

The Thickness of High-Redshift Quasar Ionization Fronts as a Constraint on the Quasar Ionizing SED

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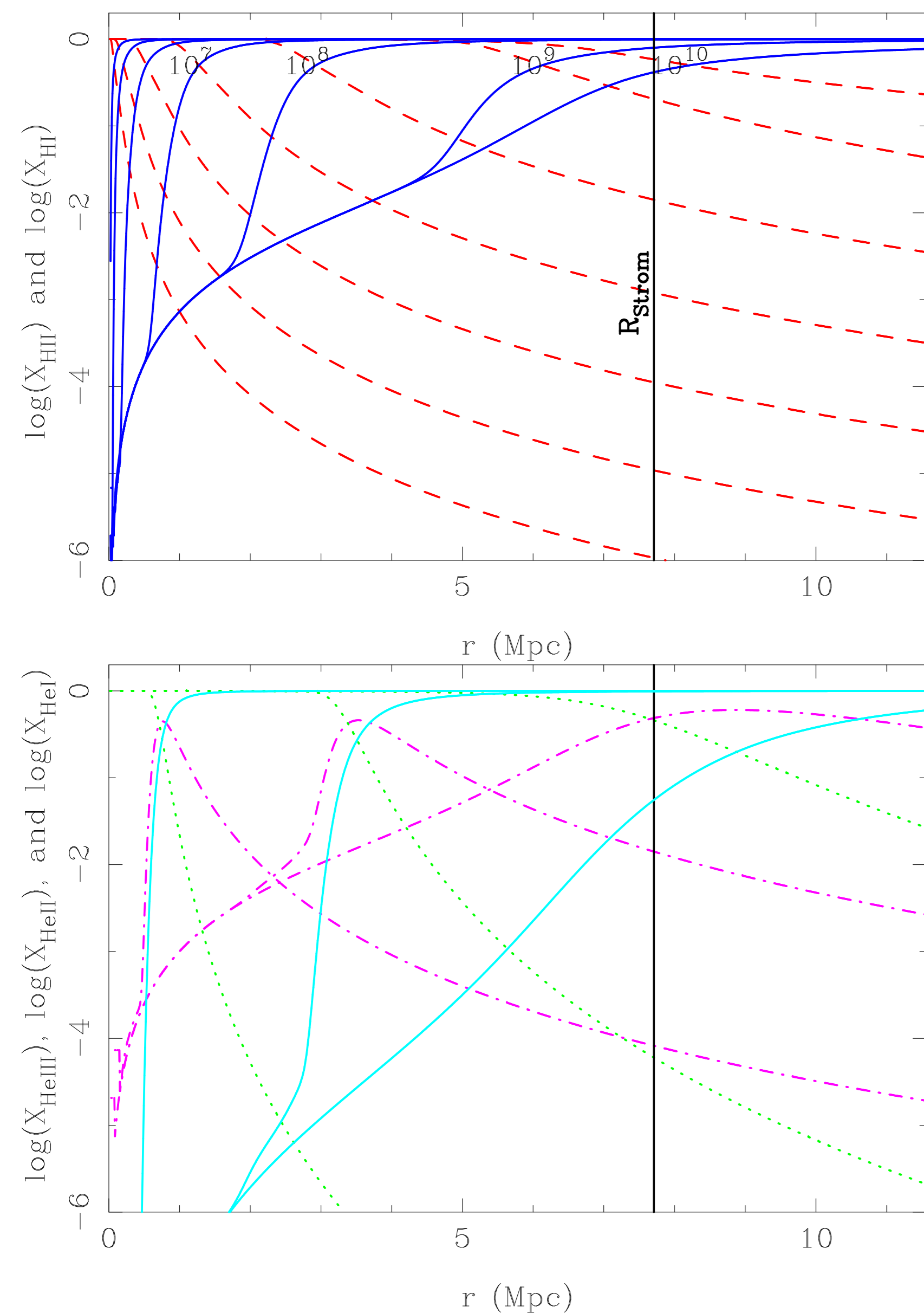
The ionizing SED of $z \gtrsim 6$ quasars in the 13.6 eV–1 keV range is important for many aspects of reionization, since it affects the thermodynamics and chemistry in the intergalactic medium and in collapsing halos.

The SED will not be directly observable, since this region of the spectrum will be obscured by the neutral IGM. We propose an alternative way to constrain the hardness of the spectra of bright $z \gtrsim 6$ quasars in 21 cm observations and Lyman-line absorption spectra.

I-front evolution with radiative transfer

High-redshift quasars ($z \gtrsim 6$) drive ionization fronts into the IGM.

Even for hard spectra, the front is initially thin — much thinner than the mean free path of ionizing photons — but gradually thickens as it approaches equilibrium in 10^8 – 10^9 years. The length of the outer ionization tail can eventually well exceed simple estimates based on the mean free path.

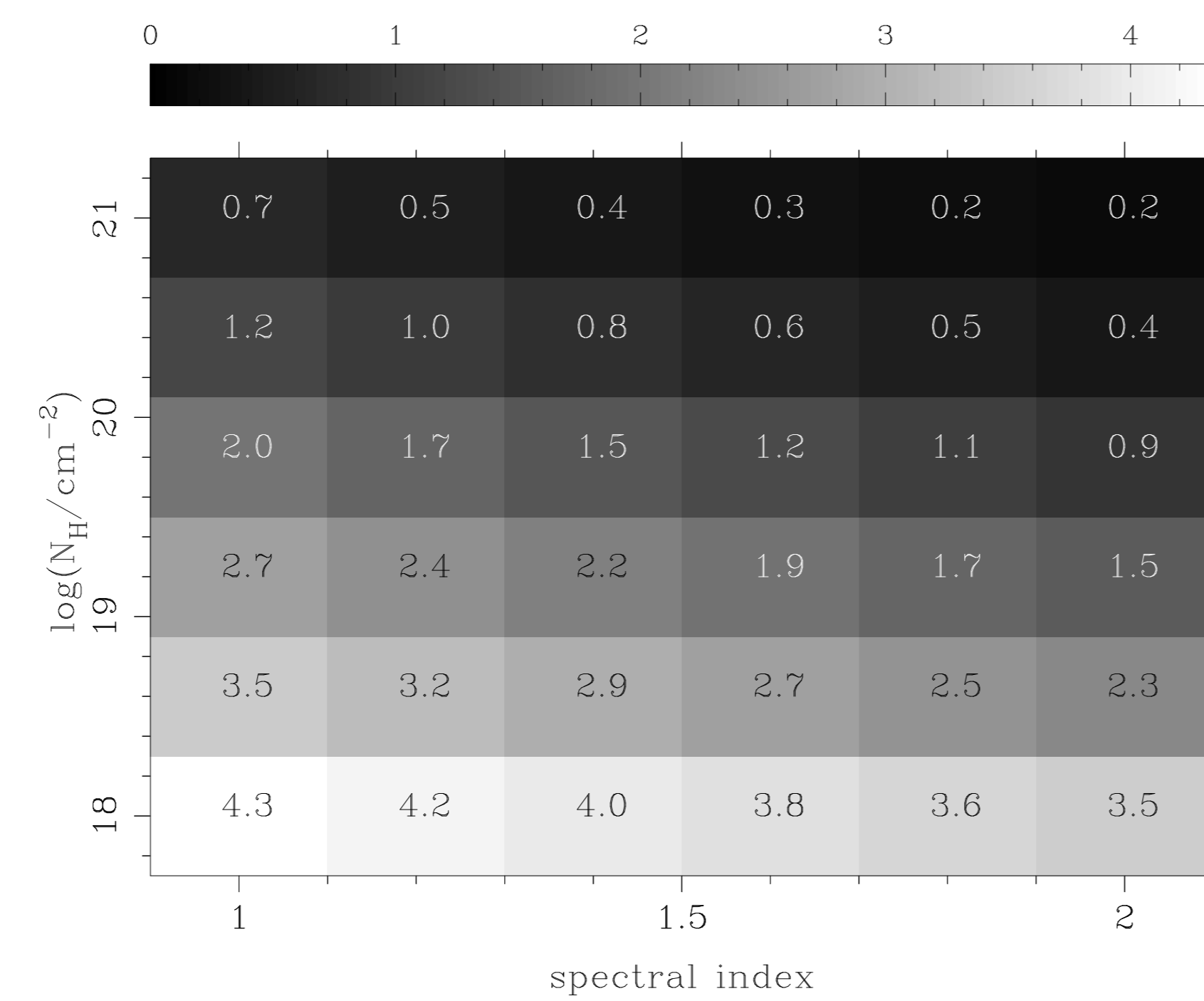


Ionized (dashed red) and neutral (solid blue) hydrogen fractions (top); and neutral (solid cyan), singly-ionized (dot-dashed magenta) and doubly-ionized (dotted yellow) helium fractions (bottom) versus radius (proper coordinates). By 10^{10} years the entire ionization structure is in equilibrium. The quasar emits photons at $Q = 2 \times 10^{57} \text{ s}^{-1}$ before absorption with $L_\nu \propto \nu^{-s} \exp(-N_{\text{H}} \sigma_{\text{HI+HeI}})$, spectral index $s = 1.6$, and neutral hydrogen column $N_{\text{H}} = 10^{19.2} \text{ cm}^{-2}$. The mean photon energy for this spectrum is ≈ 240 eV, and the corresponding mean free path is ~ 3 (proper) Mpc.

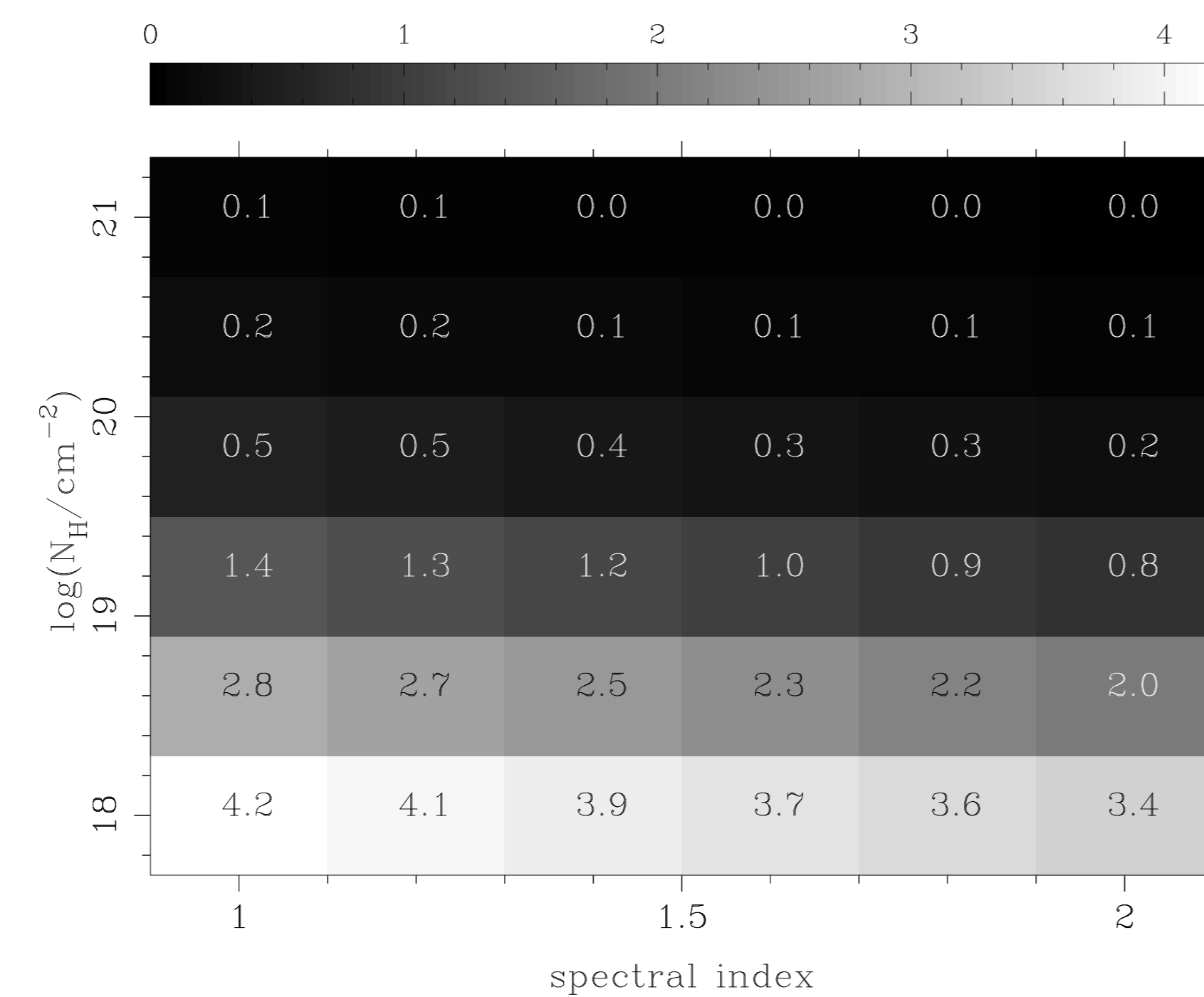
For obscured sources, the Lyman- α absorption trough underestimates the size of the H II region by a factor of $\gtrsim 4$.

The size of the ionized region

Two different measures of the size of the ionized region versus the intrinsic absorption N_{H} (in cm^{-2}) and the spectral index s at 3.16×10^7 years are shown below. Each block represents one simulation, with the size indicated in numerals and by the shading.



The size (in proper Mpc) of the ionized region out to 50% neutral ($X_{\text{HI}} = 0.5$), $r_{0.5}$ (top).



The size of the ionized region out to $X_{\text{HI}} = 0.001$, r_{-3} (bottom), which is roughly where the Lyman- α absorption trough begins in a quasar spectrum.

Highly absorbed spectra leave a relatively large neutral fraction within the H II region, meaning that the Lyman-series optical depths can be large even within the front. For $\log(N_{\text{H}}/\text{cm}^{-2}) \gtrsim 19.8$, $r_{0.5}$ exceeds r_{-3} by a factor of $\gtrsim 4$. The bias can get as large as a factor of ≈ 8 within our parameter space. This is in addition to other effects that bias this measurement by a much smaller amount, as already discussed by several authors (Maselli et al. 2007; Lidz et al. 2007; Bolton & Haehnelt 2007a; see paper for full references).

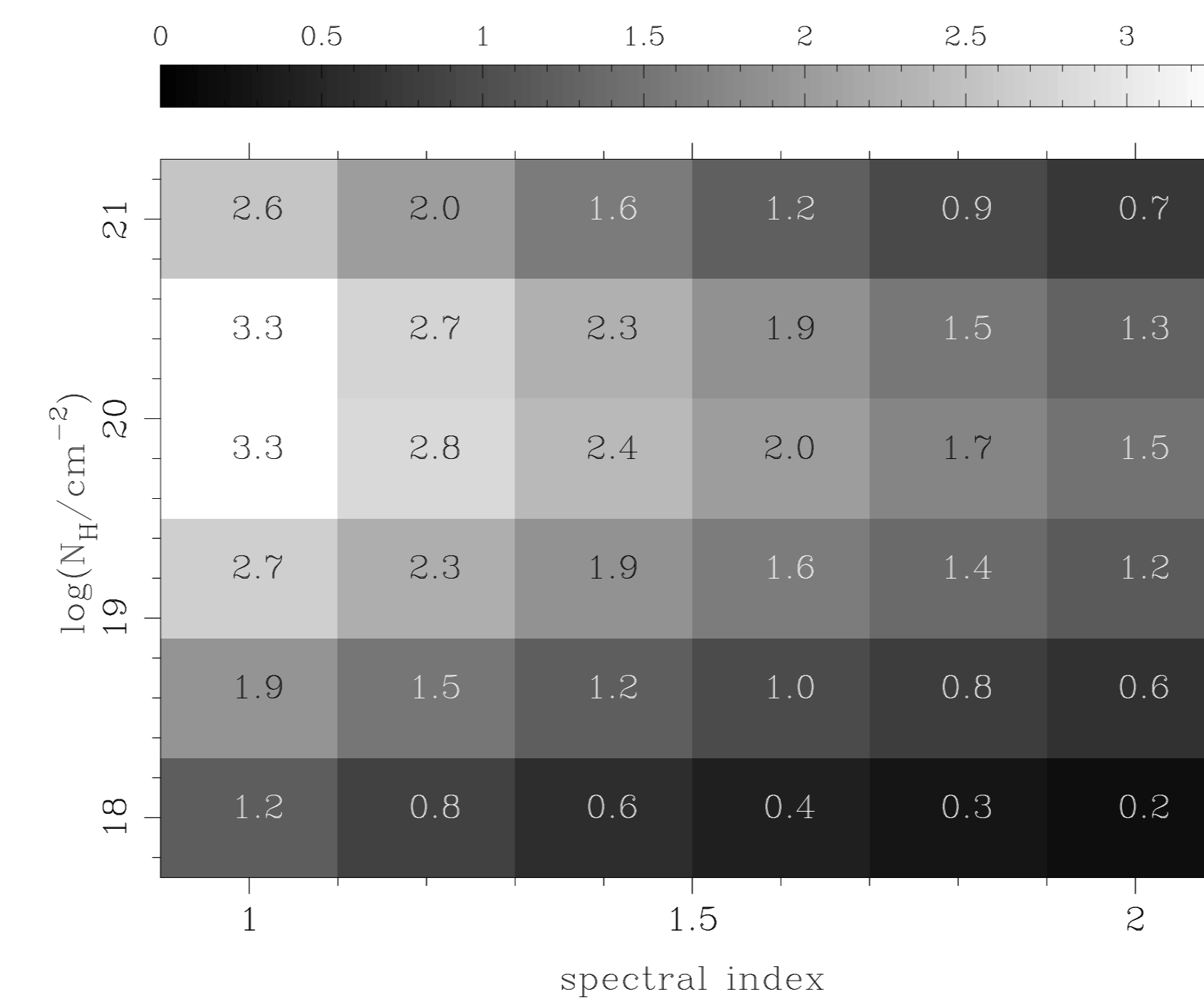
See R. H. Kramer & Z. Haiman, MNRAS, accepted, preprint arXiv:0712.3548

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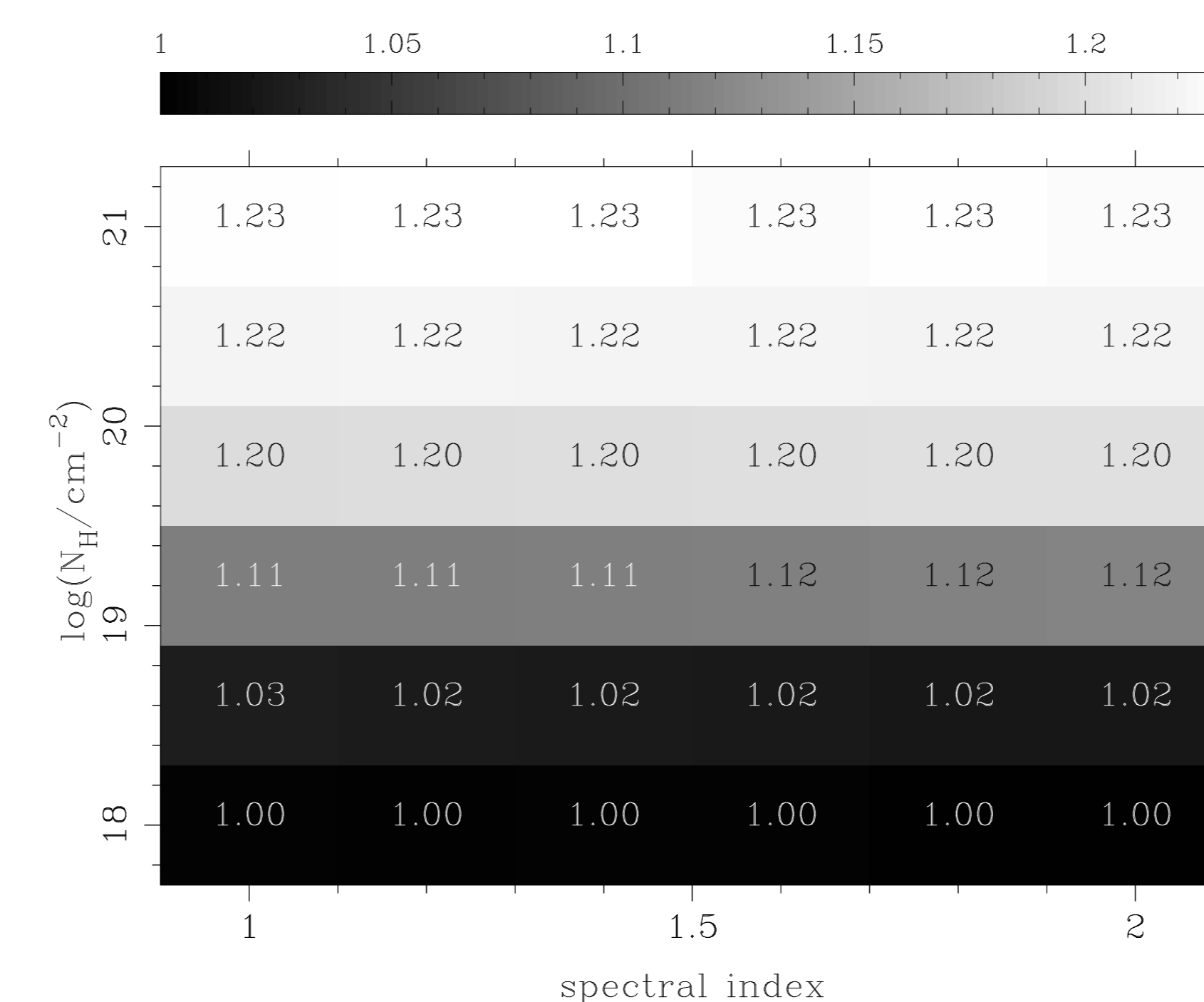
If the thickness of the front can be measured, it can provide a novel constraint on the ionizing spectral energy distribution (SED).

I-front thickness versus spectral shape

Two ionization front thickness measures are plotted below versus N_{H} and s at 3.16×10^7 years.



The thickness of the outer tail of ionization is measured by $d_{0.1}$ the difference between the radius at which $X_{\text{HII}} = 0.1$ and $X_{\text{HI}} = 0.1$ (in Mpc, top). With a high column density ($\log(N_{\text{H}}/\text{cm}^{-2}) \gtrsim 19.2$) or a hard power-law combined with some obscuration (e.g. $s \gtrsim 1.2$ at $\log(N_{\text{H}}/\text{cm}^{-2}) \gtrsim 18.0$), the outer thickness of the front exceeds ~ 1 physical Mpc and may be measurable from its redshifted 21cm signal.



The inner thickness of the front is measured by $r_{-2.5}/r_{-3}$ (bottom), the ratio of radius at which $X_{\text{HI}} = 10^{-2.5}$, and the radius at which $X_{\text{HI}} = 10^{-3}$. These radii correspond roughly to the points where flux is lost in the Ly- β and Ly- α absorption spectra, respectively, for a typical, deep, Keck spectrum of a $z = 6$ quasar. This part of the front remains thin unless a large obscuring column ($\log(N_{\text{H}}/\text{cm}^{-2}) \gtrsim 19.2$) removes most of the ionizing photons up to ≈ 40 eV.

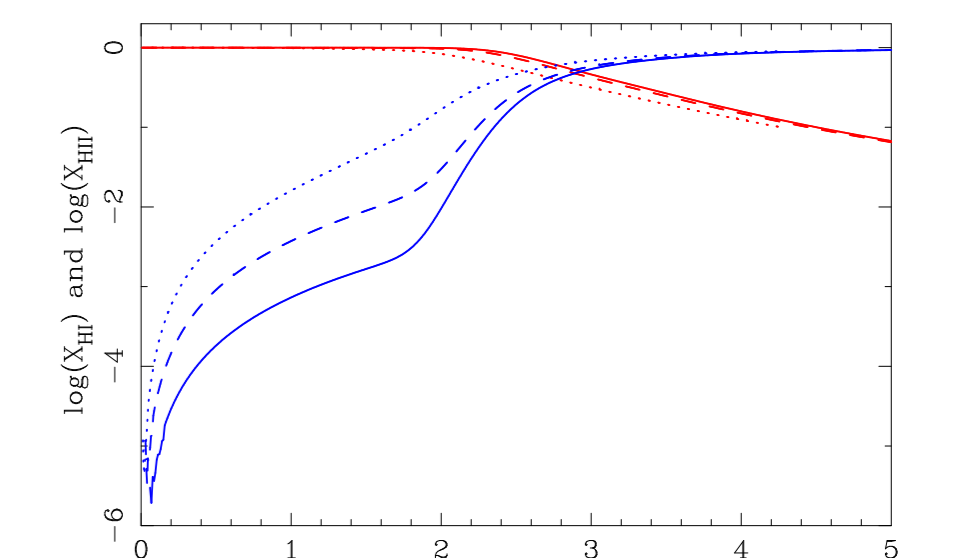
Conclusions

High-redshift quasars residing in a partially neutral IGM could produce ionization fronts with an observable thickness, given a sufficiently hard ionizing spectrum.

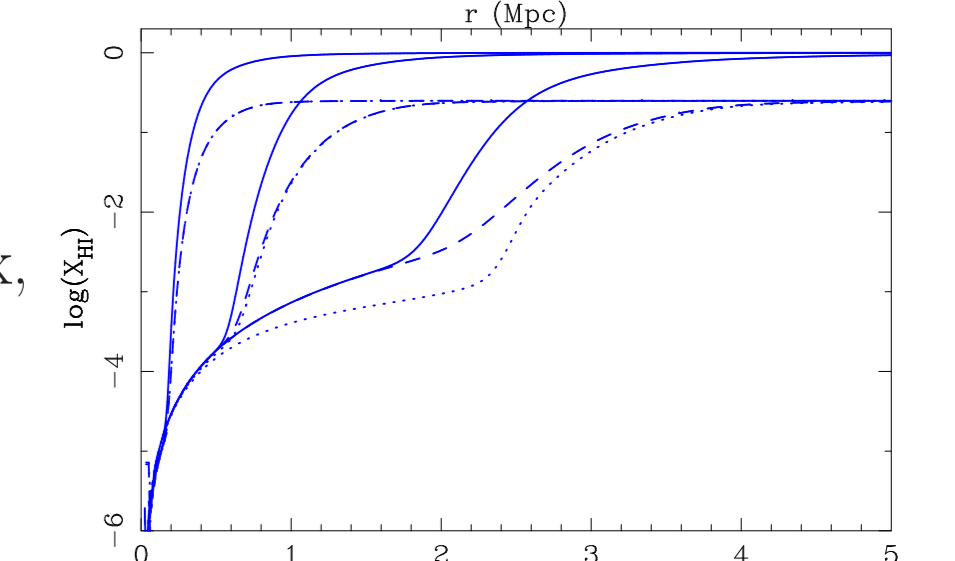
The contours of degeneracy in our parameter space for measurements using 21 cm observations are oriented differently from those for measurements using Lyman-series absorption spectra. Combining both types of observations should break the degeneracy and constrain both the intrinsic absorption column and spectral index of a quasar's ionizing radiation at $z > 6$.

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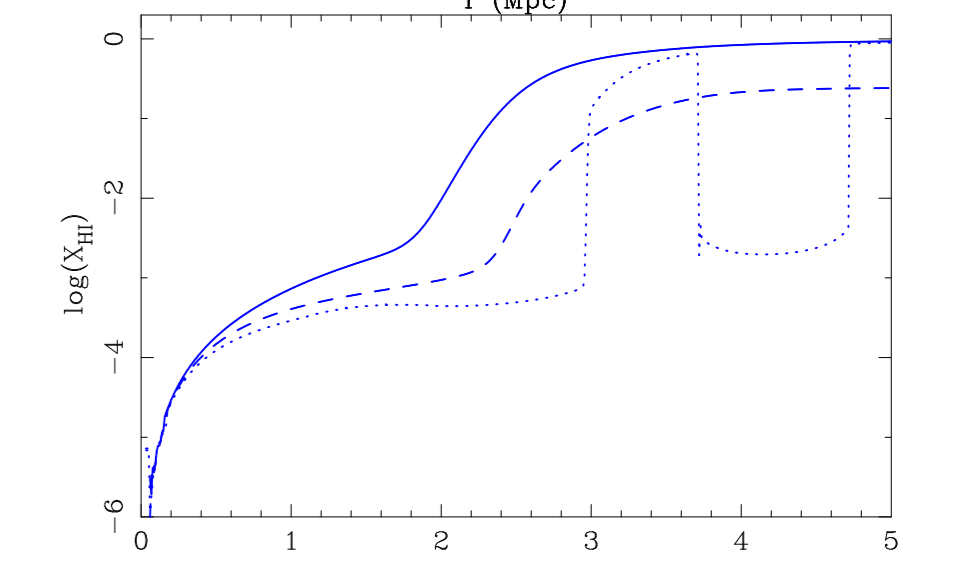
IGM clumpiness,



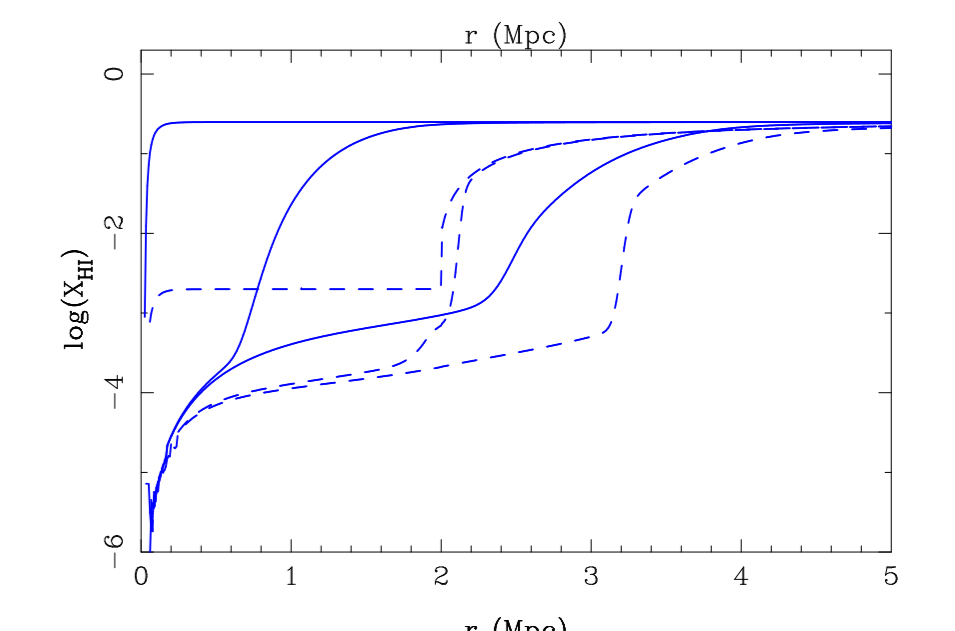
ionizing background flux,



nearby ionizing sources,



pre-ionized bubbles,



and quasar age and luminosity.

Acknowledgments

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