of the literature value of  $\log_{10} t_{\text{Q}}/\text{yr} = 4.89^{+1.15}_{-0.76}$  (J. Yang et al. 2020; A.-C. Eilers et al. 2021). Our local parameter constraints, on the other hand, are fully prior-dominated, as a comparison of the green and purple contours in the extra  $(N_{\text{H}}^{\text{DW}}, r_{\text{patch}})$  panel in the same figure suggests.

We test the robustness of the  $\langle x_{\text{H I}} \rangle$  constraint by also comparing it to the one we obtain when inferring  $\langle x_{\text{H I}} \rangle$  and  $t_{\text{Q}}$  directly in the context of the global parametrization. The corresponding model curves are shown in the lower panel of Fig. 1. The resulting posterior, depicted by the yellow contours in Fig. 2, is in good agreement with the one obtained by converting our local constraints (green). The only differences between the two are that the converted posterior exhibits a somewhat more extended tail towards longer lifetimes. Since these longer lifetimes go hand in hand with a higher IGM neutral fraction, the marginal  $\langle x_{\text{H I}} \rangle$  posterior obtained via the local parametrization (green) shows a very mild peak at around  $\langle x_{\text{H I}} \rangle \simeq 0.3$ , in contrast to the directly inferred one, which peaks very close to  $\langle x_{\text{H I}} \rangle \simeq 0$ . Overall, however, both posteriors are in clear statistical agreement, underlining the robustness of our constraints despite the highly different ways in which they were obtained.

### 3.2 J1342+0928

The second object of our study, the quasar J1342+0928 at  $z = 7.54$ , has already been extensively analysed in previous literature (E. Bañados et al. 2018; F. B. Davies et al. 2018; B. Greig et al. 2019, 2022; D. Āurovčíková et al. 2020; D. M. Reiman et al.

extend beyond the physical  $(N_{\text{H}}^{\text{DW}}, r_{\text{patch}})$  boundary enclosed by the dashed line.

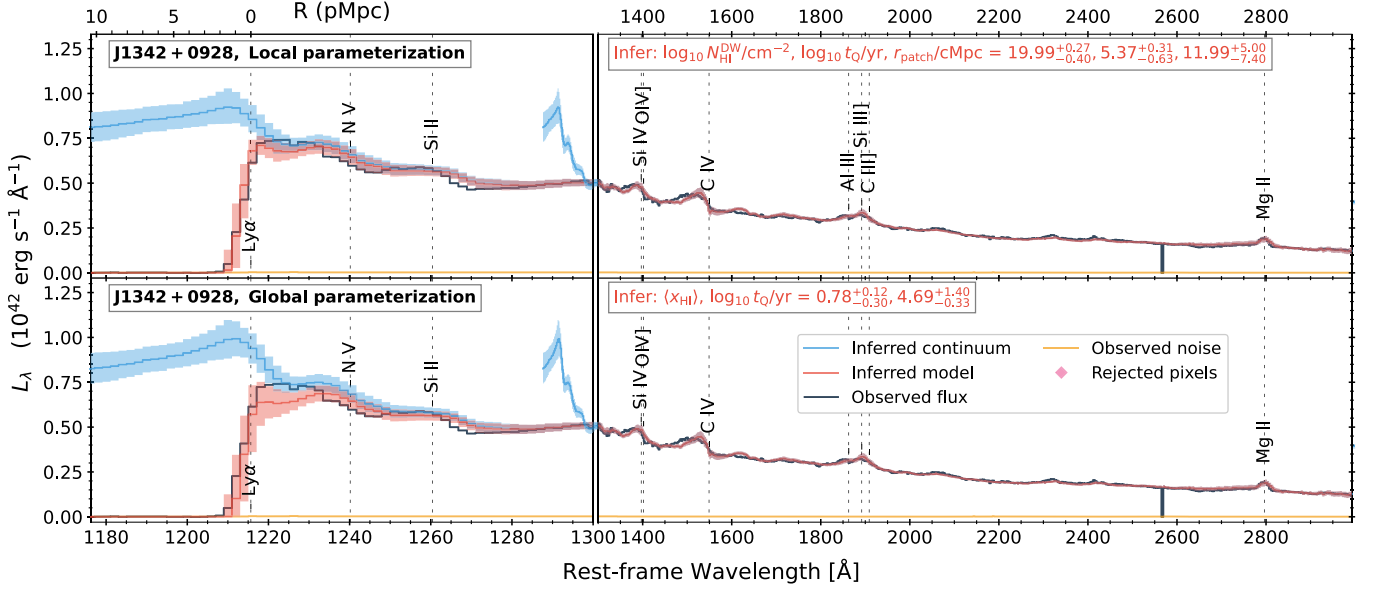


Figure 3. Inferred models like in Fig. 1 but for the *JWST*/NIRSpec spectrum of the quasar J1342+0928.

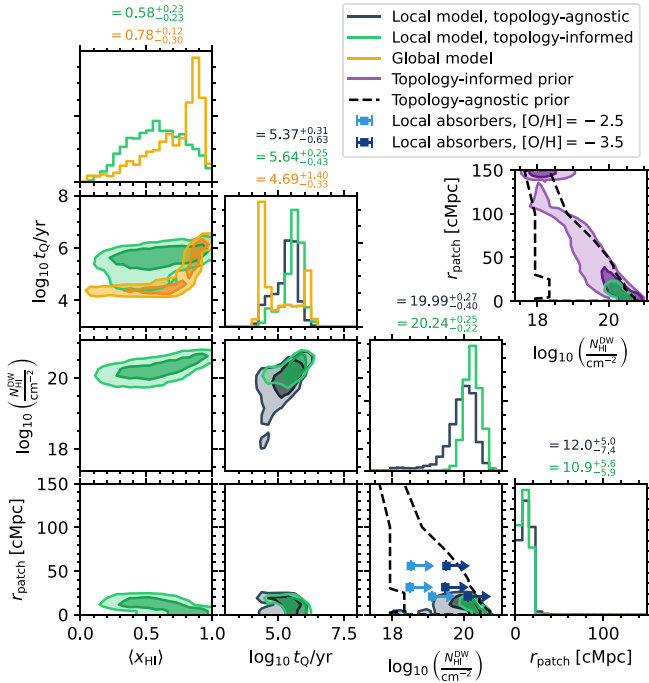


Figure 4. Like Fig. 2 but for the posterior distributions inferred from the *JWST*/NIRSpec spectrum of the quasar J1342+0928 depicted in Fig. 3. The  $(N_{\text{HI}}^{\text{DW}}, r_{\text{patch}})$  panel also shows the putative local absorber constraints obtained by F. B. Davies et al. (2025) assuming two different metallicities, which provide lower limits on  $N_{\text{HI}}^{\text{DW}}$ .

2020), resulting in varying constraints on the IGM neutral fraction, with median values ranging from  $\langle x_{\text{HI}} \rangle \approx 0.2$ – $0.6$ . We again apply both versions of our inference framework to the *JWST*/NIRSpec spectrum of this object and obtain the fits and parameter constraints shown in Figs 3 and 4, again in good statistical agreement with a reduced degree of scatter in the local parametrization. Unlike in the case of J1007+2115, we infer the clear presence of a damping wing with a correspondingly high H I column density of

$\log_{10} N_{\text{HI}}^{\text{DW}}/\text{cm}^{-2} = 19.99^{+0.27}_{-0.40}$  and a rather short distance of  $r_{\text{patch}} = 12.0^{+5.0}_{-7.4}$  cMpc to the first neutral patch, increasing/reducing further to  $\log_{10} N_{\text{HI}}^{\text{DW}}/\text{cm}^{-2} = 20.24^{+0.25}_{-0.22}$  and  $r_{\text{patch}} = 10.9^{+5.6}_{-5.9}$  after folding in the topology dependence (green contours). The lifetime posterior shows a clear degeneracy with  $N_{\text{HI}}^{\text{DW}}$  in the local parametrization, peaking at  $\log_{10} t_Q/\text{yr} = 5.64^{+0.25}_{-0.43}$ , and with  $\langle x_{\text{HI}} \rangle$  in the global one, preferring a somewhat lower value of  $\log_{10} t_Q/\text{yr} = 4.69^{+1.40}_{-0.33}$ . However, the global posterior shows a long axis of degeneracy with a second peak closer to the higher value preferred in the local model. Previous analyses inferred  $\log_{10} t_Q/\text{yr} = 5.38^{+0.72}_{-1.30}$  with a similarly wide degeneracy (F. B. Davies et al. 2018; F. B. Davies, J. F. Hennawi & A.-C. Eilers 2019; A.-C. Eilers et al. 2021). The corresponding  $\langle x_{\text{HI}} \rangle$  constraints suggest an intermediate to high IGM neutral fraction of  $\langle x_{\text{HI}} \rangle = 0.58^{+0.23}_{-0.63}$  in the context of the local parametrization, and a very high one of  $\langle x_{\text{HI}} \rangle = 0.78^{+0.12}_{-0.36}$  in the context of the global model.

These results ought to be treated with caution since F. B. Davies et al. (2025) recently pointed out the possibility of contamination of the IGM in front of J1342+0928 by proximate absorption systems located at  $r_{\text{abs}} \approx 21$ , 31, and/or 56 cMpc based on weak Mg II absorption lines they identified in the *JWST*/NIRSpec spectrum that is also the subject of this analysis. While the authors concluded that such proximate absorbers would have to be unusually metal-poor, we use this possibility to highlight an additional virtue of our local parametrization. That is, our modelling framework allows us to naturally relate the (Lorentzian-weighted) H I column density  $N_{\text{HI}}^{\text{DW}}$  to the column density  $N_{\text{HI}}^{\text{abs}}$  of a putative absorber. This offers possibilities of (1) retrospectively correcting an inferred  $N_{\text{HI}}^{\text{DW}}$  constraint for a contribution  $N_{\text{HI}}^{\text{abs}}$  from a potential local absorber, constrained by other means, or even (2) jointly inferring  $N_{\text{HI}}^{\text{DW}}$  and  $N_{\text{HI}}^{\text{abs}}$  in a fully Bayesian way. We discuss the former approach below and leave an implementation of the latter one to future work.

To that end, note that the total column density  $N_{\text{HI}}^{\text{DW}}$  giving rise to the practically observed damping wing signal comprises both the contribution from the IGM and that from any potential local absorber. Under the assumption of a cosmological H I density field  $n_{\text{HI}}^{\text{IGM}}(r) = x_{\text{HI}}(r) \cdot \Delta(r)$  sourced by the IGM, superposed by the absorber’s H I density  $n_{\text{HI}}^{\text{abs}}(r)$ , it directly follows from equation (1) that we can break

up  $N_{\text{H I}}^{\text{DW}}$  into their respective contributions:

$$N_{\text{H I}}^{\text{DW}} = N_{\text{H I}}^{\text{DW,IGM}} + N_{\text{H I}}^{\text{DW,abs}}. \quad (4)$$

By approximating the localized absorber's density field  $n_{\text{H I}}^{\text{abs}}(r)$  as a Dirac delta peak at position  $r_{\text{abs}}$ , we can straightforwardly use equation (1) to determine  $N_{\text{H I}}^{\text{DW,abs}}$  based on its classical column density  $N_{\text{H I}}^{\text{abs}}$ :

$$\log N_{\text{H I}}^{\text{DW,abs}} = \log N_{\text{H I}}^{\text{abs}} - 2 \log(r_{\text{abs}}/r_{\text{T}} + 1), \quad (5)$$

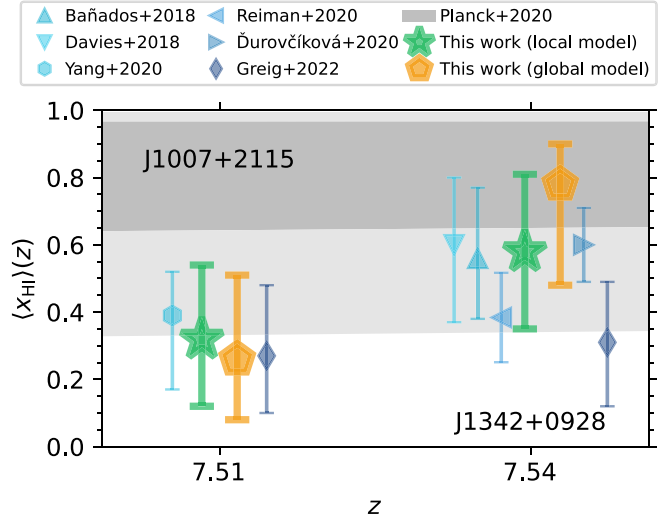
provided the absorber is located within the integration range for  $N_{\text{H I}}^{\text{DW}}$  enclosed by  $r_{\text{min}}$  and  $r_{\text{max}}$ .

As per equation (4), any inferred value of  $N_{\text{H I}}^{\text{DW}}$  only constitutes an upper limit on the column density  $N_{\text{H I}}^{\text{DW,IGM}}$  sourced by the IGM (and thus relevant to reionization), from which the contributions from any potential absorber would have to be subtracted. Vice versa, the column density  $N_{\text{H I}}^{\text{DW,abs}}$  of a given absorber places a lower limit on the full  $N_{\text{H I}}^{\text{DW}}$ . We plot these limits based on the values determined by F. B. Davies et al. (2025) assuming oxygen abundances relative to solar of  $[\text{O}/\text{H}] = -2.5$  ( $-3.5$ ) as light (dark) blue arrows in the  $(N_{\text{H I}}^{\text{DW}}, r_{\text{patch}})$  panel of Fig. 4. Note that the length of the arrows carries no information and we place these constraints at  $r_{\text{patch}} = r_{\text{abs}}$  for each absorber even though the two distances are not necessarily related given that we define  $r_{\text{patch}}$  as the first *extended* neutral patch in front of the quasar.

Note that the  $\log N_{\text{H I}}^{\text{DW,abs}}$  constraint from the closest absorber in the  $[\text{O}/\text{H}] = -3.5$  case aligns well with the peak of the posterior. This is in excellent agreement with the fact that a such metal-poor absorber at this distance would solely account for the observed damping wing imprint, leaving no room for any additional IGM contribution when subtracted from the total column density  $N_{\text{H I}}^{\text{DW}}$ . The Lorentzian-weighted H I column density of an  $[\text{O}/\text{H}] = -2.5$  absorber, on the other hand, would largely be negligible compared to our inferred  $N_{\text{H I}}^{\text{DW}}$ , and hence not bias our conclusions about the ionization state of the IGM. These simple considerations also pave the way for a principled, *joint* inference of the damping wing signal due to the IGM and potential local absorbers. To that end, one could follow F. B. Davies et al. (2025) and infer an absorber's column density  $N_{\text{H I}}^{\text{abs}}$  based on O I and Mg II absorption line fitting (with  $[\text{O}/\text{H}]$  as an additional parameter). Equations (4) and (5) then establish the connection between the absorber's column density  $N_{\text{H I}}^{\text{abs}}$  and the full damping wing column density  $N_{\text{H I}}^{\text{DW}}$ , forming the basis of a full Bayesian framework that would jointly fit for the strength of the IGM damping wing and potential local absorption systems.

#### 4 SUMMARY AND CONCLUSIONS

We summarize in Fig. 5 our constraints on the reionization history obtained by analysing the *JWST*/NIRSpec spectra of the two  $z \sim 7.5$  quasars J1007+2115 and J1342+0928 in the context of the local damping wing parametrization (green stars) put forward in T. Kist et al. (2025b, in preparation) and the conventional global one (yellow pentagons). We compare these constraints to the cosmic microwave background (CMB) constraint on the reionization optical depth inferred by the Planck Collaboration VI (2020) whose 68 and 95 per cent contours are marked as grey swathes, as well as previous IGM damping wing measurements of the two objects studied in this work (E. Bañados et al. 2018; F. B. Davies et al. 2018; D. Āurovčiková et al. 2020; D. M. Reiman et al. 2020; J. Yang et al. 2020; B. Greig et al. 2022). Our constraints are in clear statistical agreement with all these literature constraints, also owing to the comparably large statistical uncertainties that are unavoidable for individual objects due to the stochastic nature of reionization (T. Kist



**Figure 5.** Reionization history constraints obtained from the two quasars J1007+2115 at  $z = 7.51$  and J1342+0928 at  $z = 7.54$  in the context of the local IGM damping wing parametrization (green stars) and the global one (yellow pentagons). Other symbols show existing literature constraints for the same two objects, slightly offset with respect to each other for clarity, and grey swathes are 68 and 95 per cent contours of the Planck Collaboration VI (2020) CMB constraints.

et al. 2025a,b, in preparation). Note that despite the methodological improvements in our pipeline as compared to previous approaches (J. F. Hennawi et al. 2025; T. Kist et al., in preparation), our uncertainties are not necessarily smaller than those quoted in the literature. This is explained by the fact that we rigorously folded in all relevant uncertainties due to stochastic reionization, the unknown quasar lifetime, continuum reconstruction, and spectral noise.

We conclude that J1007+2115 prefers a somewhat lower neutral fraction of  $\langle x_{\text{H I}} \rangle = 0.32^{+0.22}_{-0.20}$ , compared to  $\langle x_{\text{H I}} \rangle = 0.58^{+0.23}_{-0.23}$  based on J1342+0928 (both inferred in the framework of our local parametrization). The directly inferred global  $\langle x_{\text{H I}} \rangle$  posterior of the latter object ( $\langle x_{\text{H I}} \rangle = 0.78^{+0.12}_{-0.30}$ ) peaks at the high end compared to our local and most literature damping wing constraints (though closer to Planck Collaboration VI 2020), but note here the extended axis of degeneracy of the full posterior of this object (cf. Fig. 4). In addition, *all* damping wing-based  $\langle x_{\text{H I}} \rangle$  constraints would be biased high in case an unusually metal-poor absorber was indeed present in the foreground of this object (F. B. Davies et al. 2025), which would pull the actual corrected IGM neutral fraction closer to the value inferred from J1007+2115. Our local parametrization provides a natural framework for studying this possibility more carefully in future work, particularly relevant also to *JWST* observations of IGM damping wings towards galaxies (M. Huberty et al. 2025; C. A. Mason et al. 2025). More conclusive statements about the ionization state of the IGM at  $z \sim 7.5$  will be enabled by applying our robust inference approach to the spectra of additional objects identified at these redshifts by the Euclid wide field survey (Euclid Collaboration 2019, in preparation; E. Bañados et al. 2025).

In addition, we constrained the lifetimes of the two objects of this study and found J1007+2115 to be remarkably young with  $\log_{10} t_{\text{Q}}/\text{yr} = 4.14^{+0.74}_{-0.18}$ , whereas J1342+0928 (with  $\log_{10} t_{\text{Q}}/\text{yr} = 5.64^{+0.25}_{-0.43}$ ) is closer to the average expected lifetimes of  $t_{\text{Q}} \sim 10^6$  yr (I. S. Khrykin et al. 2021; K. A. Morey et al. 2021). Most importantly, we also obtained the first constraints on the local ionization topology in front of these two sources. With a Lorentzian-weighted H I column

density of  $\log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2} = 19.70^{+0.35}_{-0.86}$  and a first neutral patch at  $r_{\text{patch}} = 28.9^{+54.0}_{-14.4}$  cMpc, we remained in the prior-dominated regime for the pre-quasar sightline originating from J1007+2115, but we measured  $\log_{10} N_{\text{H I}}^{\text{DW}}/\text{cm}^{-2} = 20.24^{+0.25}_{-0.22}$  and  $r_{\text{patch}} = 10.9^{+5.6}_{-5.9}$  cMpc for J1342+0928. While this work was focused on the conversion of these measurements to constraints on the global timing on reionization, constraining  $N_{\text{H I}}^{\text{DW}}$  and  $r_{\text{patch}}$  for larger statistical samples of objects will also open the doors to direct constraints on the topology of reionization with quasar IGM damping wings (Y. M. Sharma et al. 2025).

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## DATA AVAILABILITY

The derived data generated in this research will be shared on reasonable requests to the corresponding author.

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