A tale of three histories: distinguishing reionization scenarios in the JWST era

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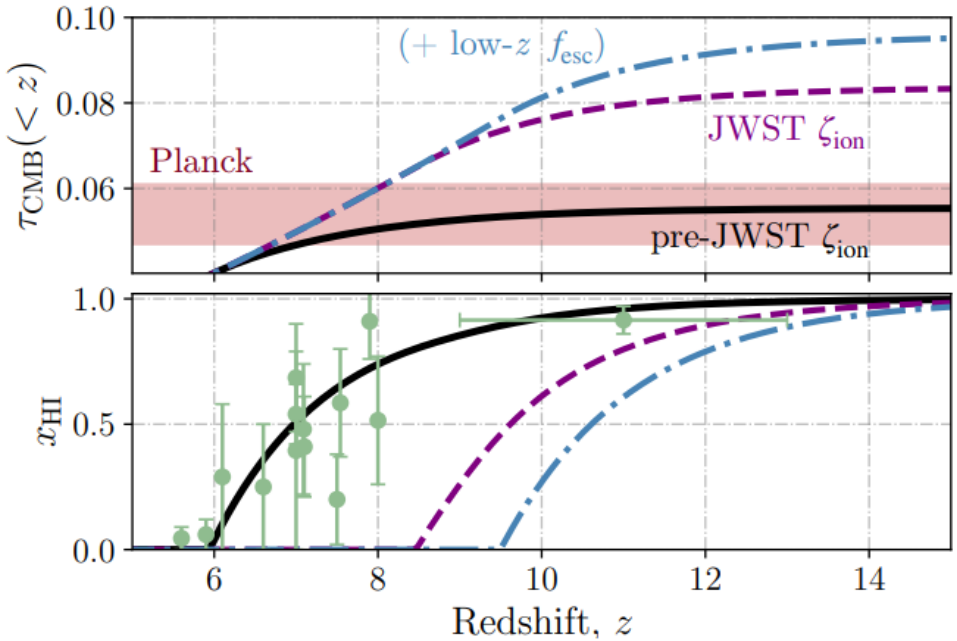
Can galaxies drive cosmic reionization?

- Recent work (Munoz+24) suggest ionizing output of galaxies may have been enough to re-ionize the universe by $z \sim 8 - 9$

- Based on JWST UVLF and measurements of $\xi_{\rm ion}$ (Simmonds+24), and $f_{\rm esc}$ inferred from UV slopes (Chisholm+22)

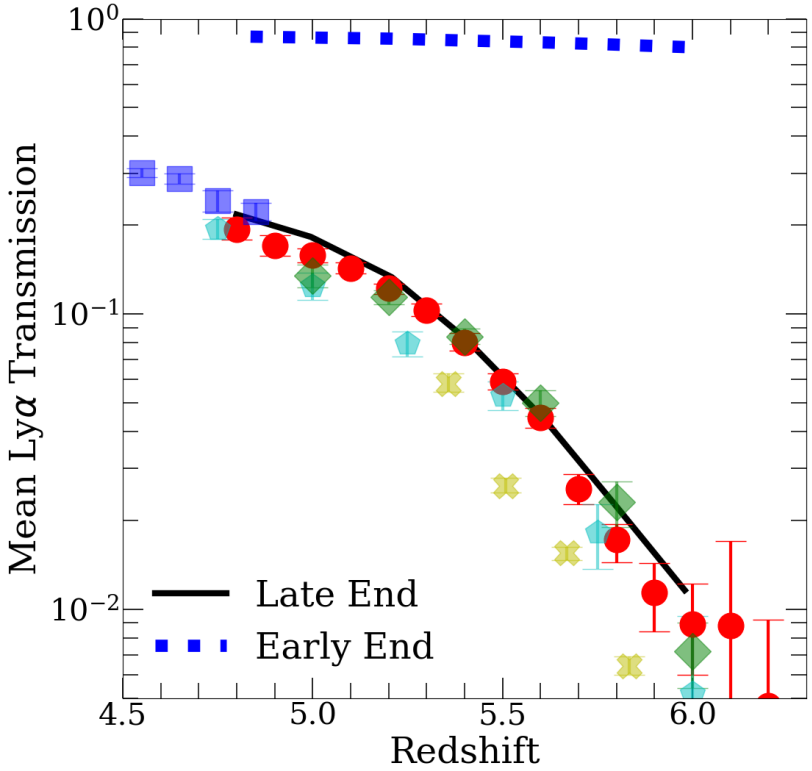


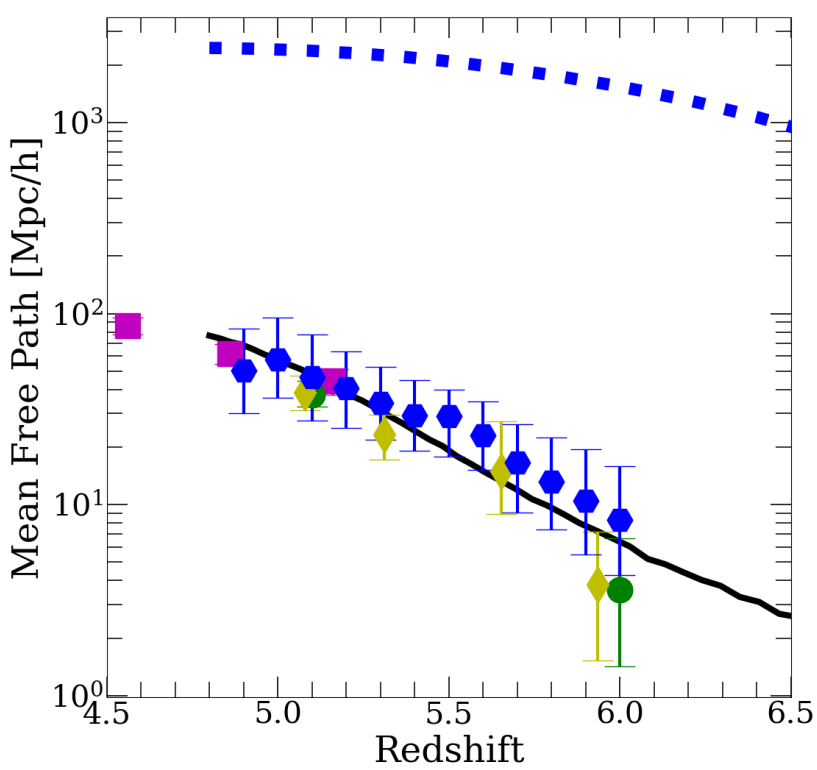
Seems like yes!

Why is late reionization ($z_{\rm end} < 6$) necessary?

1. Mean transmission of Lyα at $z \leq 6$
2. Mean free path to ionizing photons

early end = too many photons!

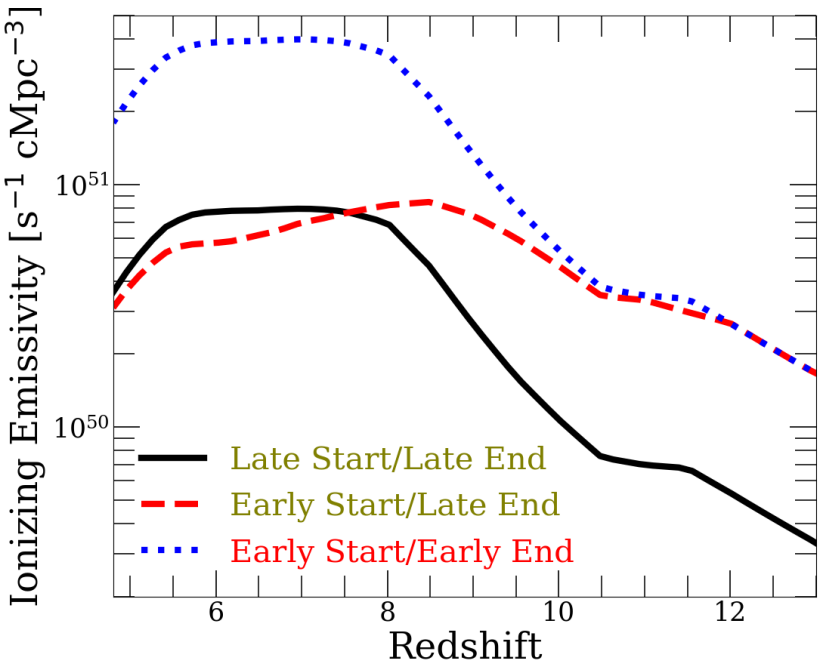


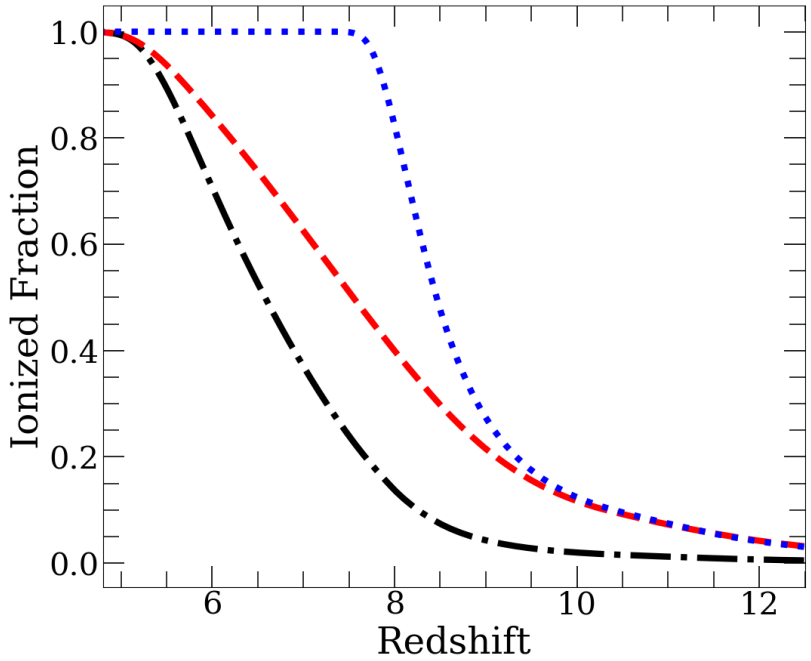


How can we get rid of photons?

Two ways:

1. Across all redshifts → Late Start/Late End
2. At lower redshifts only → Early Start/Late End

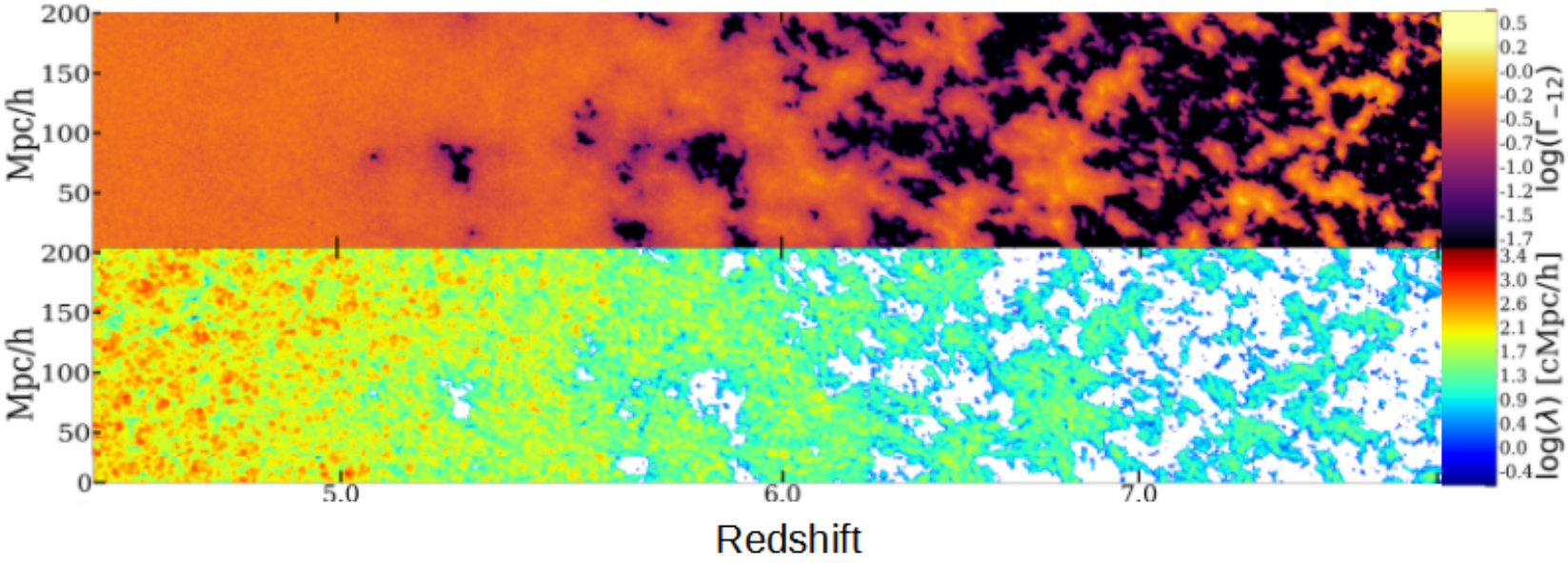




Which one is favored by observations?

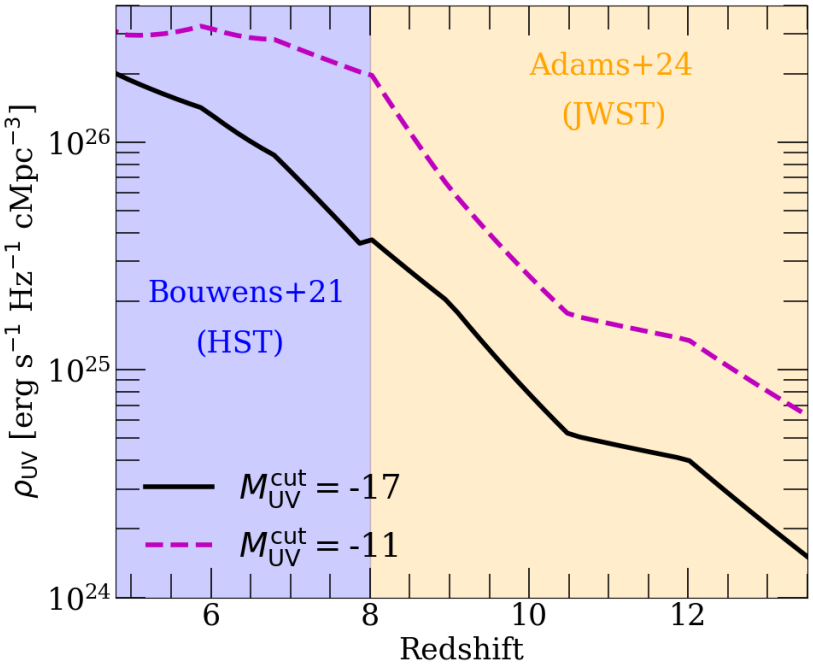
Simulations of Reionization with FlexRT

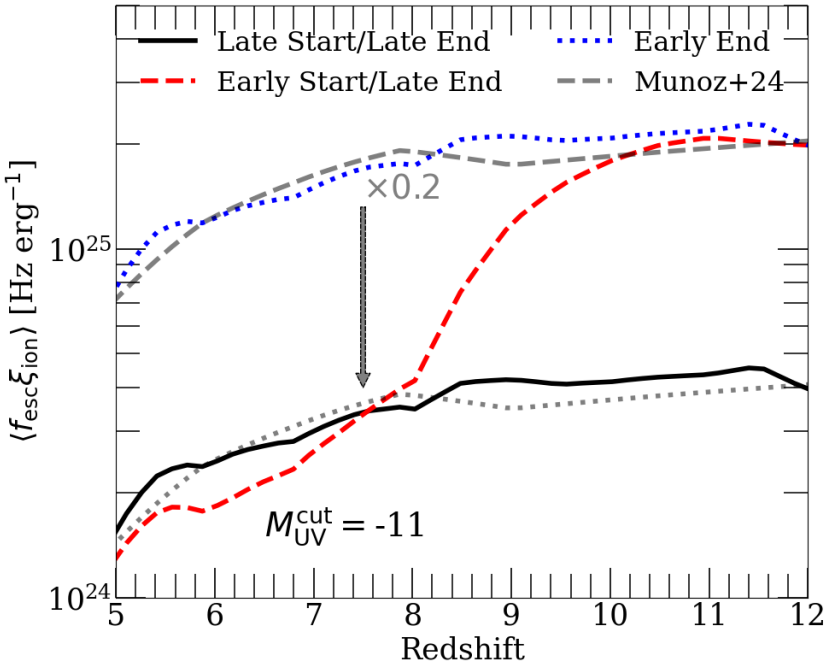
- Adaptive ray-tracing RT in a cosmological volume ($N_{\rm RT} = 200^3$, $L_{\rm box} = 200\ h^{-1}$Mpc)
- Sub-grid opacity model based on high-res hydro/RT sims
- Both late-ending models are calibrated to **reproduce Lyα forest mean transmission at $5 < z < 6$ (Bosman+22)**



UVLF/Ionizing properties of galaxies

- New JWST UVLF (Adams+24) evolves rapidly at $z > 8$
- Scaled down Munoz+24 model $\rightarrow$ late start/late end
- Early start/late end $\rightarrow \sim 10\times$ evolution in $\langle f_{\rm esc}\xi_{\rm ion}\rangle$

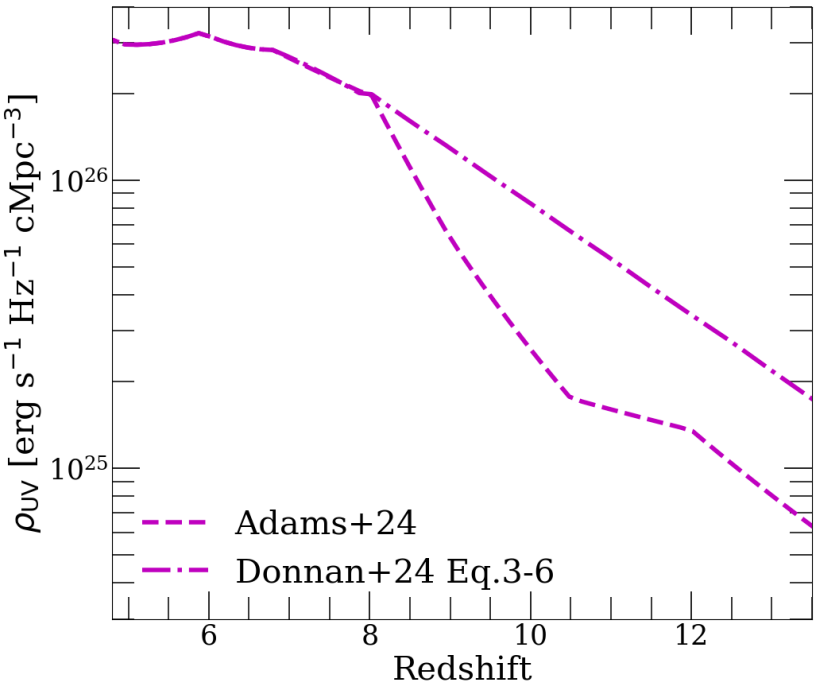


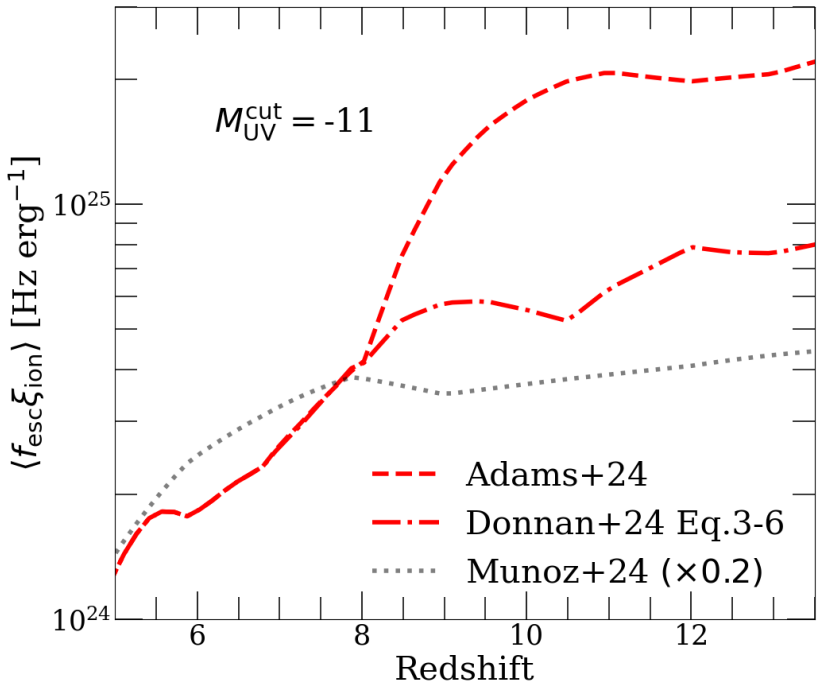


Early start needs steeper evolution than observations suggest

Can galaxies accommodate an early start?

- Factor of $\gtrsim 3$ uncertainty in $\rho_{\rm UV}(z > 8)$
- Extrapolation of $\xi_{\rm ion}$ measurements to high z/faint galaxies?
- Evolution in $M_{\rm UV}^{\rm cut}$ (feedback)??





Certainly possible!

Can galaxies accommodate an early start?

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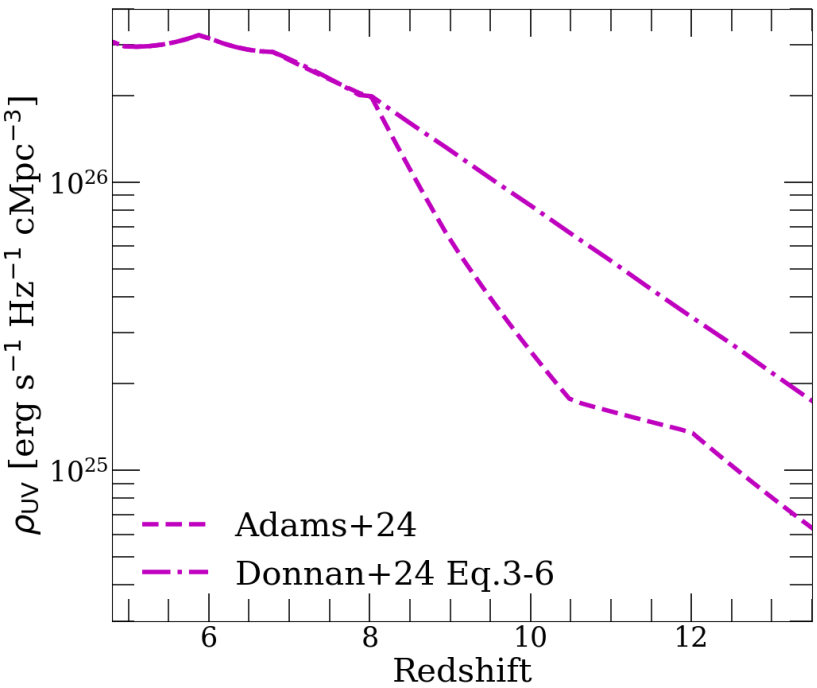
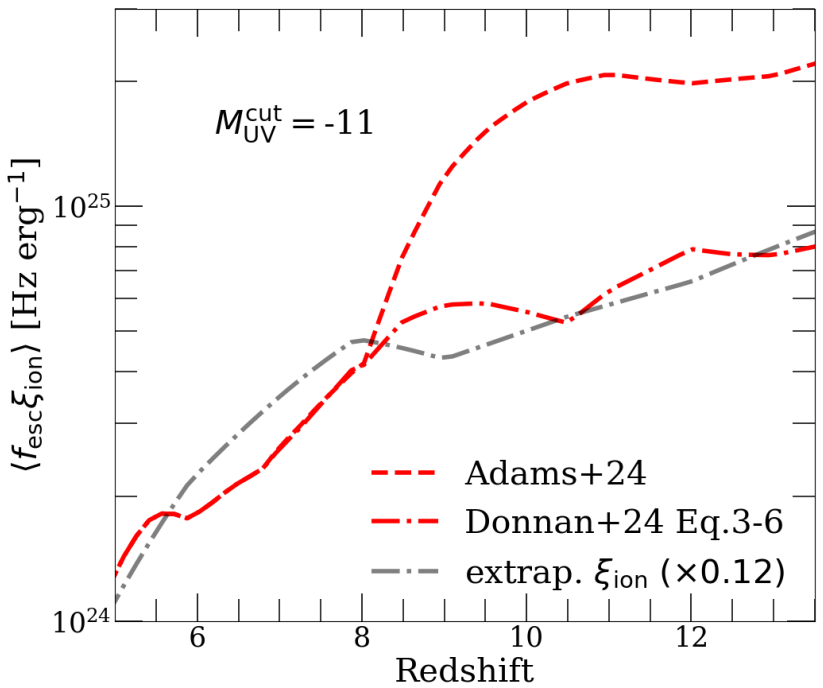
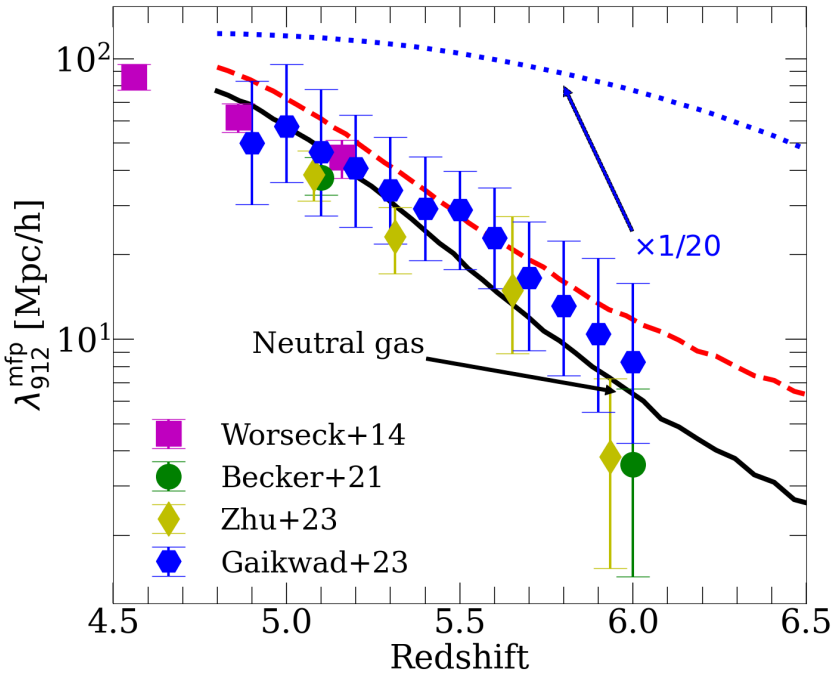


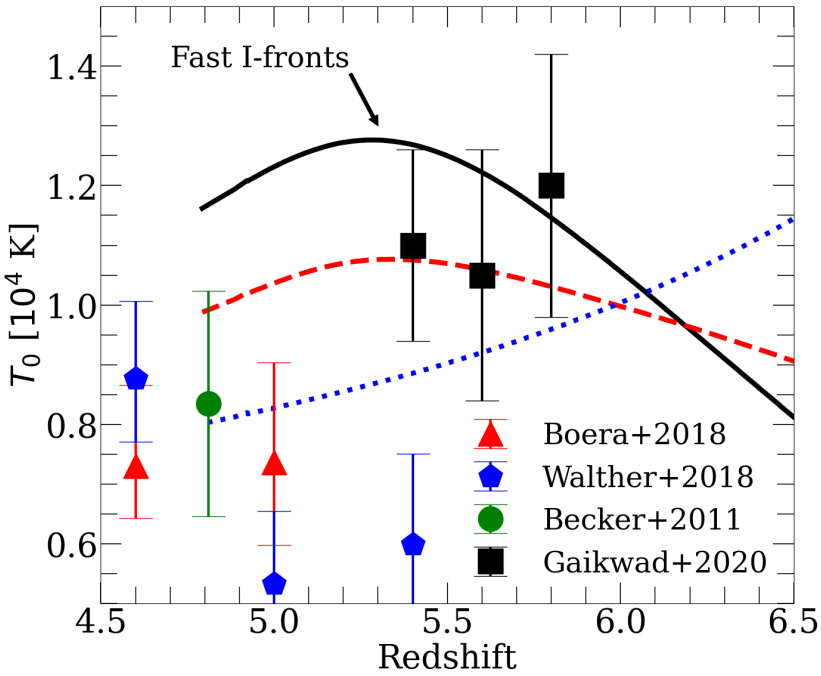


Certainly possible!

QSO Observations at $5 < z < 6$

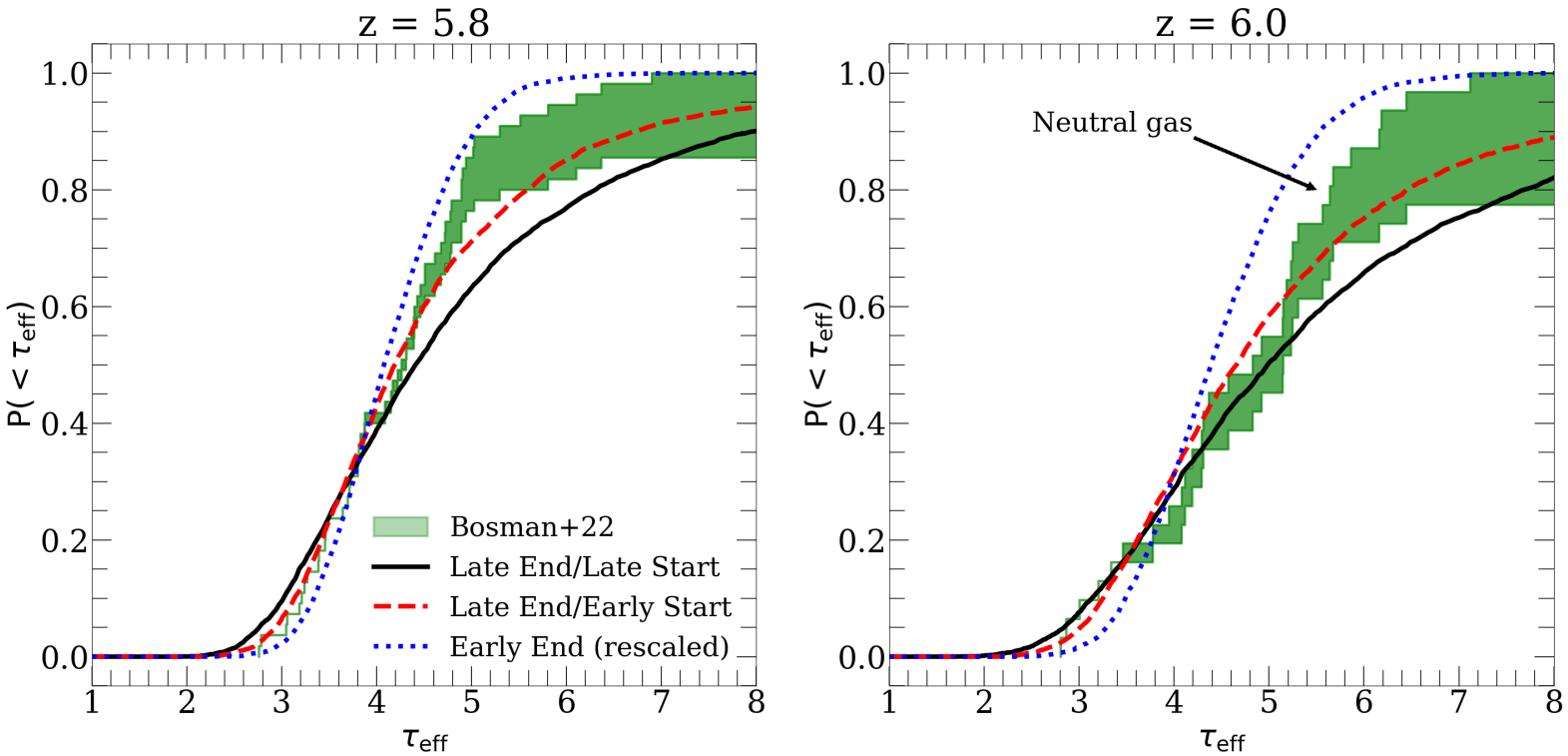
- The ionizing photon mean free path prefers a late start
- The thermal history of the IGM prefers an early start





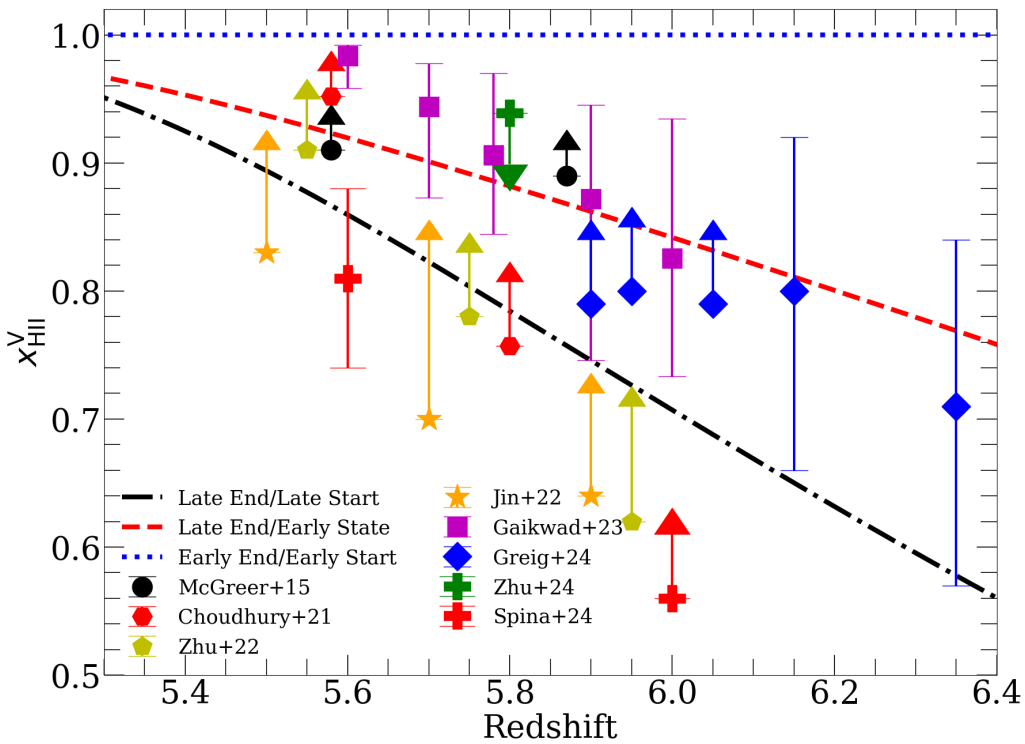
QSO Observations at $5 < z < 6$

- Distribution of forest optical depths - sensitive to $x_{\rm HI}$
- Early start/late end model is preferred



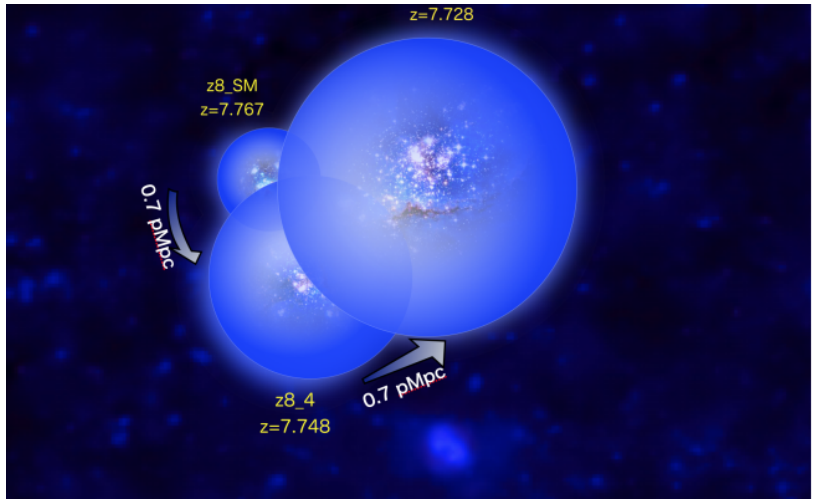
QSO Observations at $5 < z < 6$

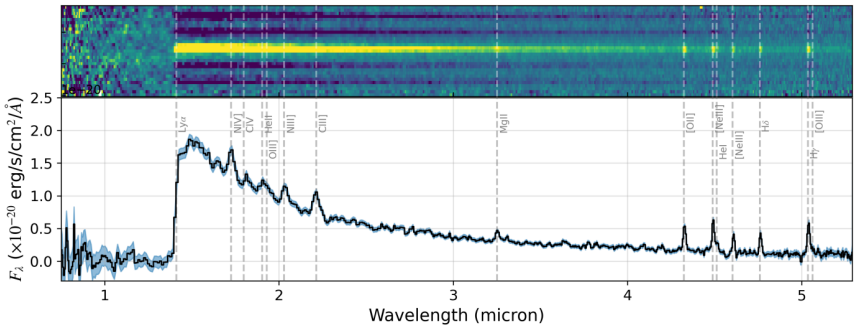
- Constraints on the neutral fraction at $z < 6.5$ from dark gaps, dark pixels, QSO damping wings, and the forest opacity
- Recent forest damping wing constraints (Zhu+24, Spina+24) disfavor early end
- Some limits prefer an early start



Lyα emitters at $z \geq 8$

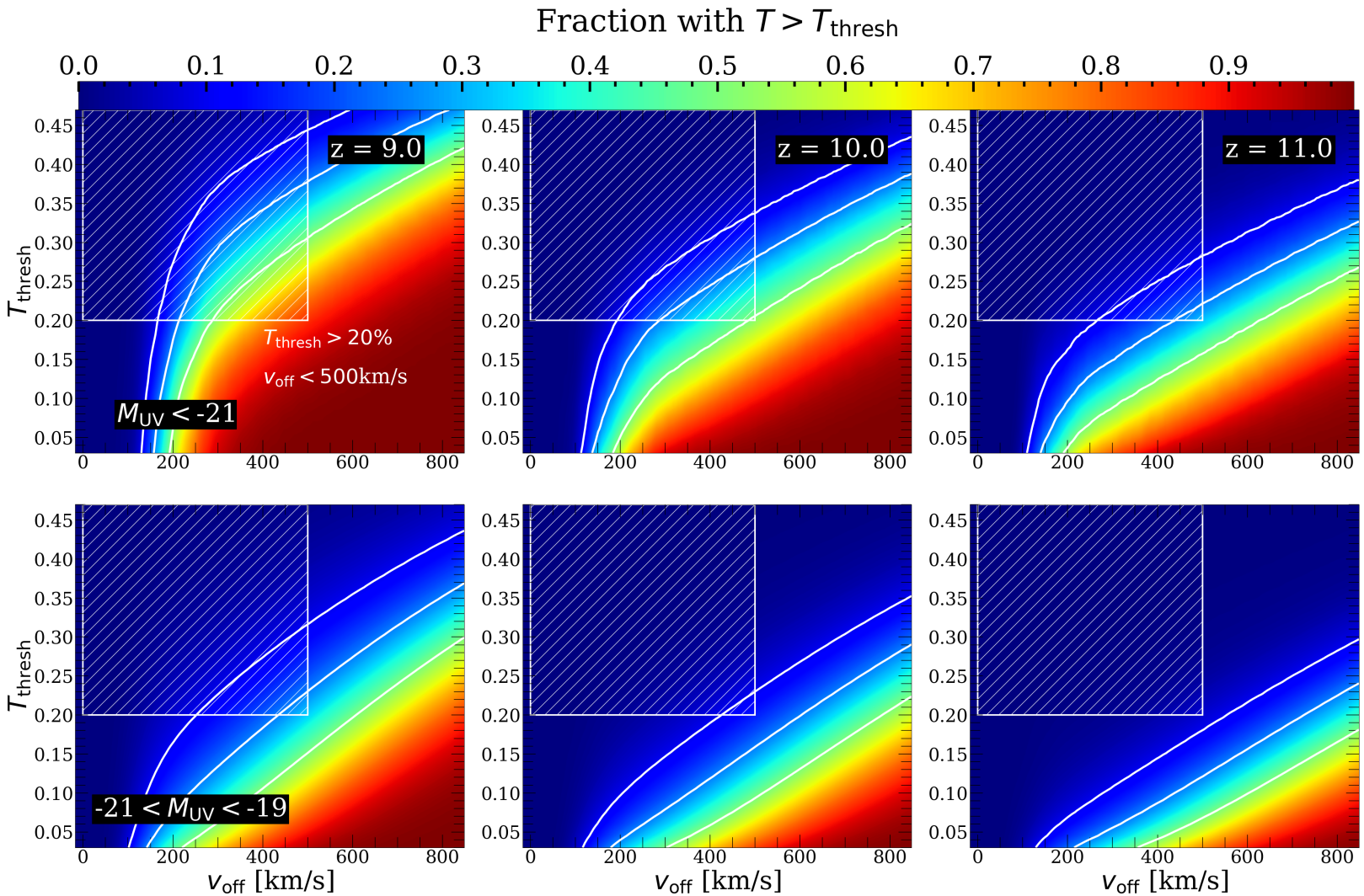
- Several recent detections (Zitrin+15, Larson+22, Bunker+23)
- Lyα requires some ionization around galaxies to escape damping wing absorption
- Most extreme example: GNz-11 at $z = 10.6$



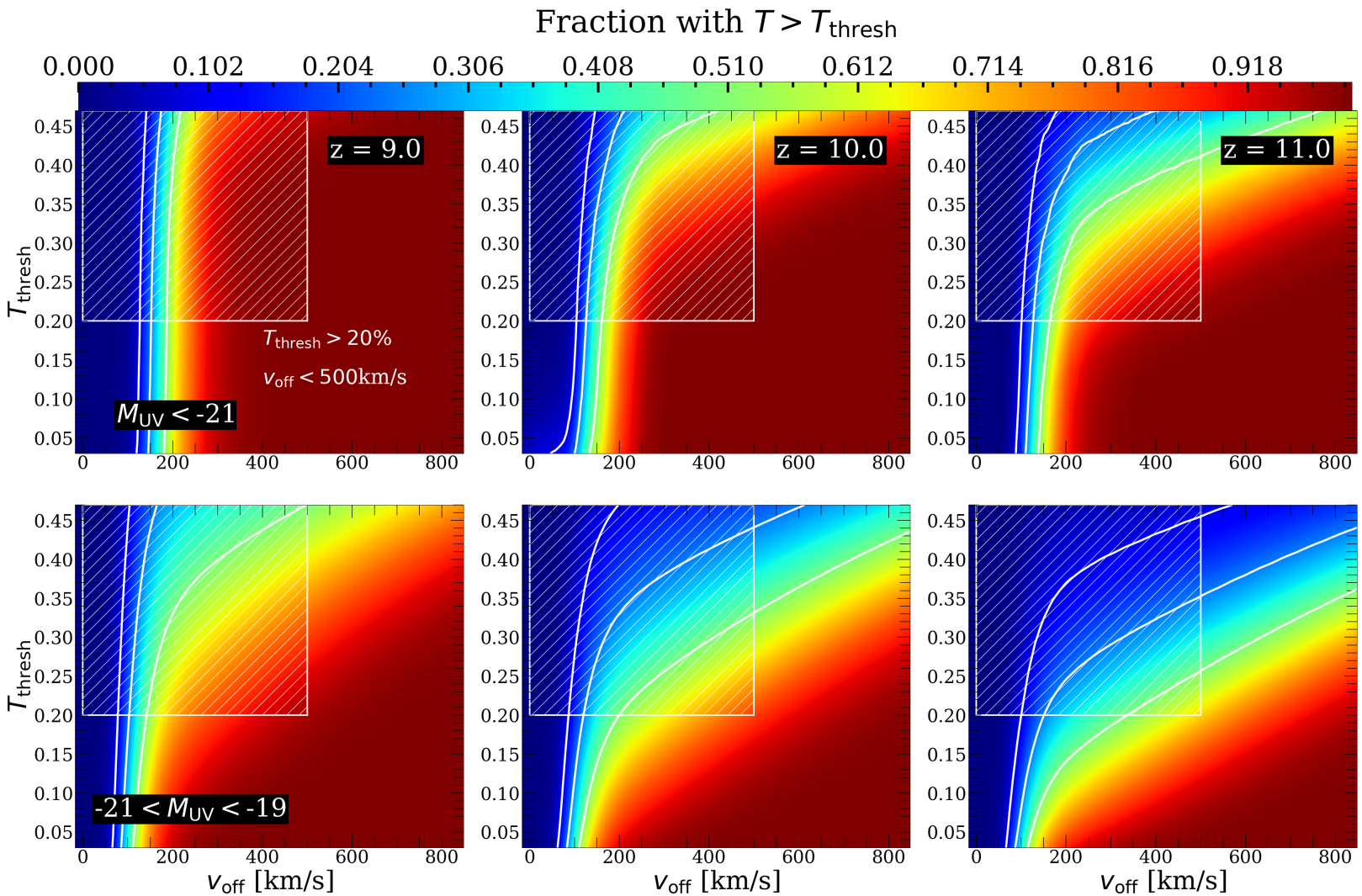


Figures: Tilvi+20, Bunker+23

Lyα transmission at $z > 8$ in the late start model



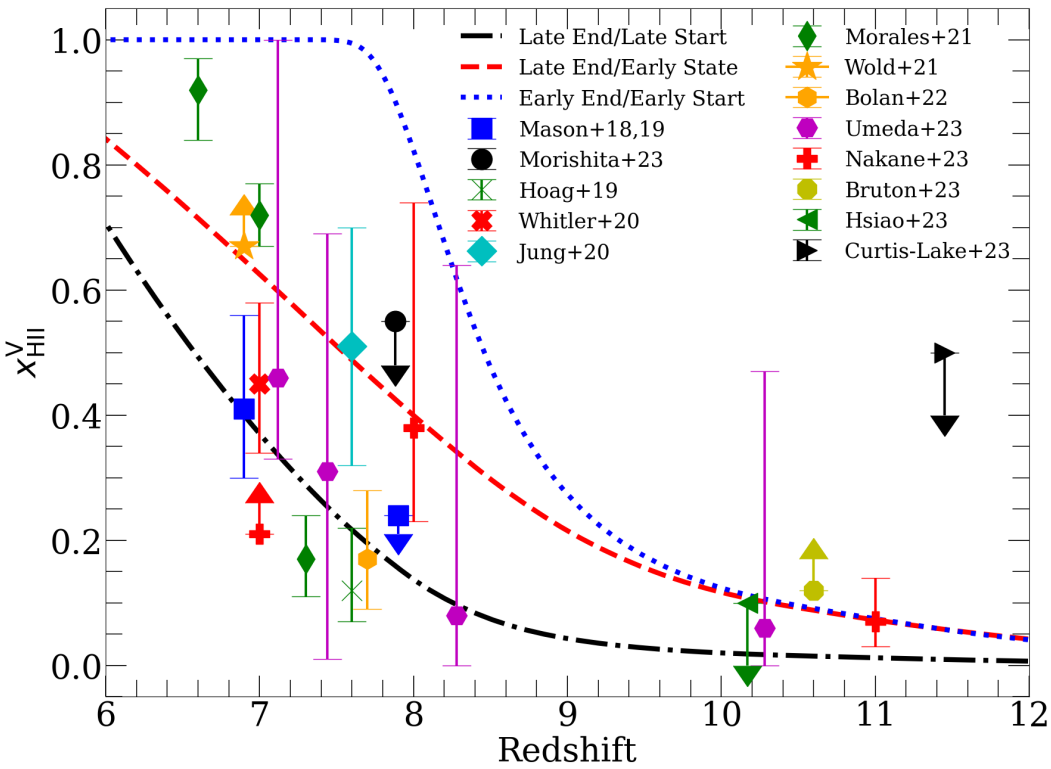
Lyα transmission at $z > 8$ in the early start model



Do LAEs *require* an early start?

- Can infer $x_{\rm HI}$ with LAE detections and/or damping wings
- Measurements at $7 < z < 8$ do not favor late or early start
- Very few constraints at $z > 8$

Inconclusive



Which model is favored?

An interesting puzzle emerges...

Probe	Late Start	Early Start
$\tau_{\rm CMB}$	No Preference	No Preference
UVLF/$\xi_{\rm ion}$/$f_{\rm esc}$	Preferred	Not Preferred
Lyα Forest $\langle T \rangle$	No Preference	No Preference
Forest $\tau_{\rm eff}$ dist.	Not preferred	Preferred
Mean Free Path	Preferred	Not preferred
Thermal History	Not preferred	Preferred
$x_{\rm HI}(z < 6.5)$	Not preferred	Preferred
$x_{\rm HI}(z > 6.5)$	No Preference	No Preference
LAEs at $z > 8$	Not preferred	Preferred

Preferred model: ????

Conclusions

- An early ($z > 6$) end to reionization is incompatible with $5 < z < 6$ QSO observations
- Late or early start? Different observations (seem to) prefer difference scenarios
- New JWST observations may have complicated our understanding of reionization!

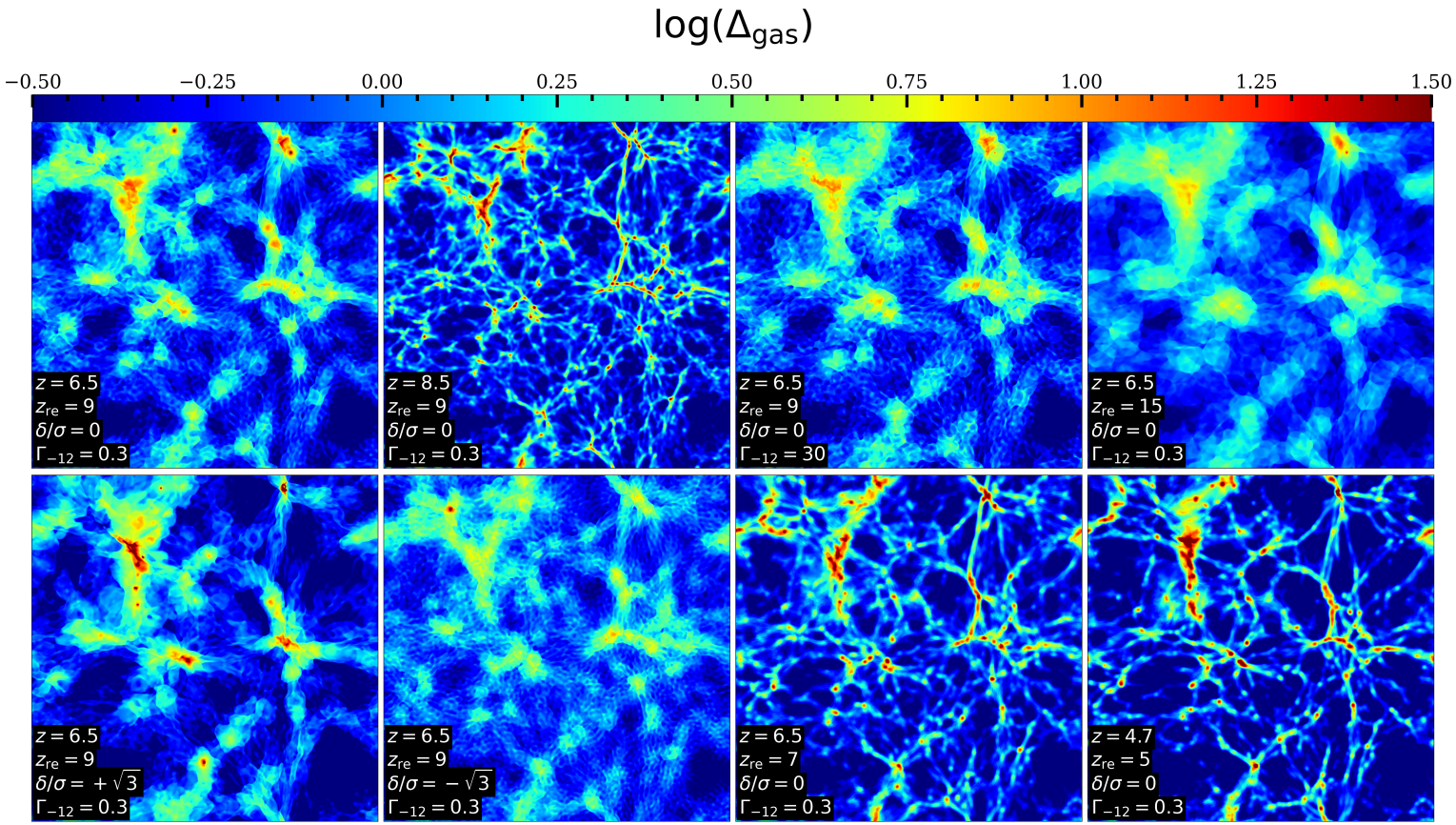
Extra Slides

Improvements in IGM modeling

- Introducing **SAGUARO** (**S**imul**a**ting **IG**M Evol**u**tion and Environments **a**t High **R**es**o**lution)
- Suite of high-resolution coupled RT/hydro simulations of the IGM using RadHydro (Trac & Cen 2004, Trac+07)
- Spans $4 < z < 15$ (useful for post-reionization studies)
- Large-scale IGM environments: $\Gamma_{\rm HI}$ (ionizing background), $\Delta_{\rm box}$ (box-scale density), $z_{\rm reion}$ (redshift of reionization)
- 2 h^{-1}kpc (250 h^{-1}pc) resolution for $L_{\rm box} = 2$ h^{-1}Mpc (250 h^{-1} kpc)
- Phase 1: 64 simulations, $\sim$ 1.5 million CPU hours

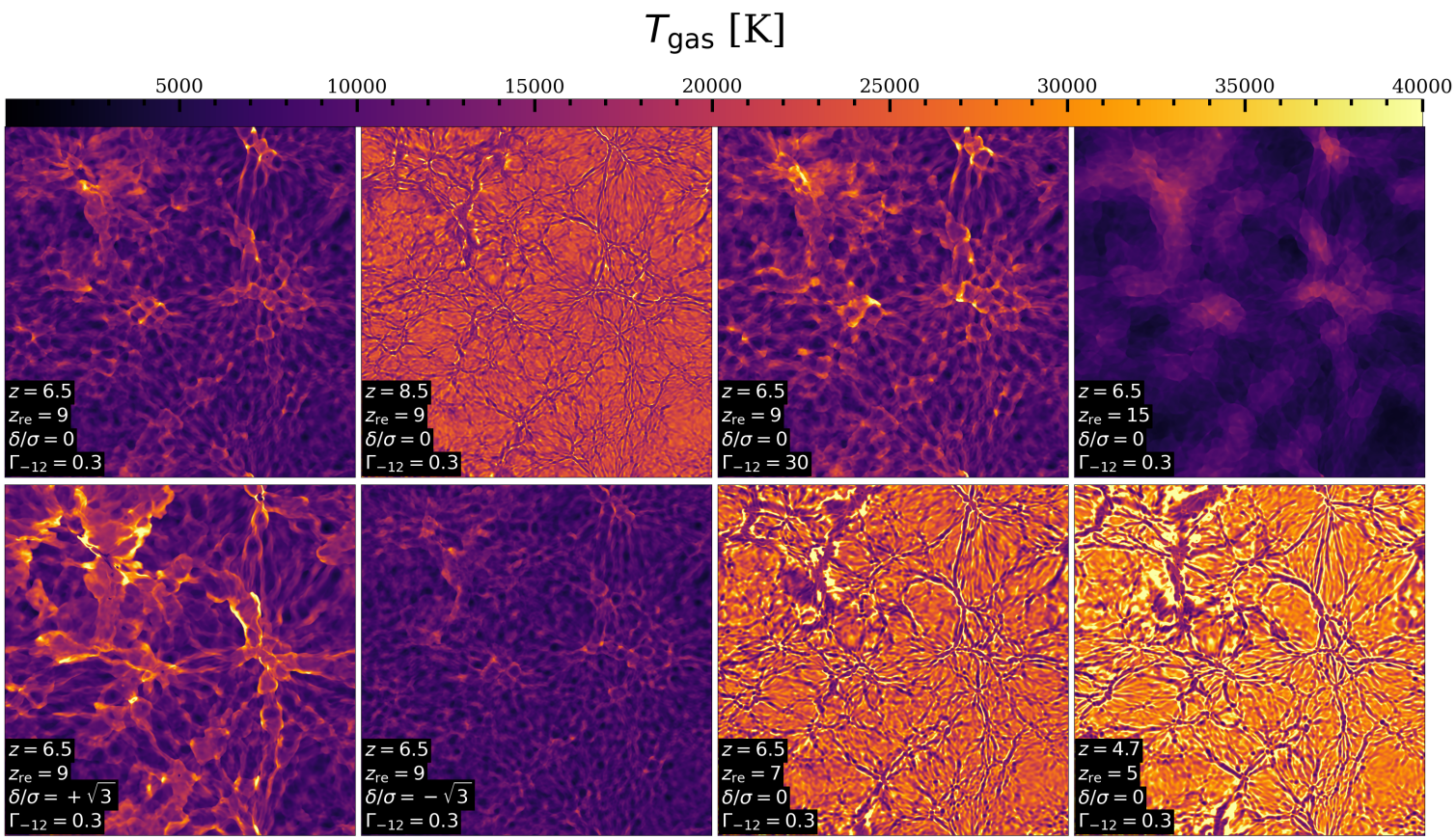
IGM Density

Model the dynamics of the IGM in a wide range of large-scale environments throughout reionization



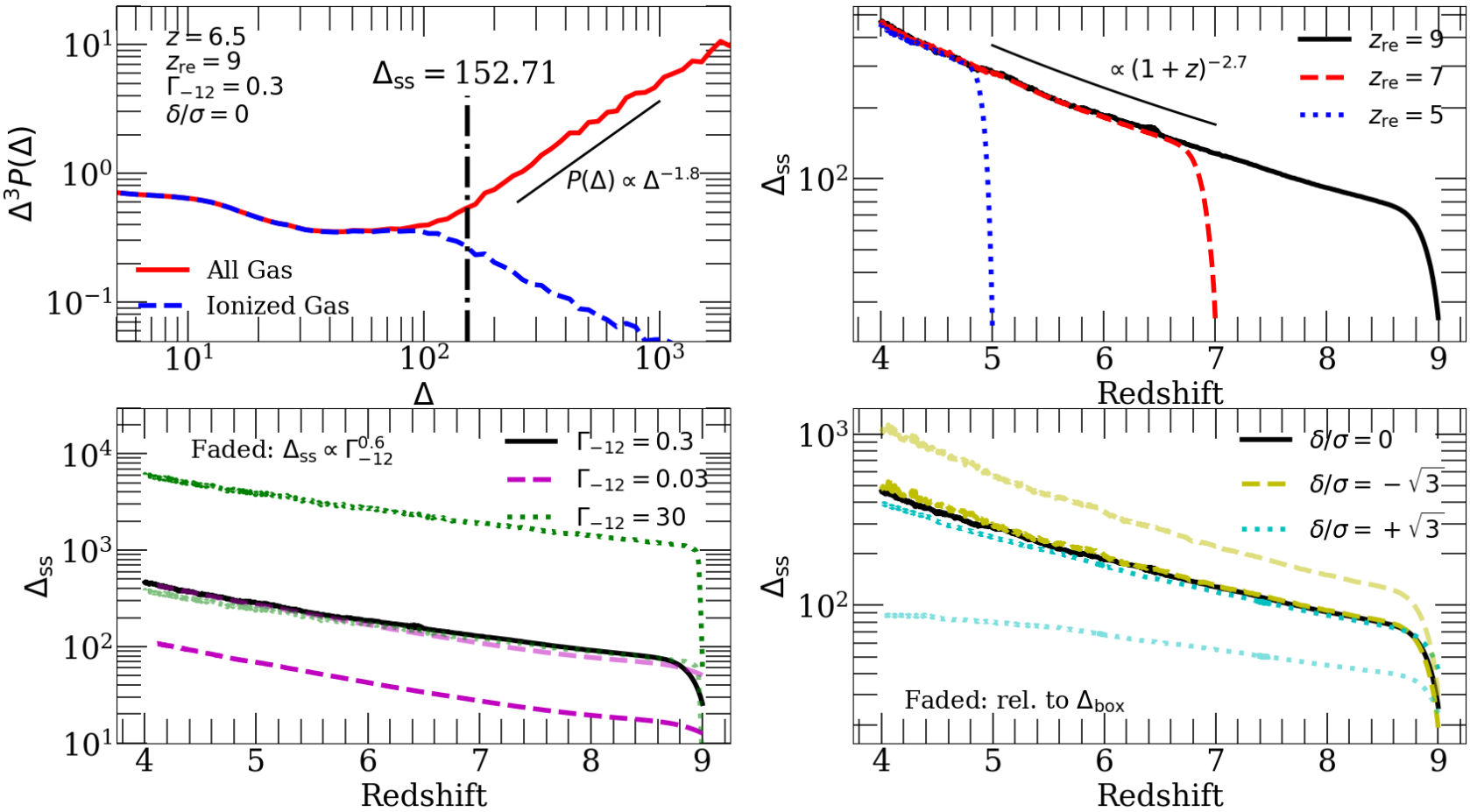
IGM Temperature

High resolution reveals a complex, hydrodynamics-driven thermal structure (https://arxiv.org/abs/2405.02397)



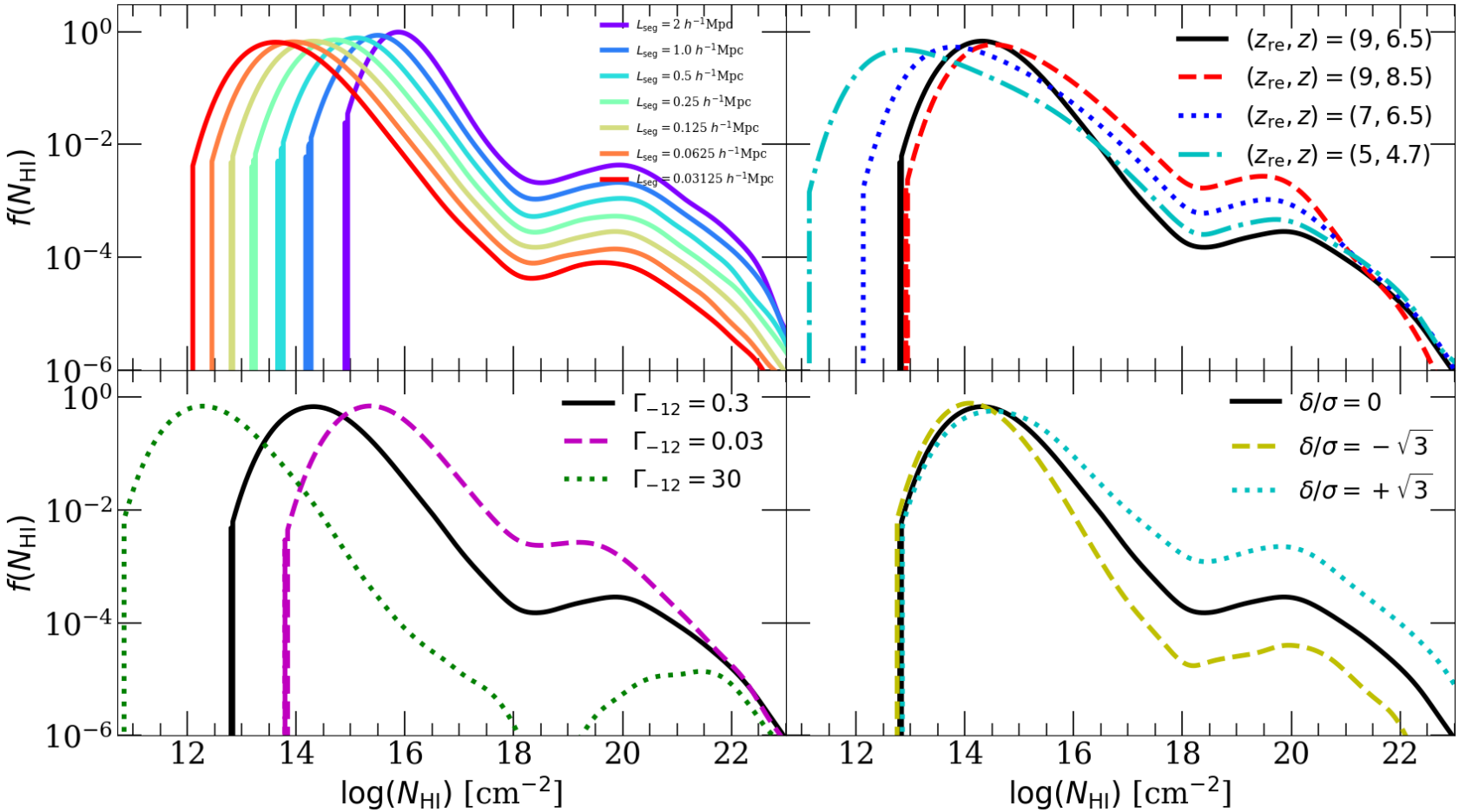
Preliminary Results

Characterization of self-shielding density across environments



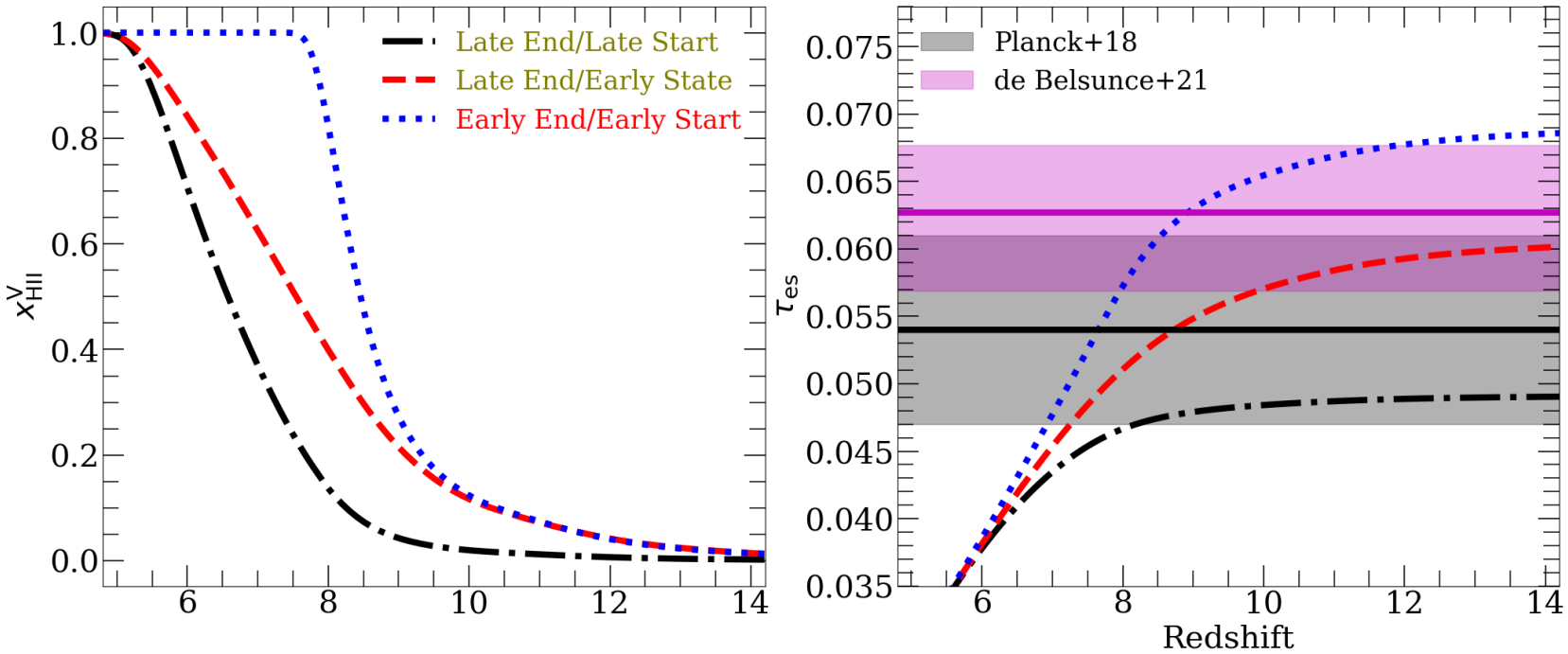
Preliminary Results

Dynamics of the HI column density distribution



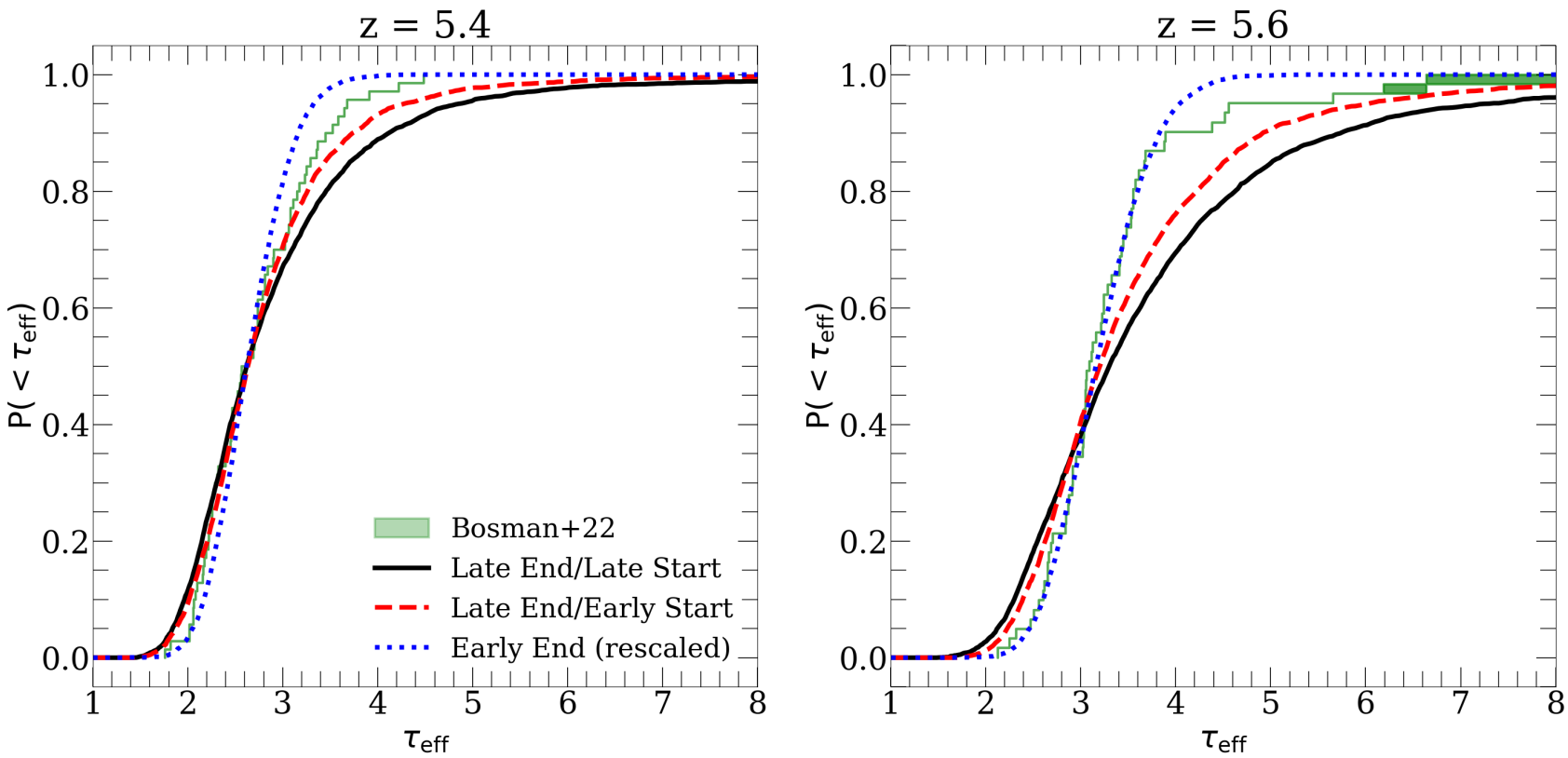
Ionization History + $\tau_{\rm CMB}$

- Both late-ending models are 1σ consistent with the Planck+20 $\tau_{\rm CMB}$ measurement



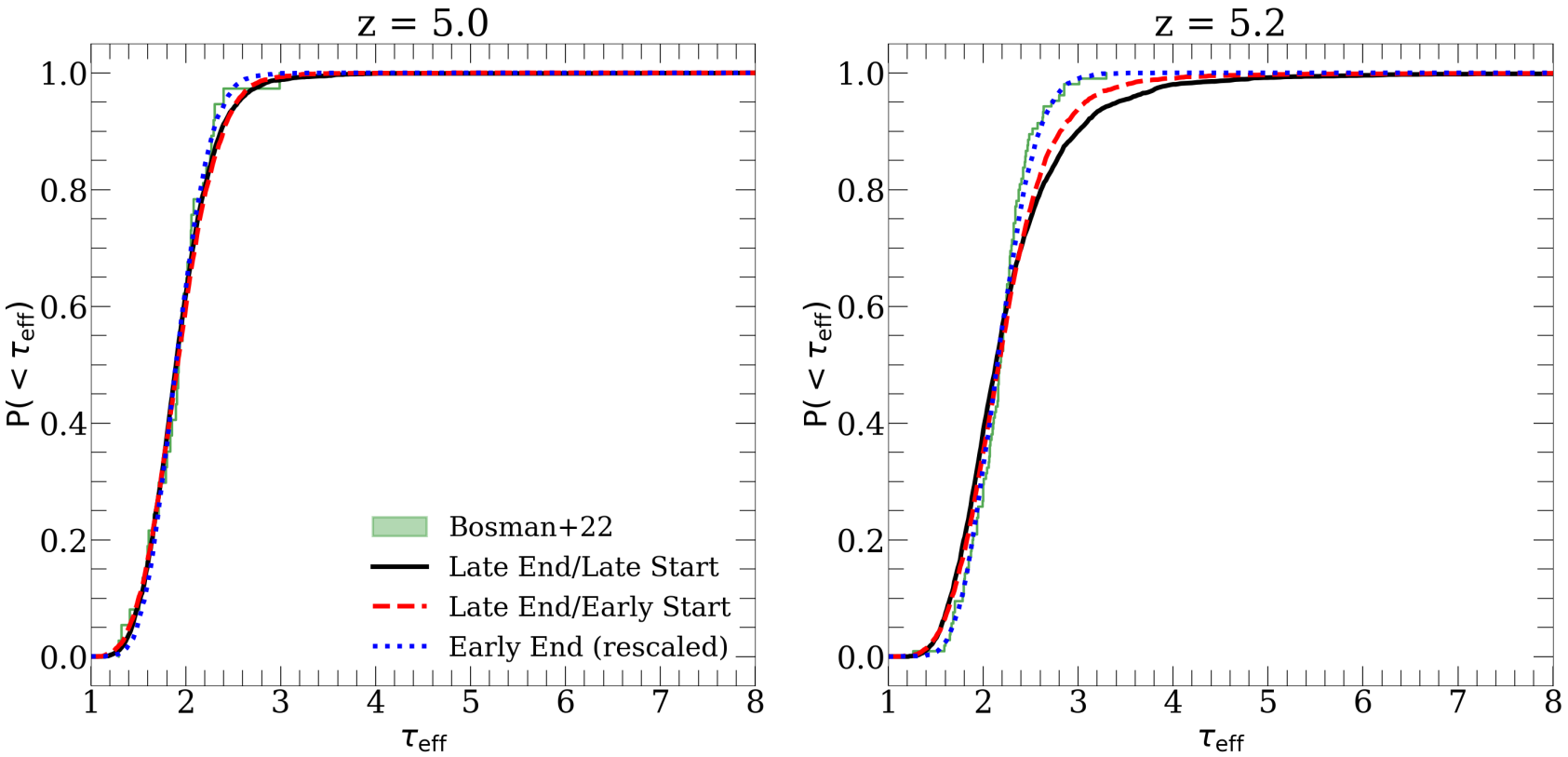
$\tau_{\rm eff}$ distribution at $z = 5.4$, 5.6

- None of the models agree very well at these redshifts



$\tau_{\rm eff}$ distribution at $z = 5.0$, 5.2

- $z = 5.2$ suggests both of our models end reionization slightly too late



What about GN-z11?

- At $z = 10$ (11), 50% (30%) of $M_{\rm UV} < -21$ LAEs visible for $\Delta v = 550$ km/s, $T_{\rm IGM} > 0.2$
- $\approx$ 50% (25%) chance of $\mathrm{EW}_{\rm intrinsic} < 100$ Å at $z = 10$ (11)
- Significant chance of $\mathrm{EW}_{\rm intrinsic} < 50$ Å for early-starting model