Chasing the beginning of reionization in the JWST era

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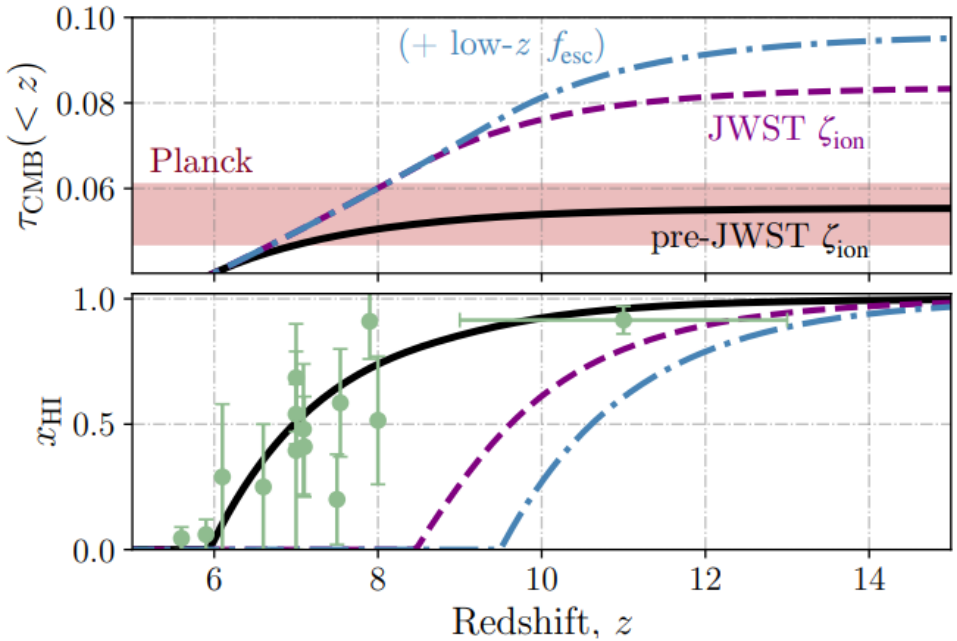
Can galaxies drive cosmic reionization?

- 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)

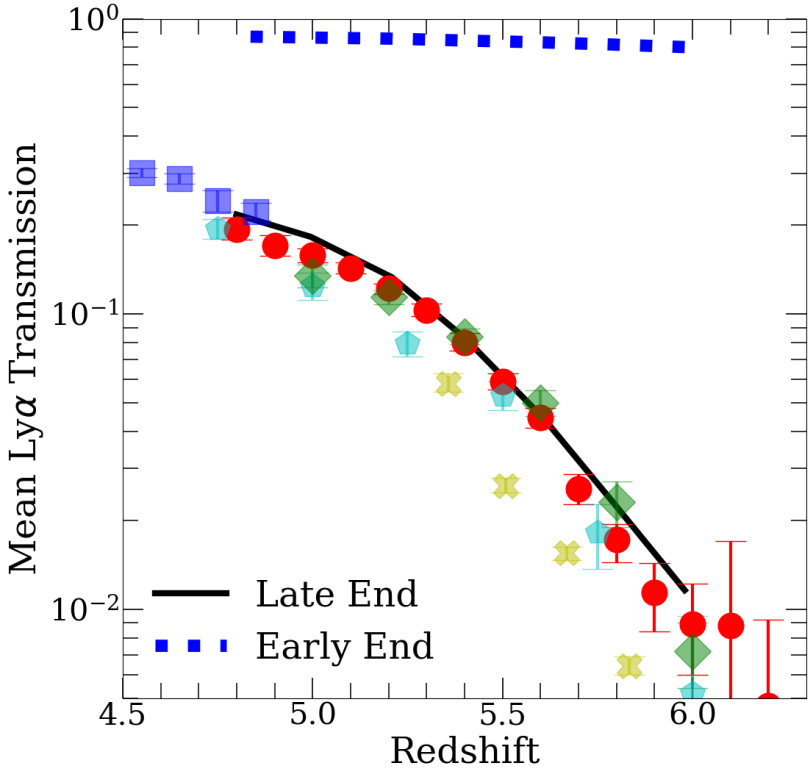


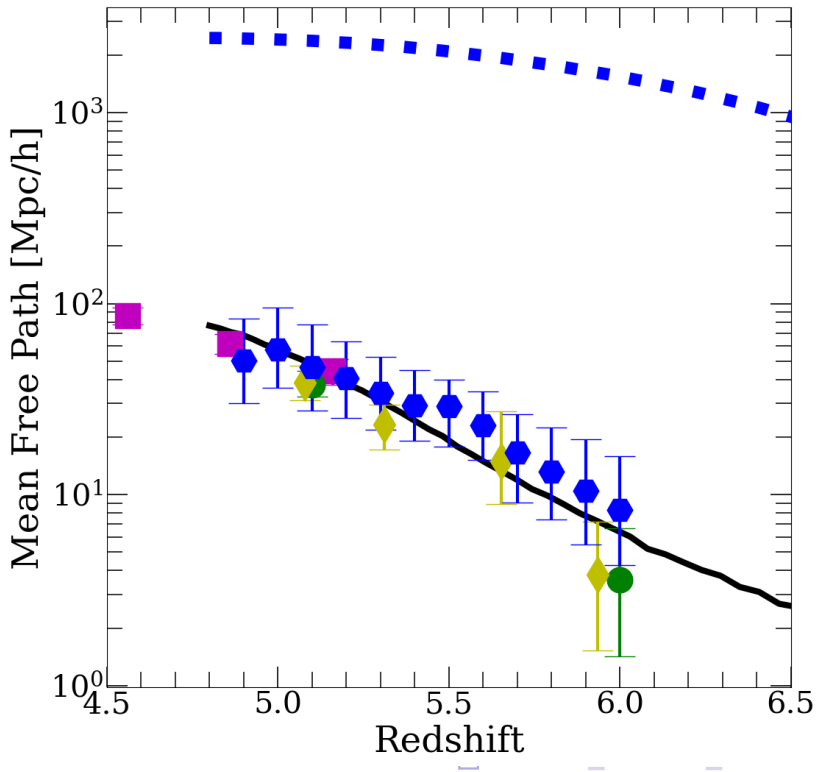
Seems like yes!

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 = IGM too transmissive!

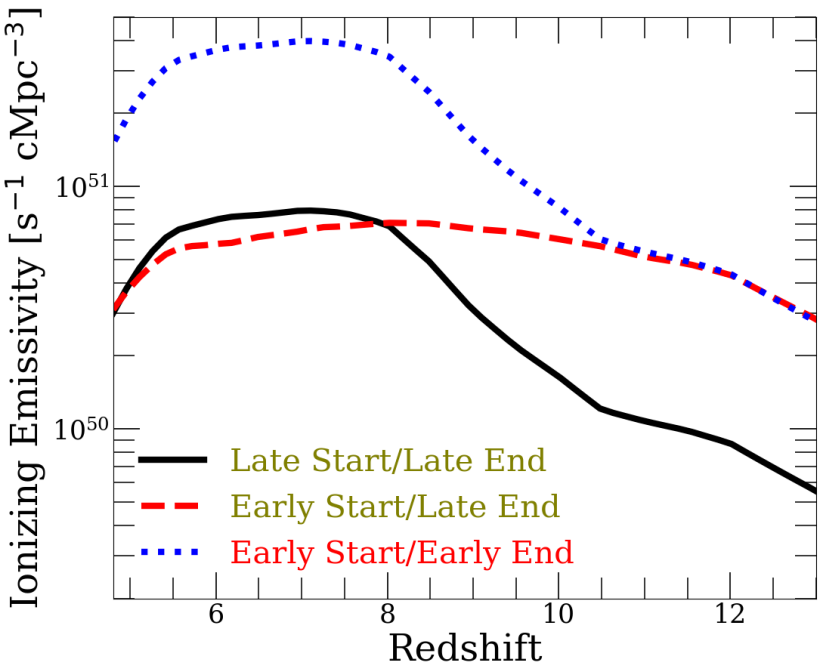


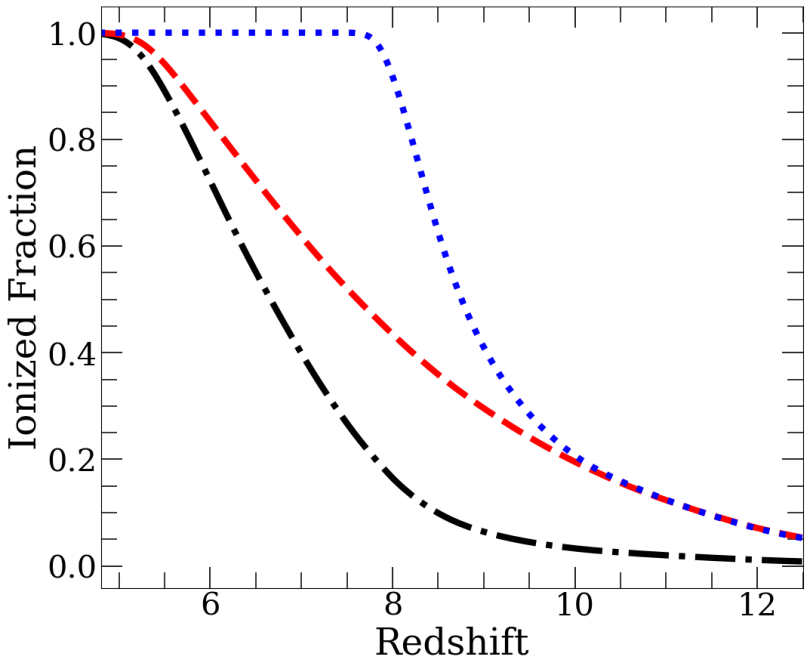


How can we get rid of photons?

Two ways:

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

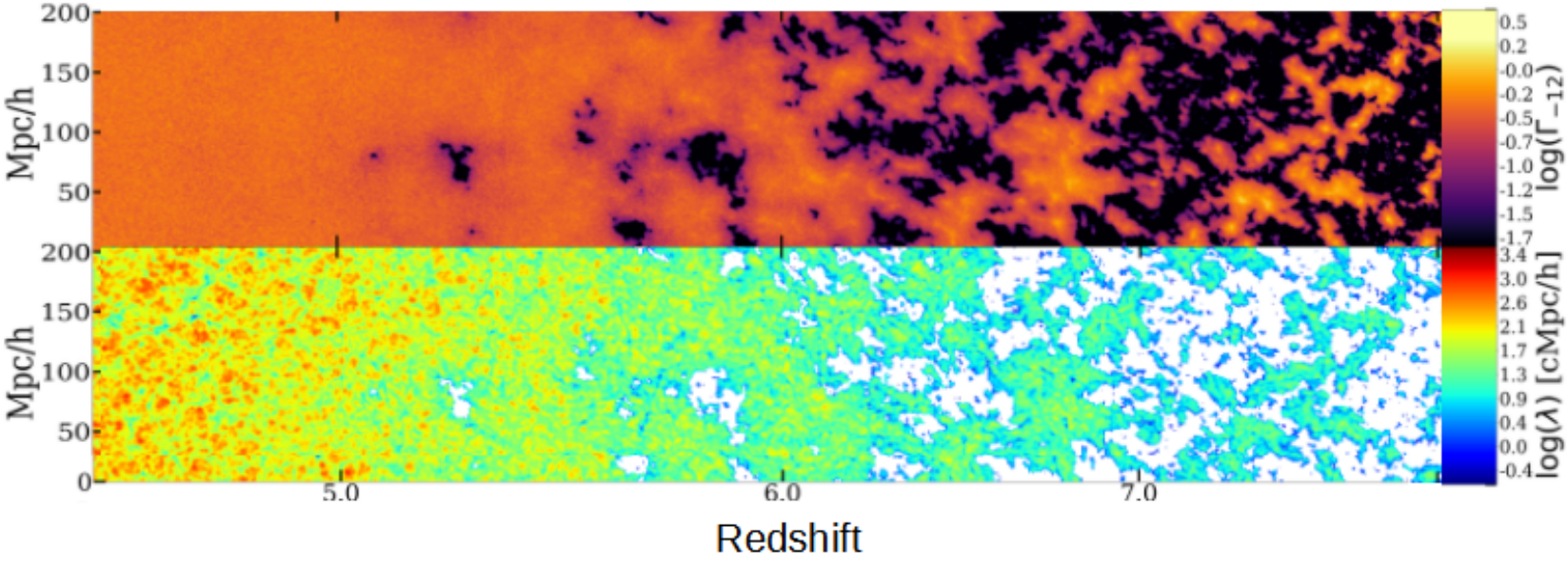




Which one is favored by observations?

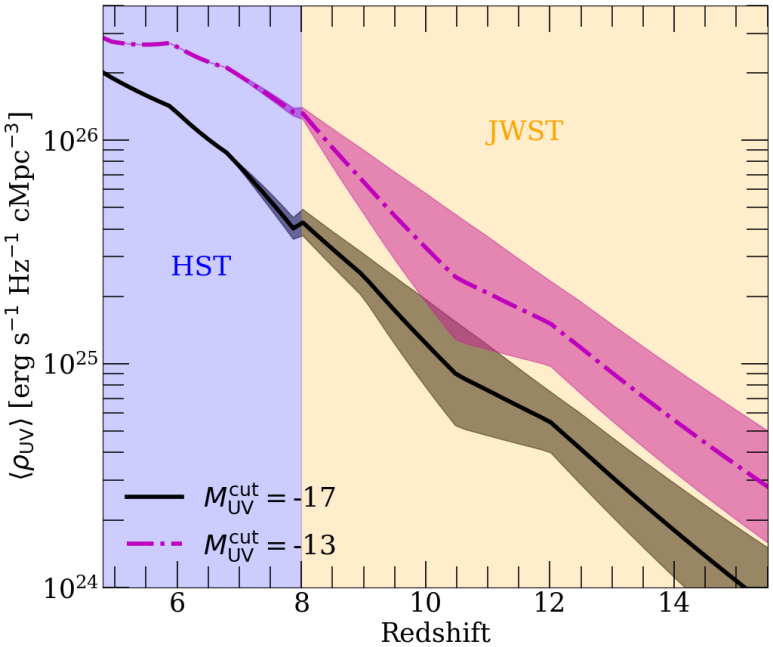
Simulations of Reionization with FlexRT

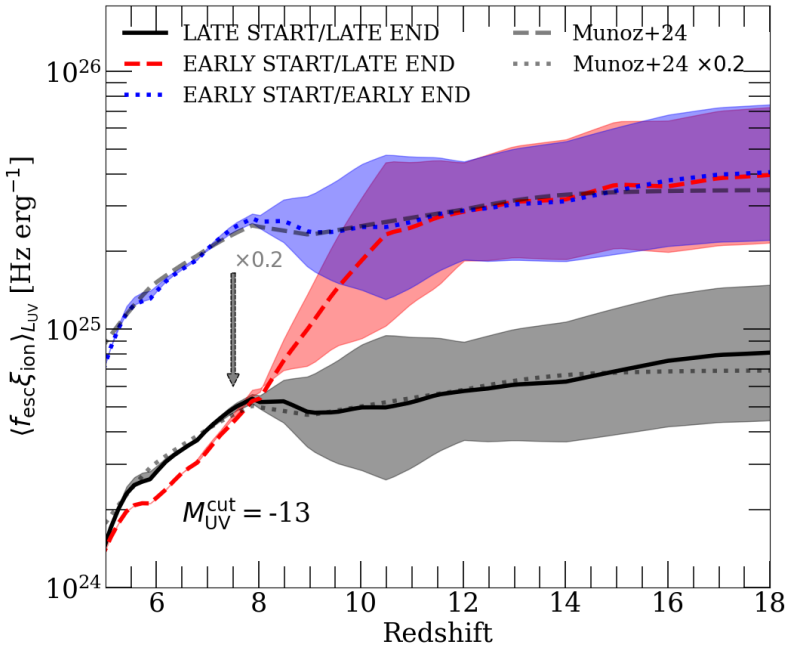
- Adaptive ray-tracing RT in a cosmological volume ($N_{\rm RT} = 200^3$, $L_{\rm box} = 200\ h^{-1}$Mpc)
- Sub-grid opacity model based on high-res hydro/RT sims
- Both late-ending models are calibrated to **reproduce Lyα forest mean transmission at $5 < z < 6$ (Bosman+22)**



UVLF/Ionizing properties of galaxies

- JWST UVLF (Adams/Donnan+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 $\langle f_{\rm esc}\xi_{\rm ion}\rangle$

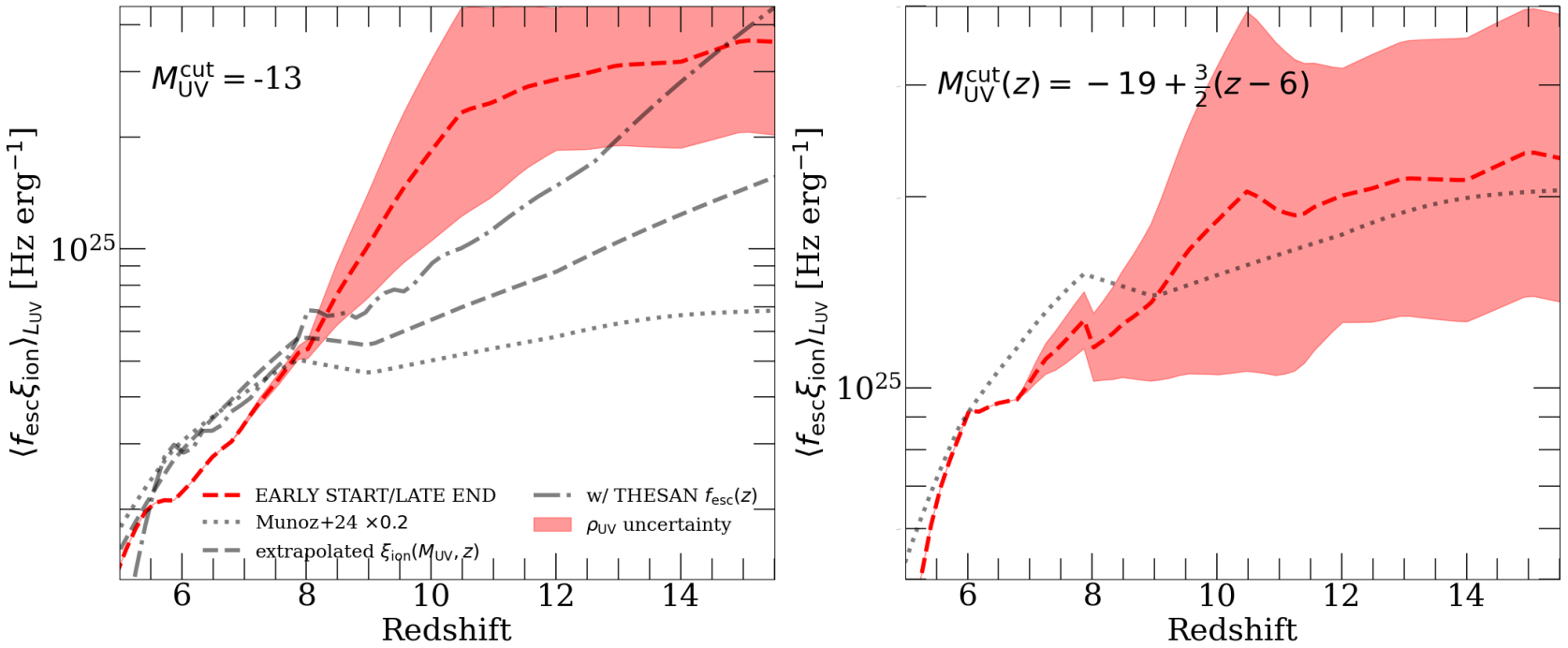




Early start needs steeper evolution than observations suggest

Can galaxies accommodate an early start?

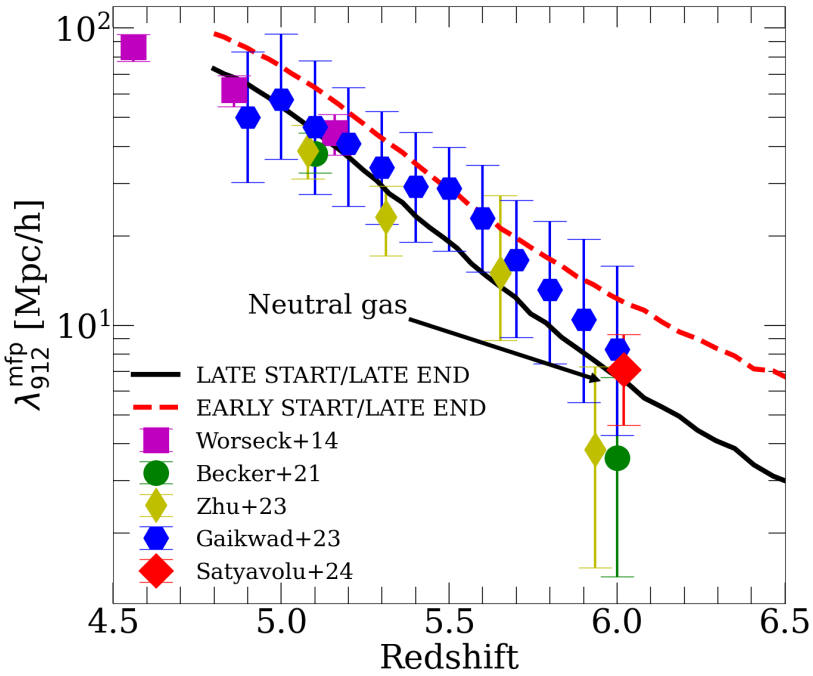
- Extrapolation of $\xi_{\rm ion}$ measurements to high z/faint galaxies?
- Evolution in $f_{\rm esc}$?
- Evolution in $M_{\rm UV}^{\rm cut}$ (feedback)??

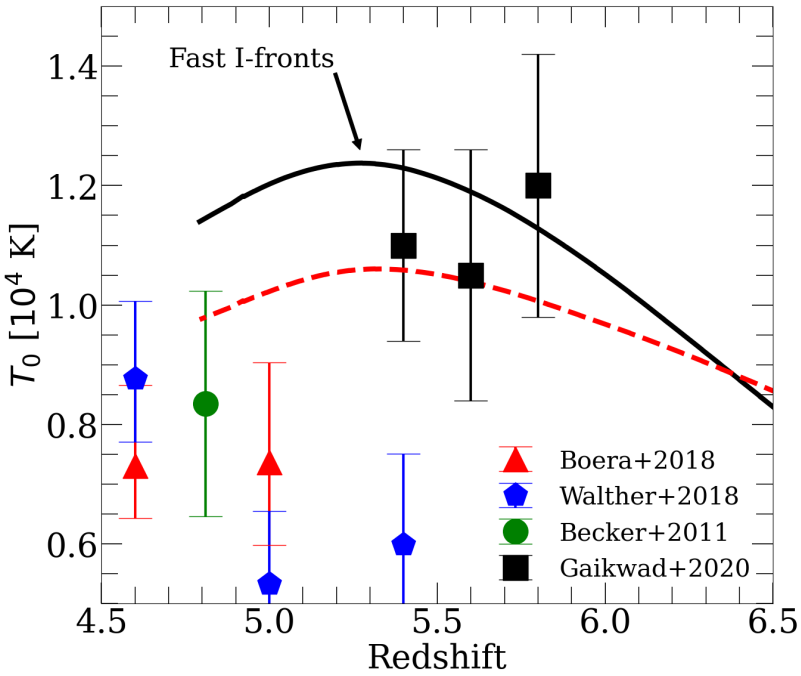


Certainly possible!

QSO Observations at $5 < z < 6$

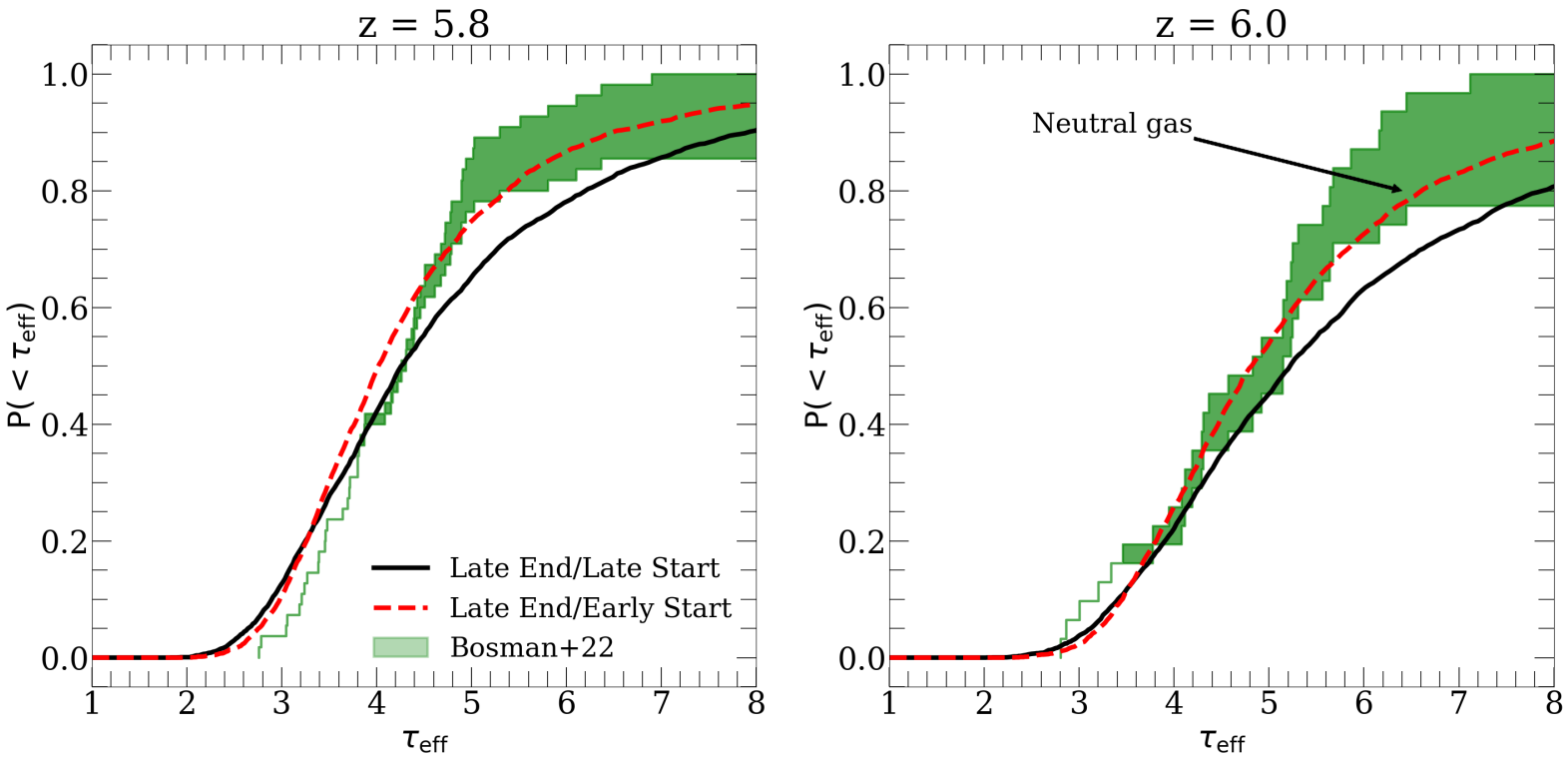
- The ionizing photon mean free path prefers a **late start**
- The thermal history of the IGM prefers an **early start**





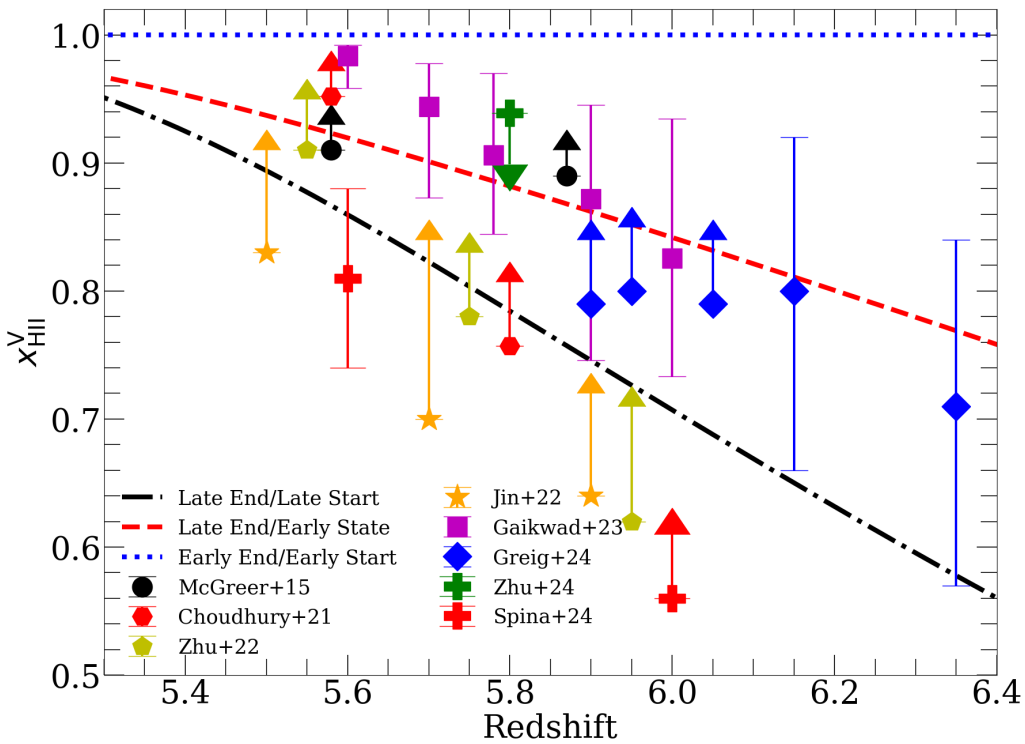
QSO Observations at $5 < z < 6$

- Distribution of forest optical depths - sensitive to $x_{\rm HI}$
- An **early start** is preferred



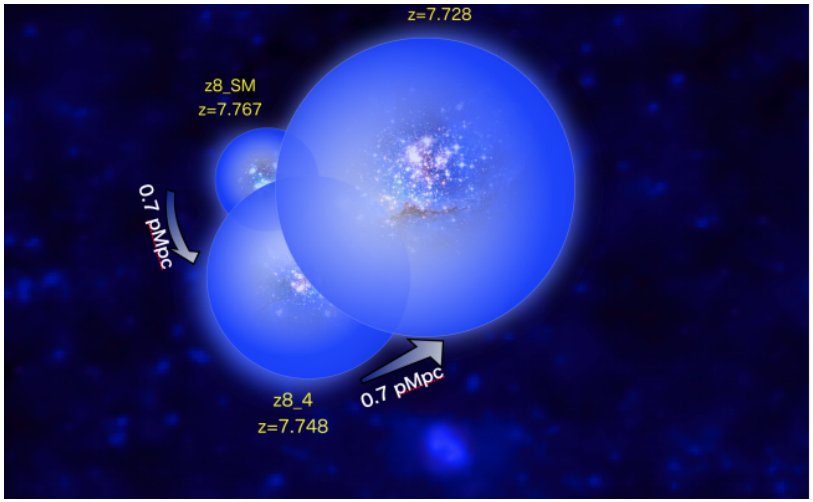
QSO Observations at $5 < z < 6$

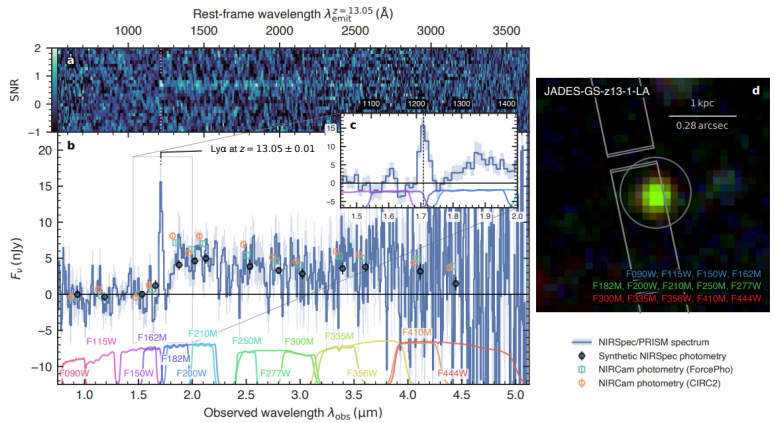
- Constraints on the neutral fraction at $z < 6.5$ from dark gaps, dark pixels, QSO damping wings, and the forest opacity
- Recent forest damping wing constraints (Zhu+24, Spina+24) disfavor early end
- Some limits prefer an **early start**



Lyα emitters at $z \geq 8$

- Several recent detections (Larson+22, Bunker+23, Witstock+24)
- Lyα requires some ionization around galaxies to escape damping wing absorption
- Most extreme example: JADES-GS-z13-1-LA at $z = 13$

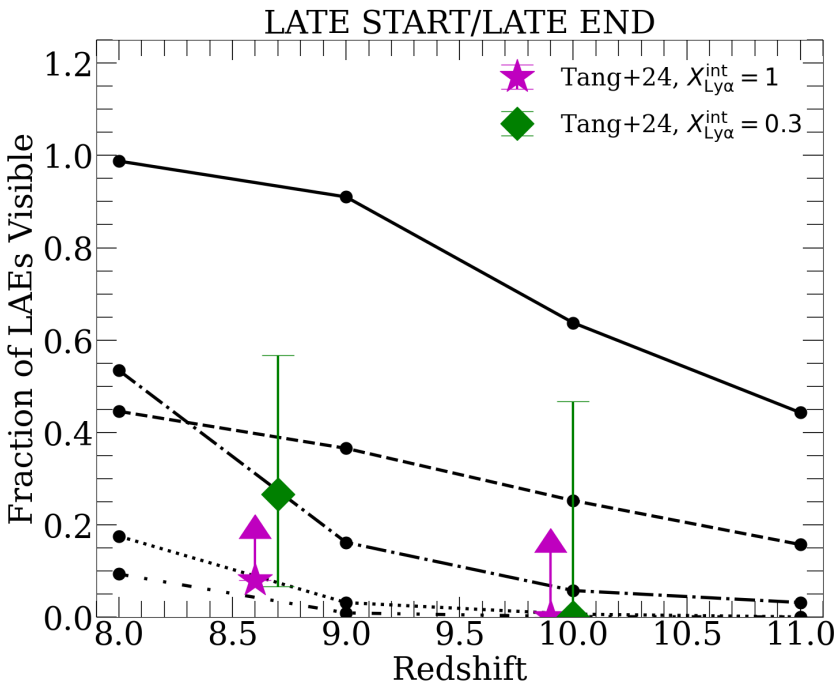


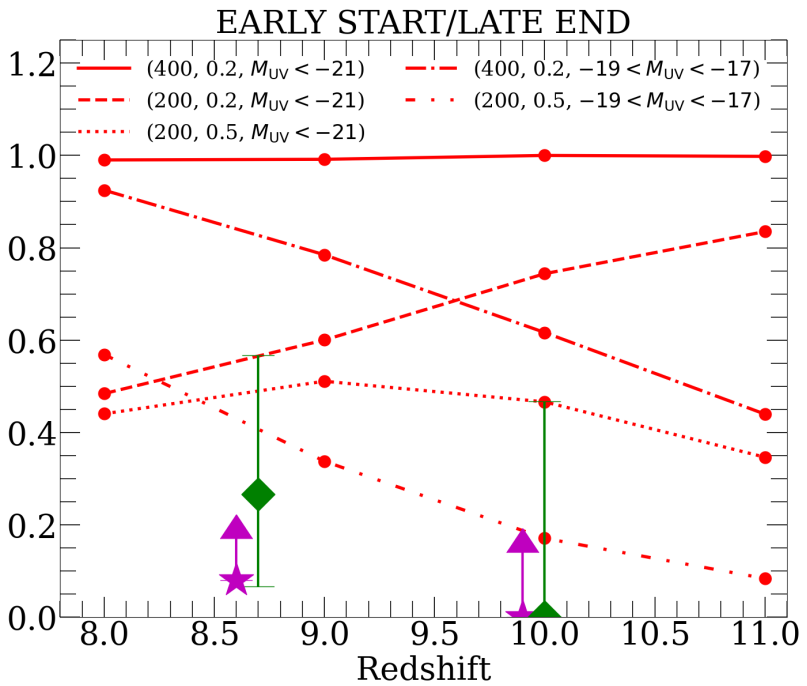


Figures: Tilvi+20, Witstok+24

How does LAE visibility evolve?

- Recent measurements (Tang+24) show sharp drop to $z \sim 10$
- We can estimate visibility in simulations for LAEs with different properties (detection criteria, velocity offset, $M_{\rm UV}$)
- Low visibility $\rightarrow$ **late start**





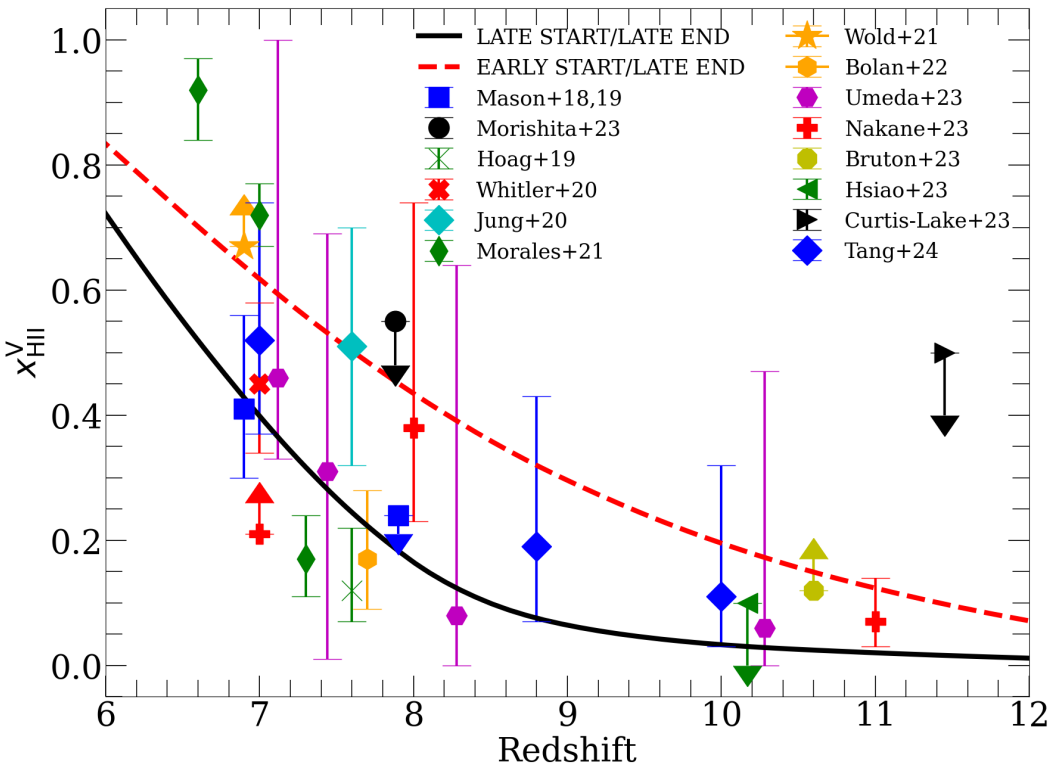
Neutral fraction measurements?

- Can infer $x_{\rm HI}$ with LAE detections and/or damping wings

- Measurements at $7 < z < 8$ do not favor late or early start

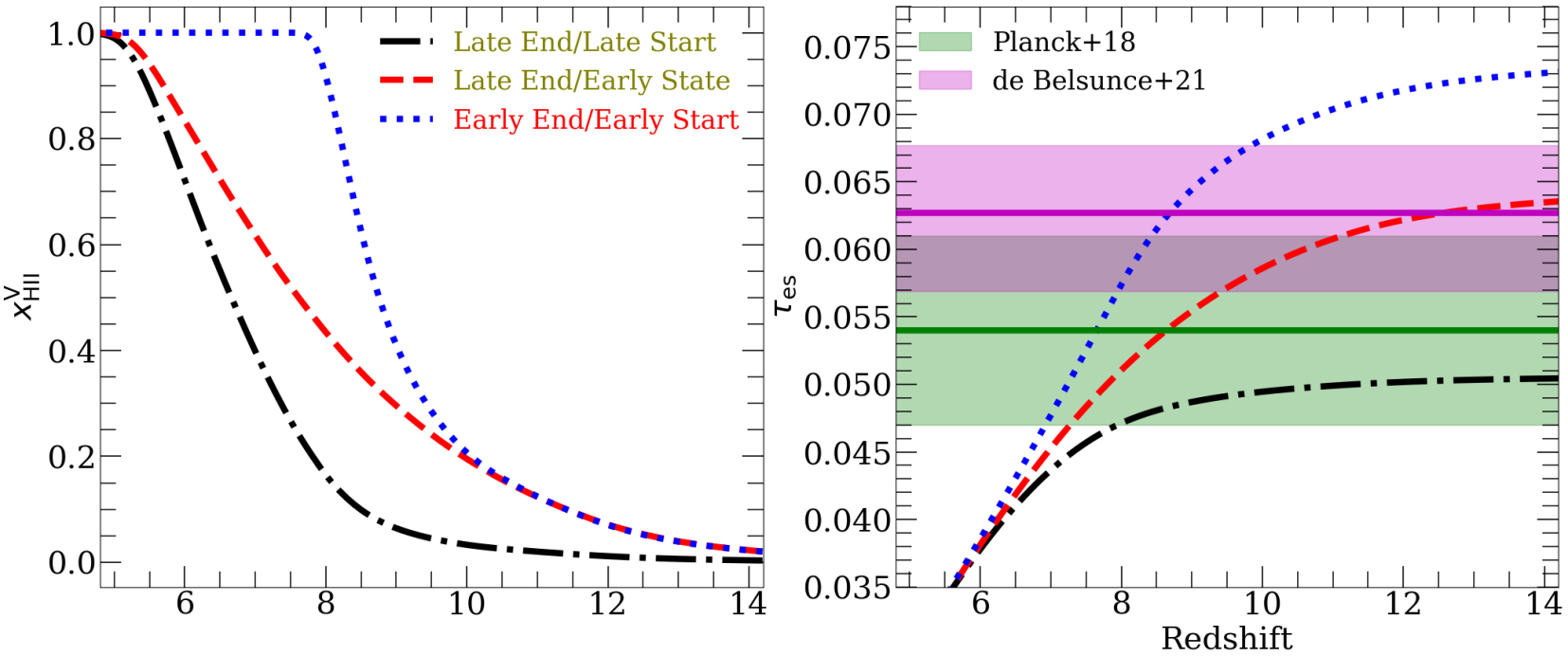
- Very few constraints at $z > 8$

Inconclusive



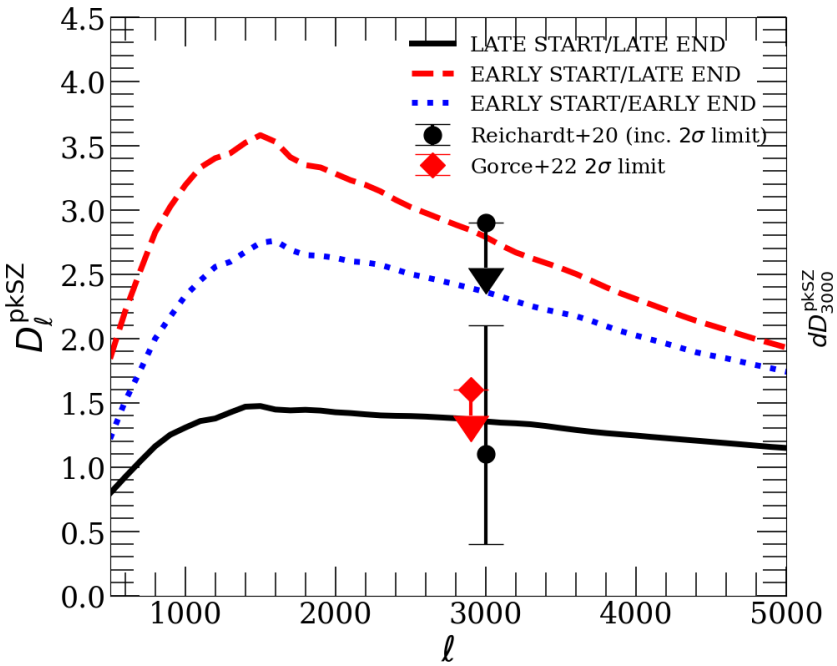
What about the CMB?

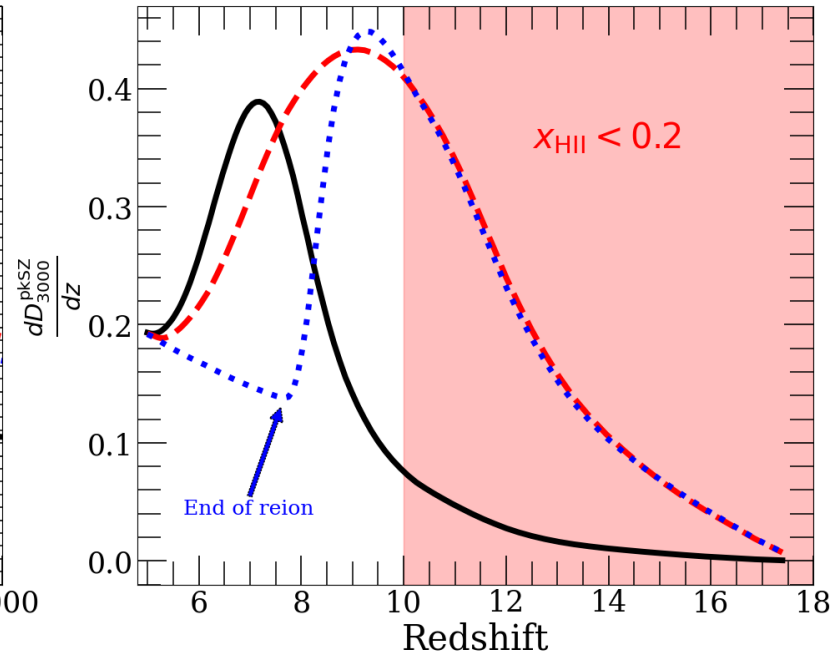
- Both late-ending models are 1σ-consistent with either Planck+18 or de Belsunce+21 measurements of $\tau_{\rm CMB}$
- No clear preference



What about the CMB?

- A **late start** is clearly favored by SPT measurement of the pkSZ effect (Reichardt+21)
- Much of the power in the early start case comes from reionization's beginning ($x_{\rm HI} < 0.2$)





Do observations prefer a late or early start?

Category	Probe	Late Start	Early Start
CMB	$\tau_{\rm es}$	No Pref.	No Pref.
	Patchy kSZ	Preferred	Not preferred
High-z Galaxies	UVLF/$\xi_{\rm ion}$/$f_{\rm esc}$	Preferred	Not preferred
	LAEs at $z > 8$	Preferred	Not preferred
	$x_{\rm HI}(z > 6.5)$	No Pref.	No Pref.
$z < 6.5$ QSOs	$\langle F_{\rm Ly\alpha} \rangle$	No Pref.	No Pref.
	$P(< \tau_{\rm eff}^{50})$	Not preferred	Preferred
	Mean Free Path	Preferred	Not preferred
	Thermal History	Not preferred	Preferred
	$x_{\rm HI}(z < 6.5)$	Not preferred	Preferred

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	Mean Free Path	Preferred	Not preferred
	Thermal History	Not preferred	Preferred
	$x_{\rm HI}(z < 6.5)$	Not preferred	Preferred
Final Score	All Data	Preferred	Not preferred

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
- A late start is preferred by results from multiple data sets, making it the (mildly) preferred scenario overall
- New JWST observations may have complicated our understanding of reionization!