Ending Reionization Gracefully: Properties of the Ionizing Photon Sources (& IGM) at the End of Reionization

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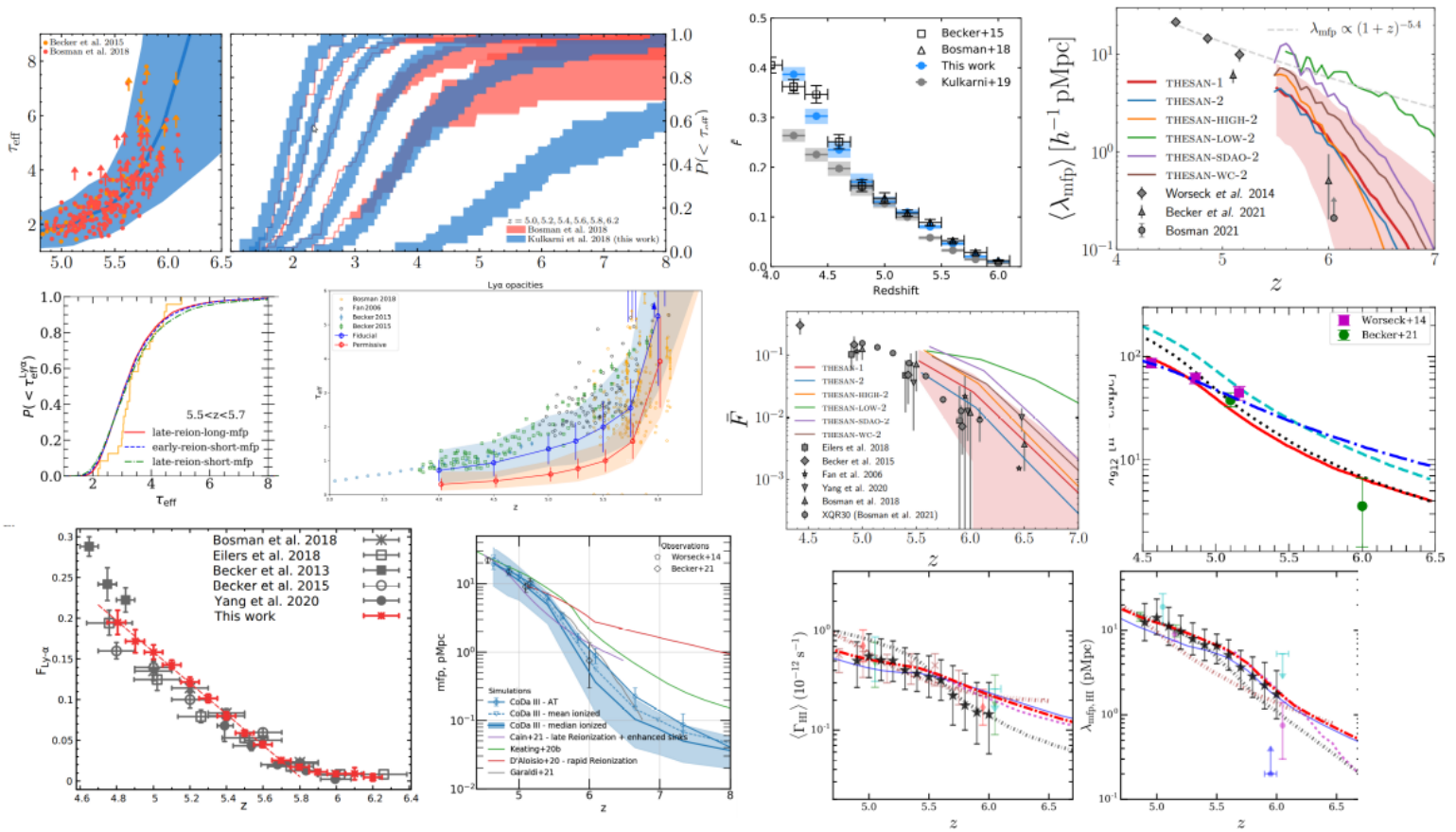
December 6, 2024

Late Reionization ($z_{\rm end} < 6$)

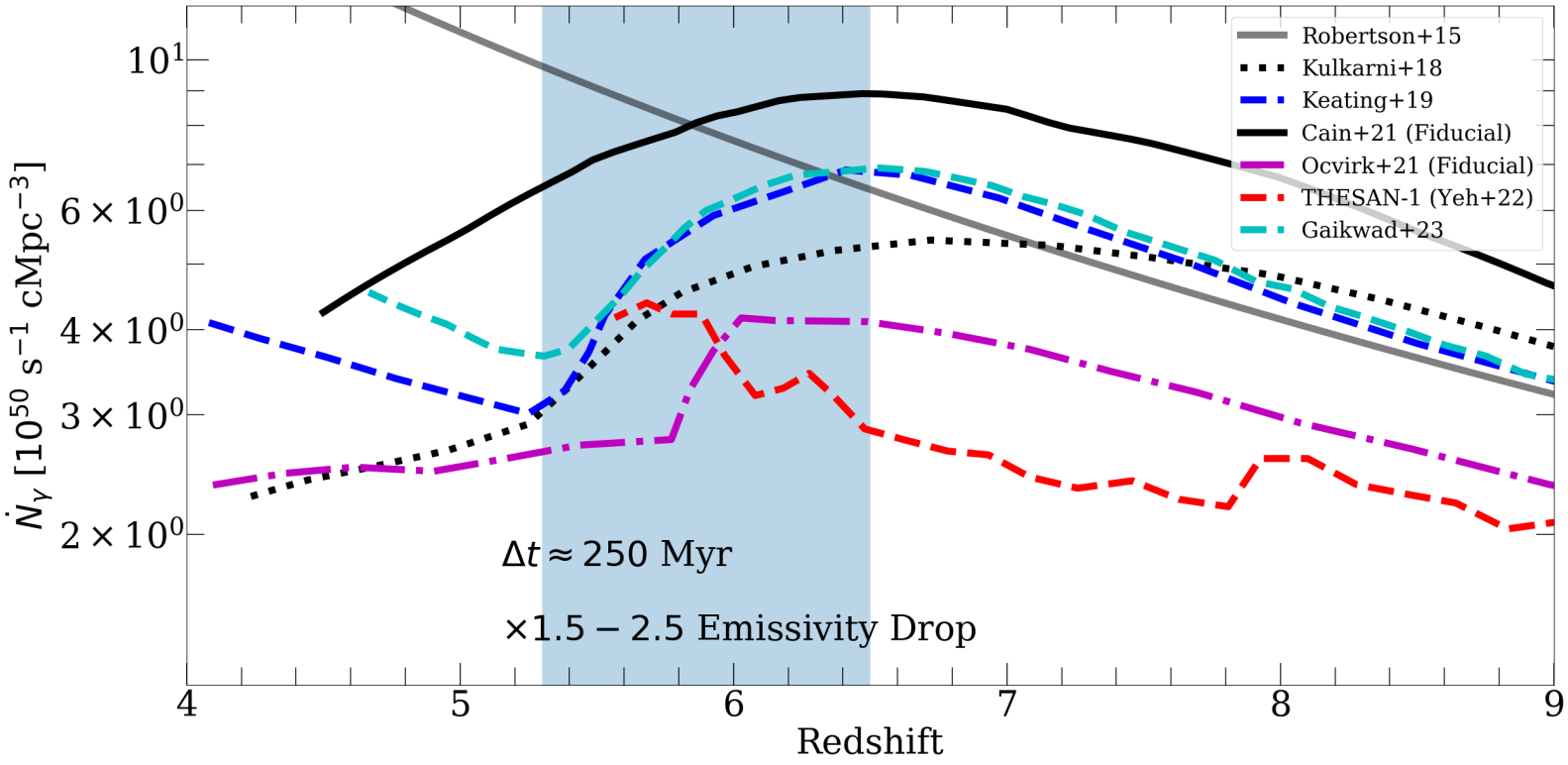
Supported by QSO observations (Lyα forest/mean free path)



Kulkarni+18, Keating+19, Nasir & D'Aloisio+20, Cain+21, Bosman+22, Garaldi+22, Lewis+22, Gaikwad+23

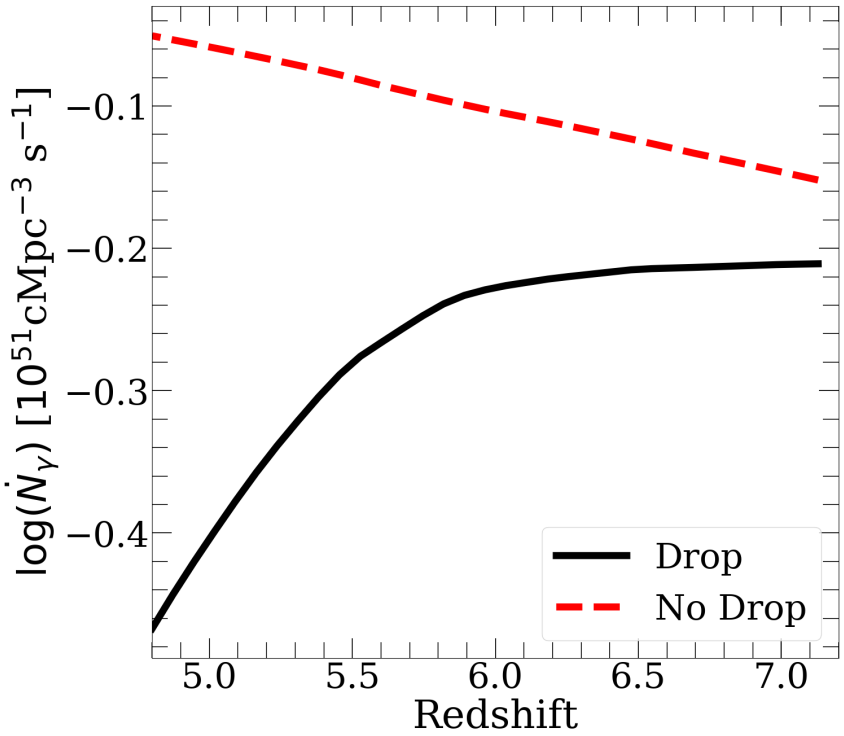
A Puzzling Detail

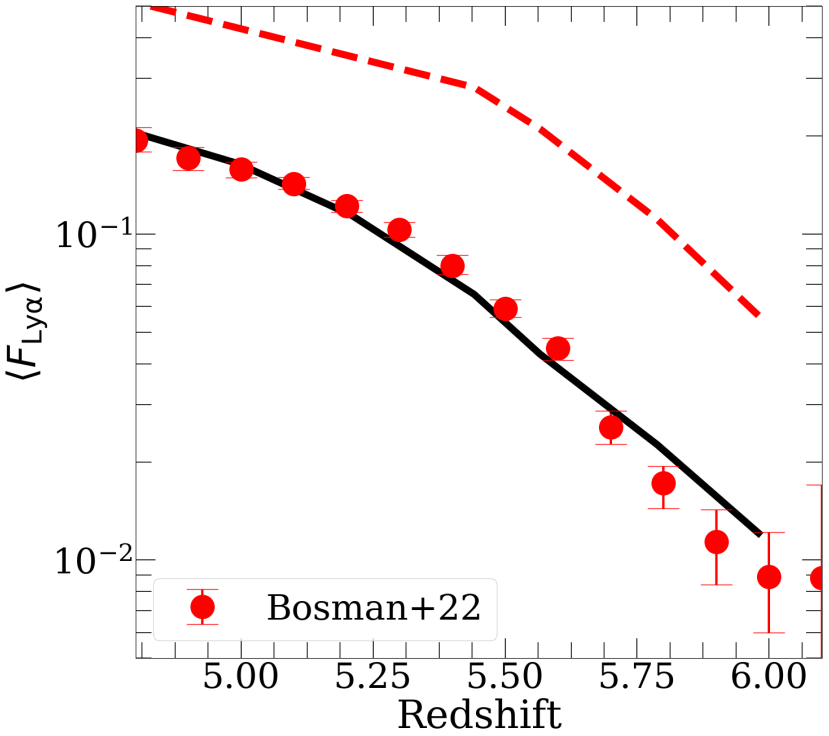
- A quick drop in ionizing emissivity at the end of reionization
- Seen often in simulations that reproduce QSO observations



Why is the drop needed?

- Without it, models tend to overshoot the $5 < z < 6$ forest





Some Possible Explanations

- Evolving escape fraction (Haardt & Madau 2012)
- Evolving ionizing efficiency
- Feedback-driven SFR suppression (Ocvirk+21)

What could we be missing in the IGM?

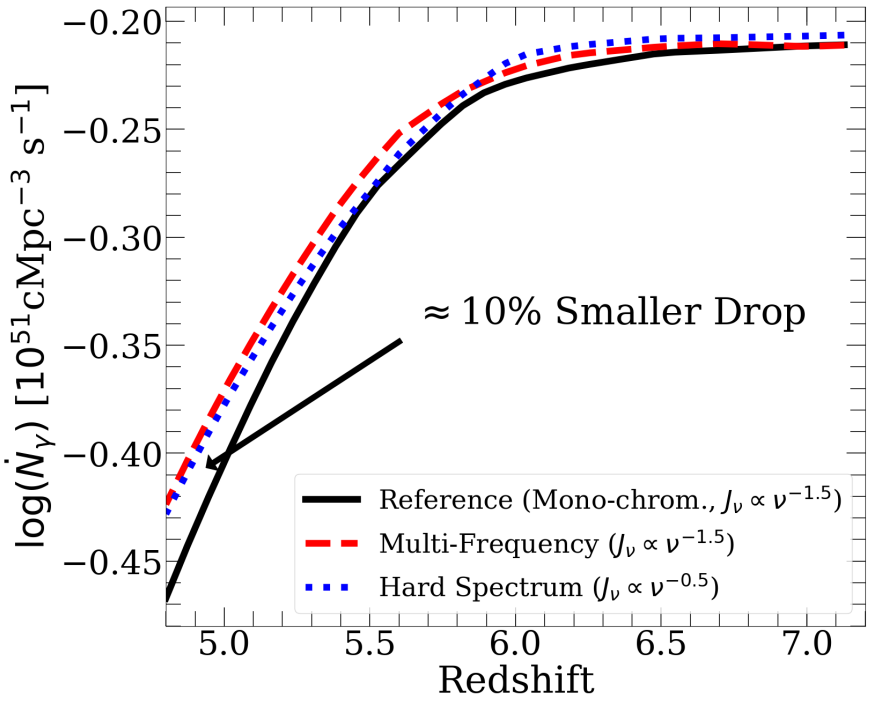
- Thermal history of the IGM? (Keating+19)
- Missing spatial resolution? (un-resolved sinks)
- Rare, massive sinks? (Munoz+15, Cain+21)
- Something else?

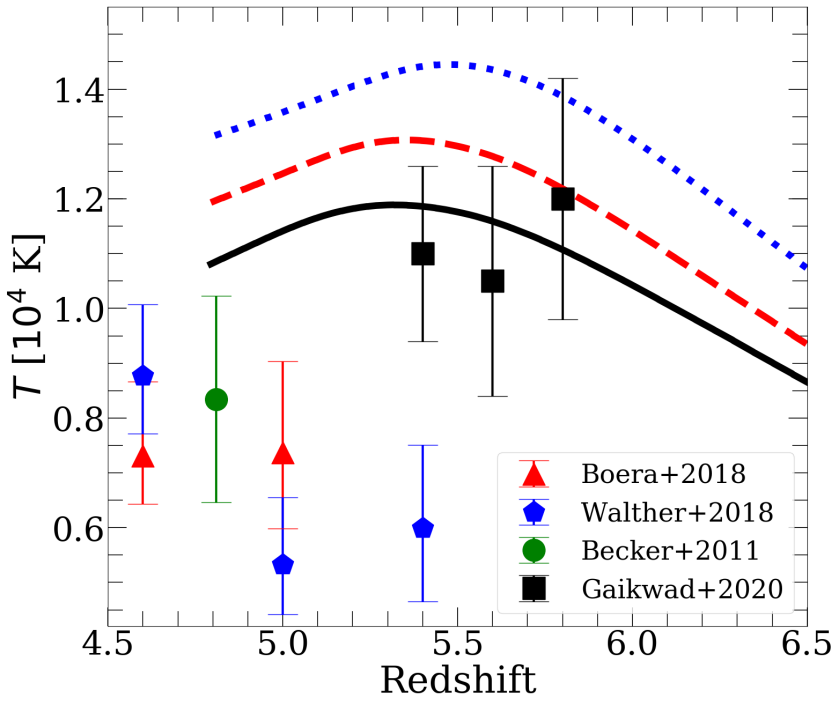
Numerical Methods

- Ionizing RT on coarse-grained density fields ($N_{\rm RT} = 200^3$)
- Subgrid opacity model based on high-res hydro/RT sims
- Key upgrades: multi-frequency RT, recombination radiation, improvements to the subgrid model
- Lyα forest statistics calculated on $N = 2048^3$ (200 h^{-1}Mpc) density field + resolution correction

Ionizing Spectrum (for fixed mean forest flux vs. z)

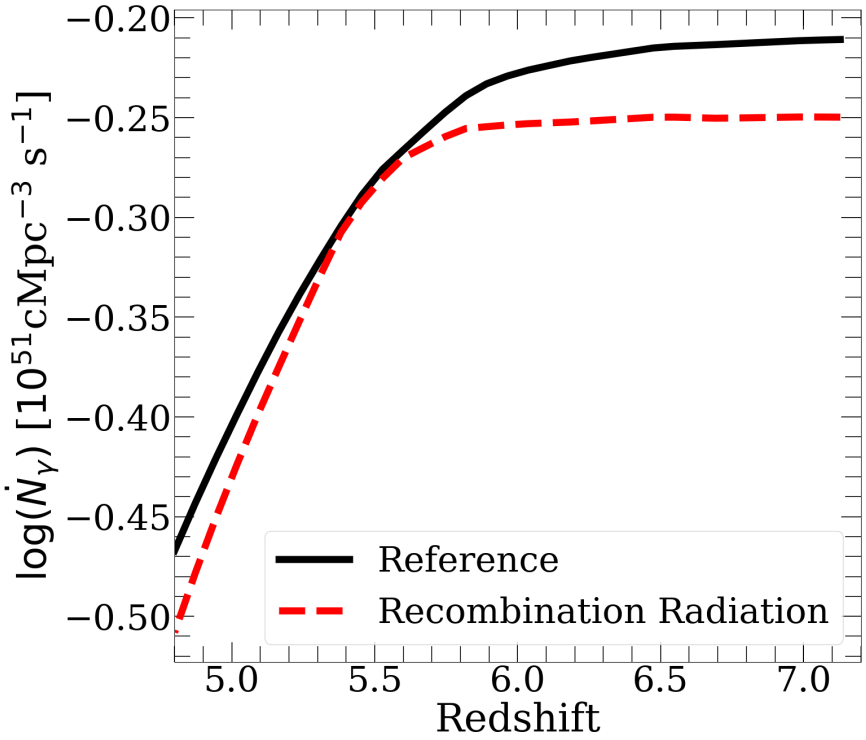
- Harder ionizing spectra lower $\Gamma_{\rm HI}$ but raise T
- Small effect on $\dot{N}_\gamma$ drop, limited by T measurements

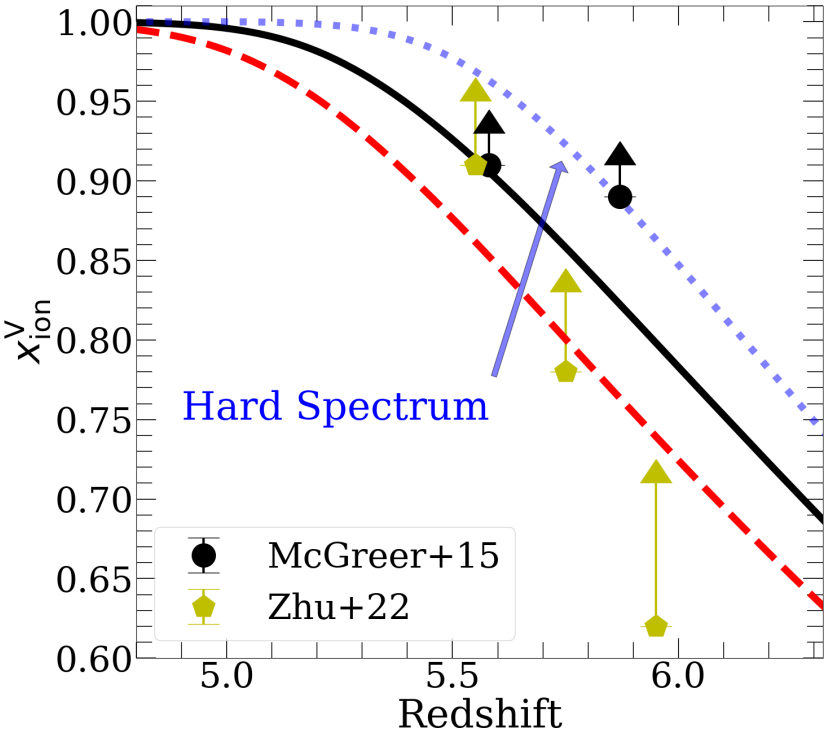




Recombination Radiation (for fixed mean forest flux vs. z)

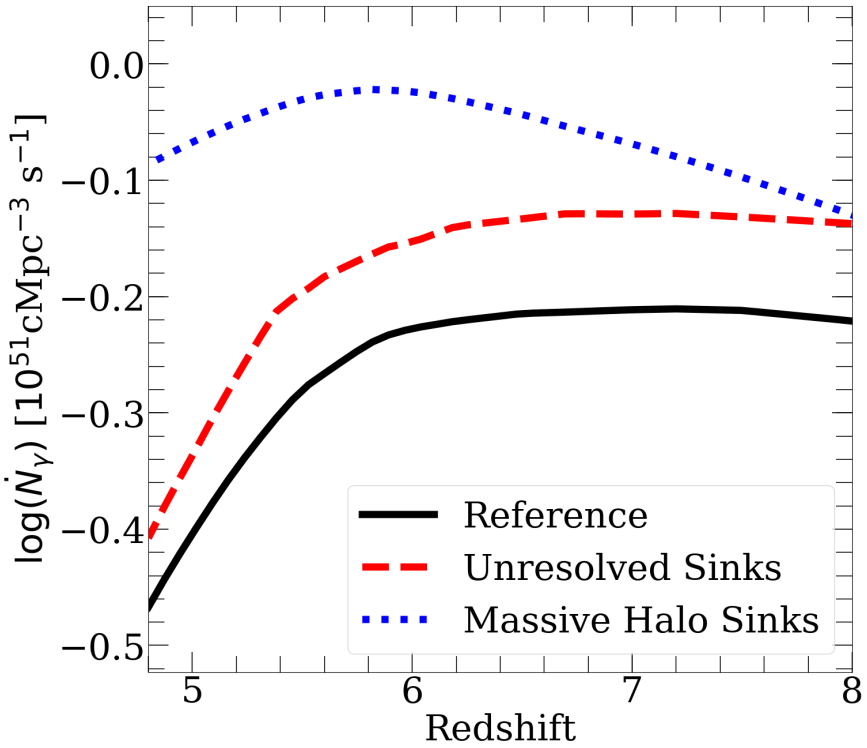
- Recombination radiation makes ionizing spectrum softer
- No improvement to $\dot{N}_\gamma$ drop + later end to reionization

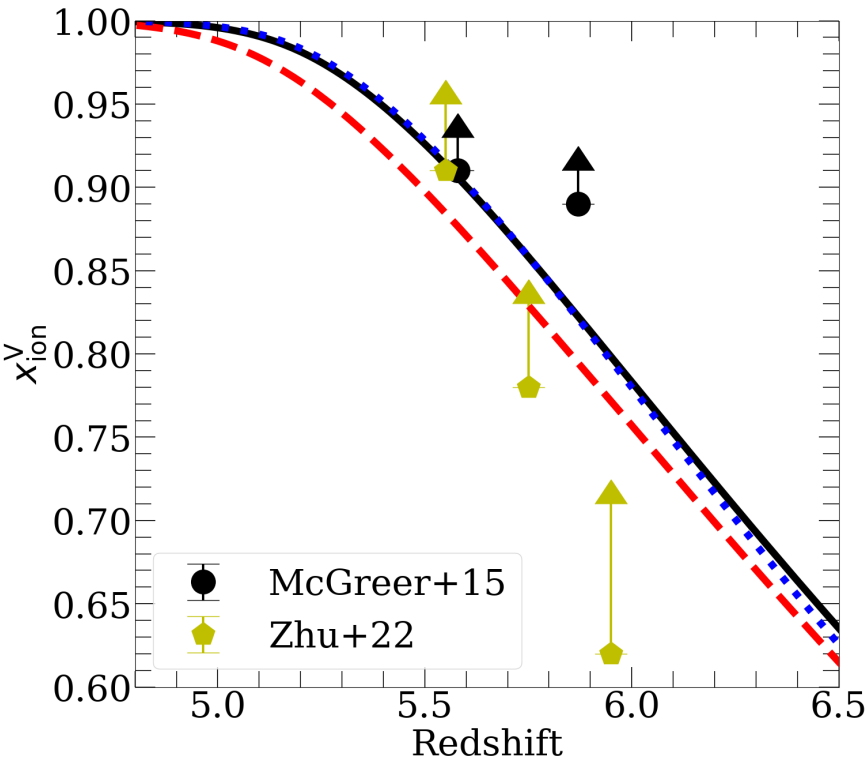




Missing Sinks (for fixed mean forest flux vs. z)

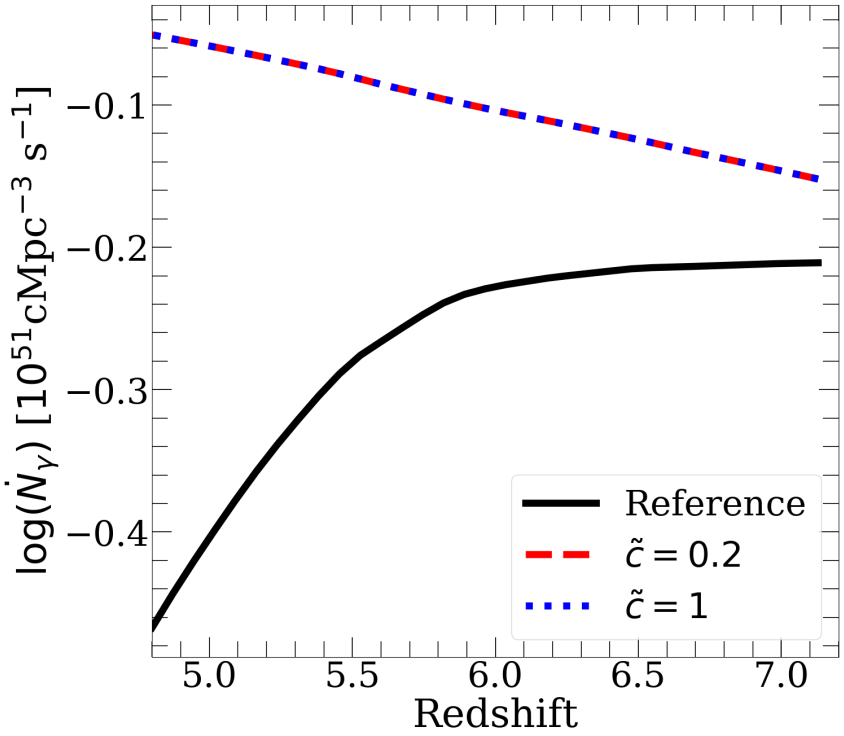
- Un-resolved sinks push reionization later & increases $\dot{N}_\gamma$ drop
- Extra rare, massive sinks significantly reduce the drop

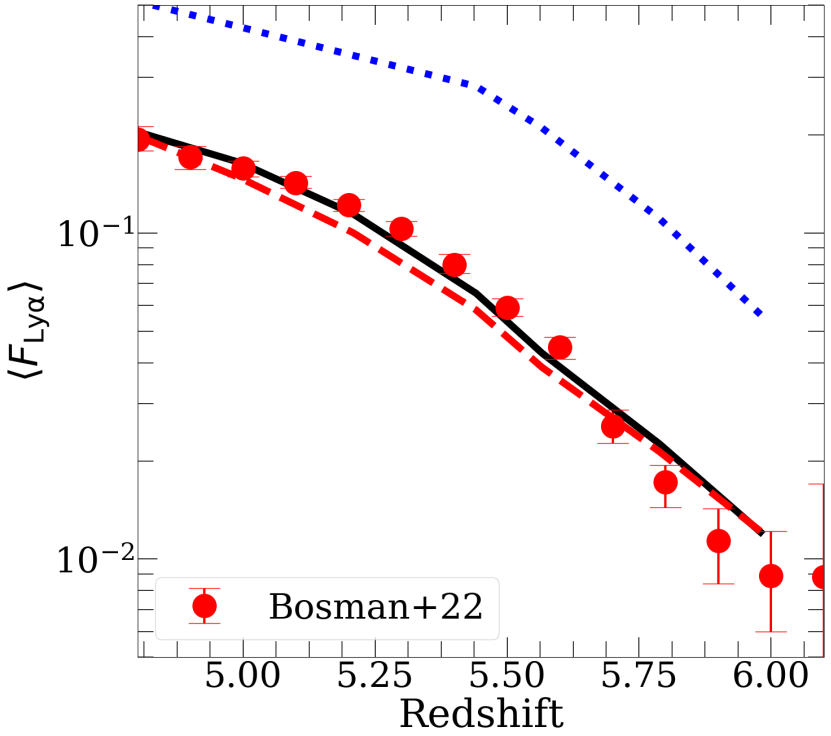




The Speed of Light (a cautionary tale)

- Using the RSL approximation eliminates the need for a drop
- The correct speed of light is crucial for the $\dot{N}_\gamma$-forest relationship





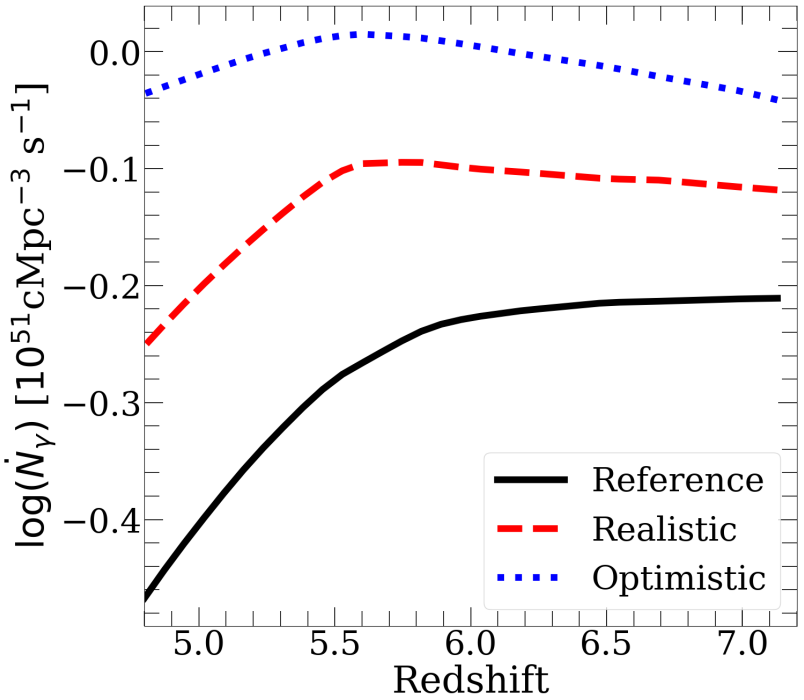
Taking Stock...

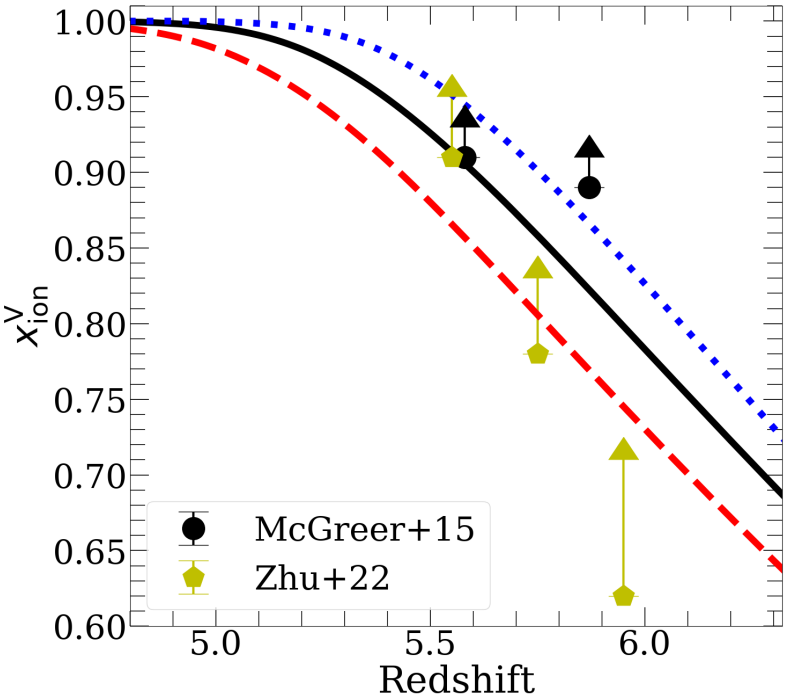
Various effects work in different directions

Physical Effect	Emissivity Drop	End of Reionization
Harder ionizing spectrum	small change	earlier
Recombination radiation	small change	later
Missing small sinks	steeper	later
Missing massive sinks	shallower	small change

Realistic & Optimistic Scenarios

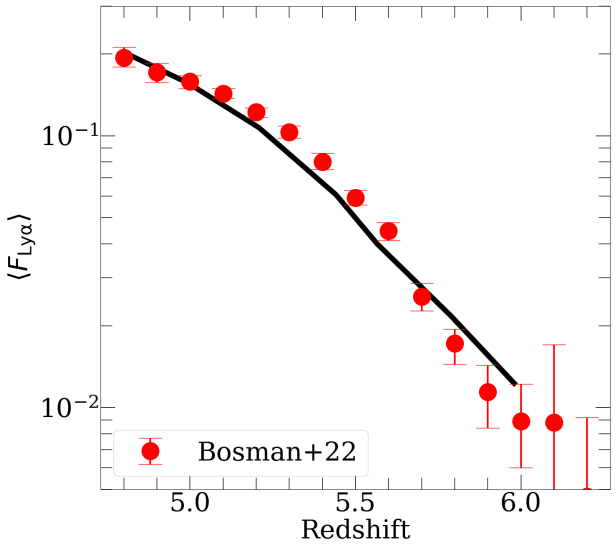
- Only our most optimistic scenario requires (almost) no drop in $\dot{N}_\gamma$ (hard spectra + rare sinks)
- Realistic models that include all effects suggest some evolution of source properties at the end of reionization

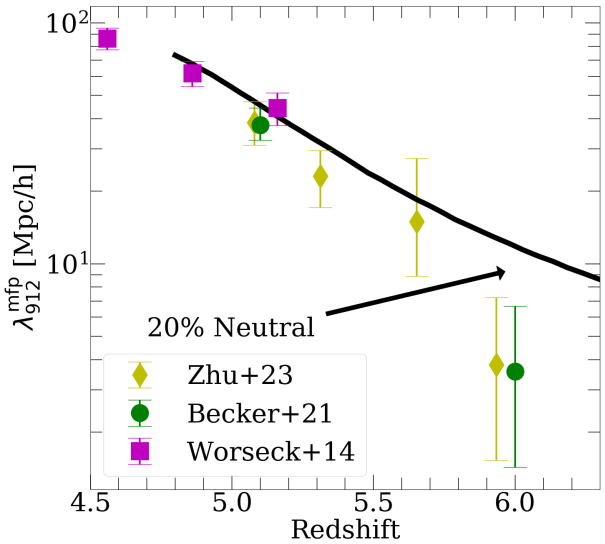




Neutral islands & Short QSO lifetimes: implications for direct MFP measurements

- High-redshift QSO spectra may contain neutral islands
- Requires QSO lifetimes to be short enough





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Neutral islands & Short QSO lifetimes: implications for direct MFP measurements

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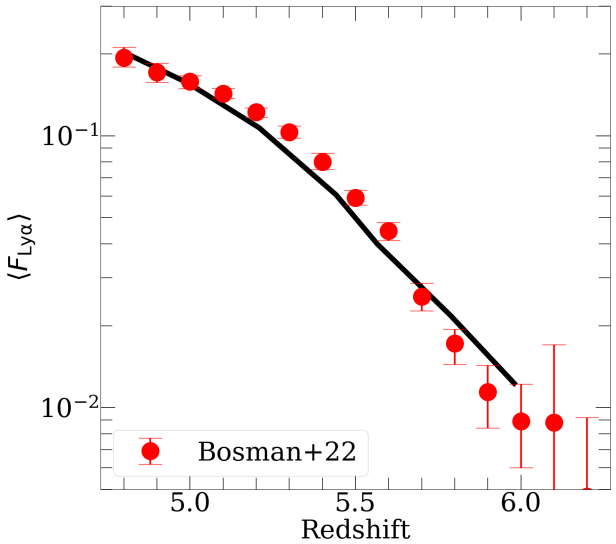

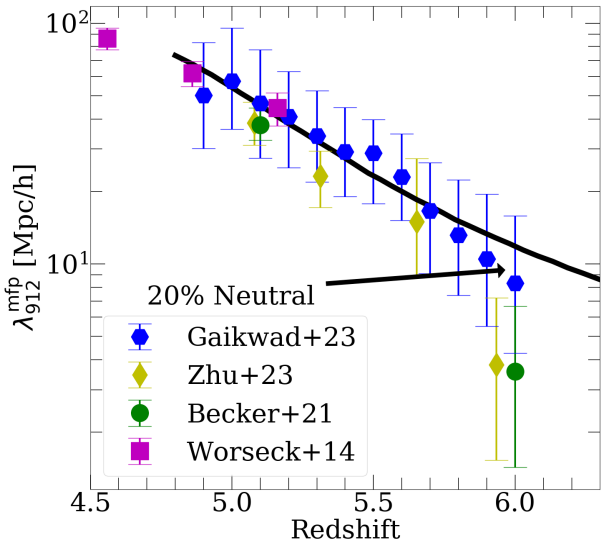

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Highlights (Preliminary!)

- 1D RT simulation of QSO spectra with neutral islands
- Neutral islands can bias the measured MFP low
- The effect is sensitive to QSO lifetimes & environments

Check the arxiv soon!

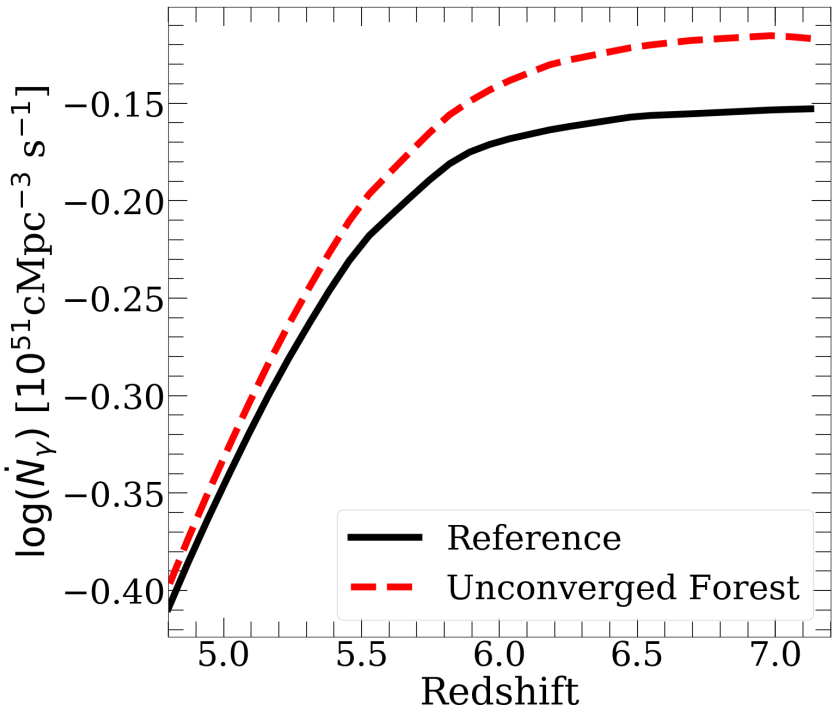
Summary

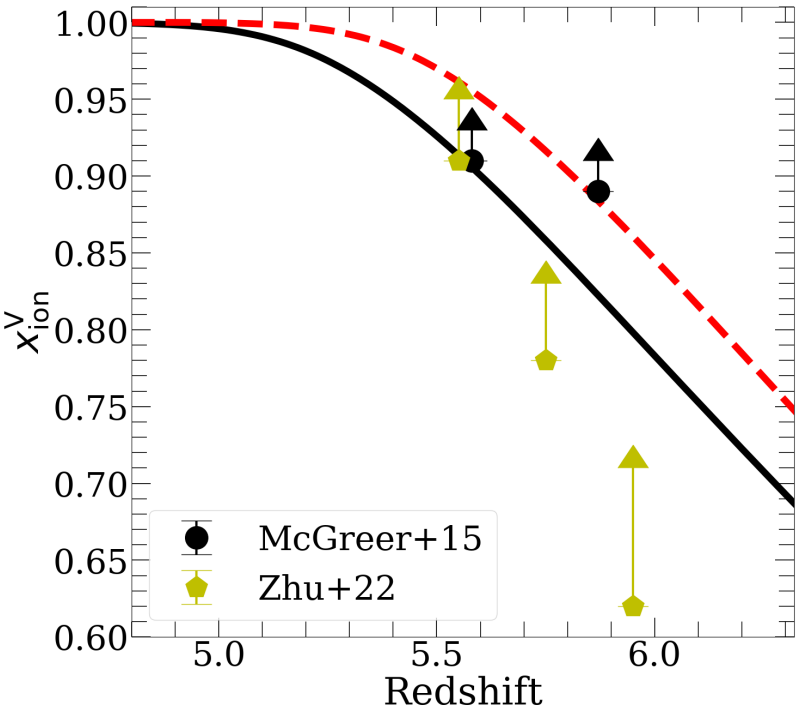
- Properties of the IGM affect the required emissivity evolution to reproduce Lyα forest observations
- Most promising IGM solution to the $\dot{N}_\gamma$ drop: sinks in massive halos regulate UVB (Munoz+15, Cain+21)
- Realistic models require some evolution in source properties
- Neutral islands in QSO spectra at $z > 5$ might bias direct measurements of the MFP low

Backup Slides

Convergence of the Lyα Forest

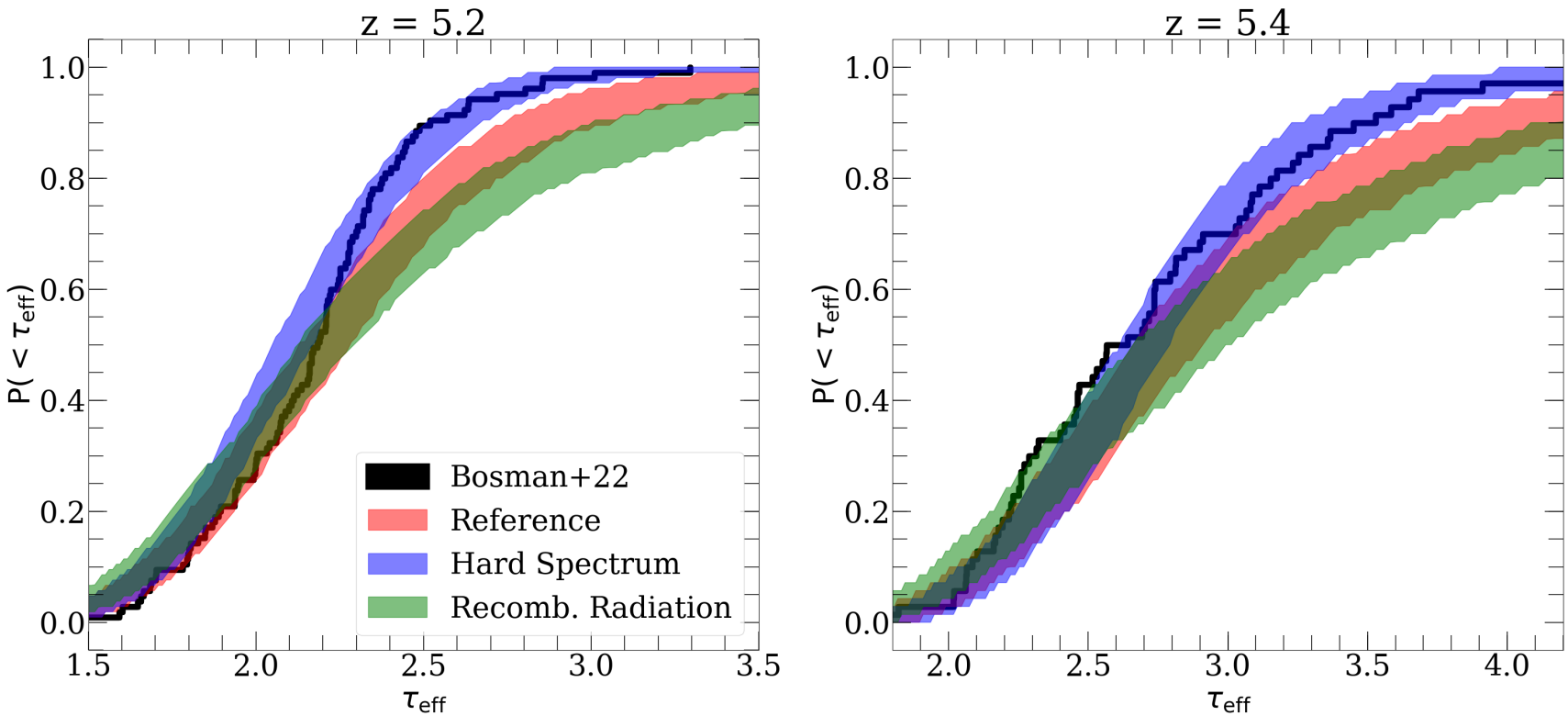
- Drop in $\dot{N}_\gamma$ is slightly steeper
- Reionization ends slightly sooner without missing the forest





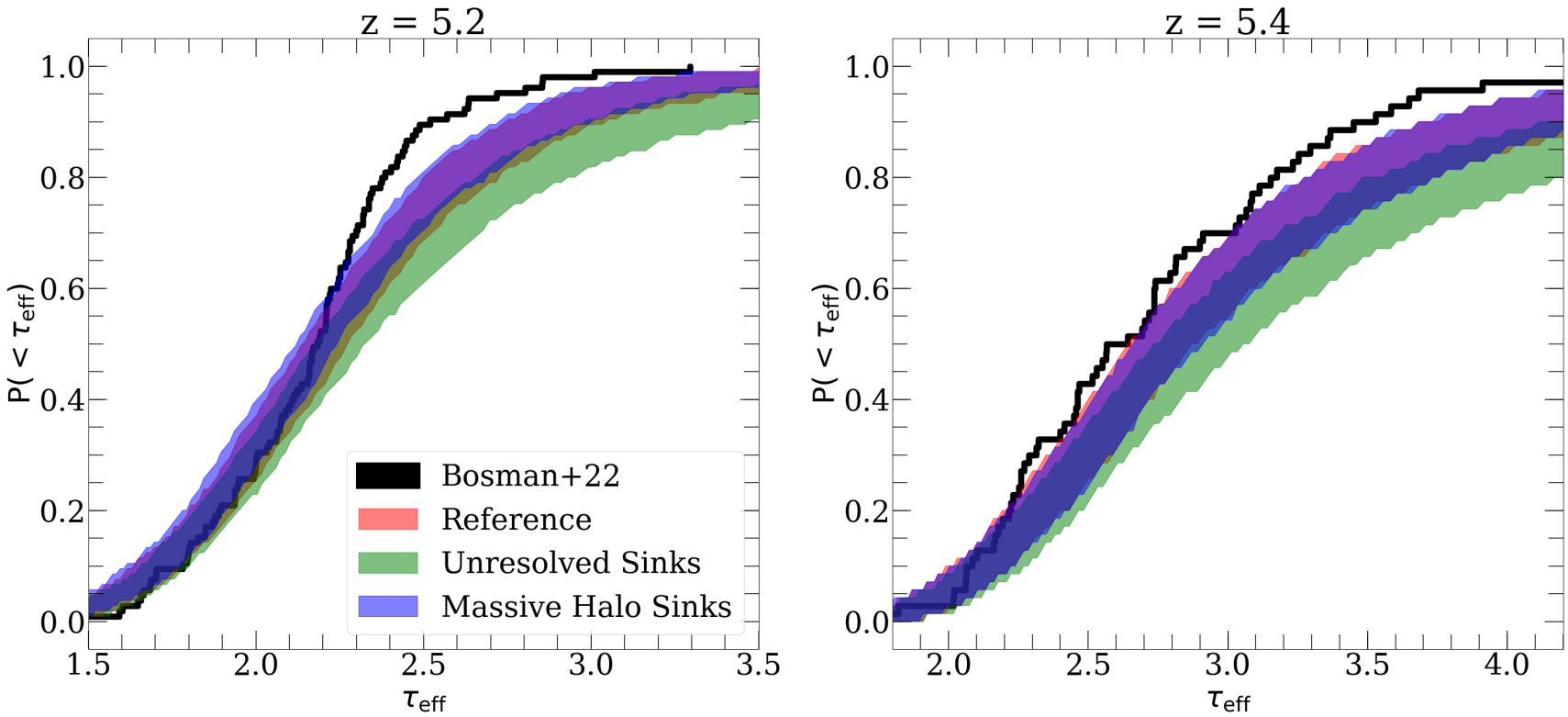
$\tau_{\rm eff}$ fluctuations: Ionizing Spectrum/Recombination Radiation

- Earlier reionization history $\rightarrow$ better agreement with $\tau_{\rm eff}$ fluctuations



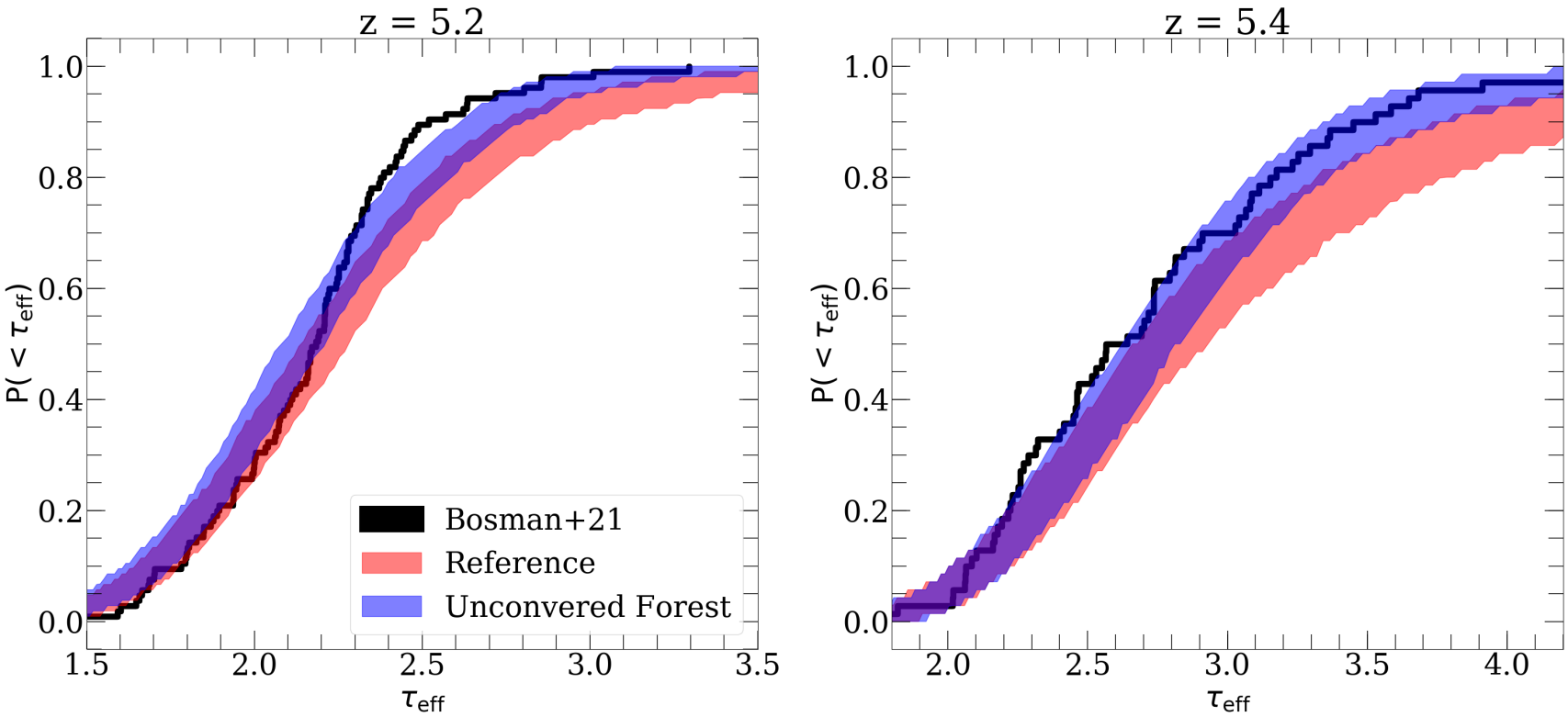
$\tau_{\rm eff}$ fluctuations: Missing Sinks

- Later reionization history in the model with added small-scale sinks produces worse agreement



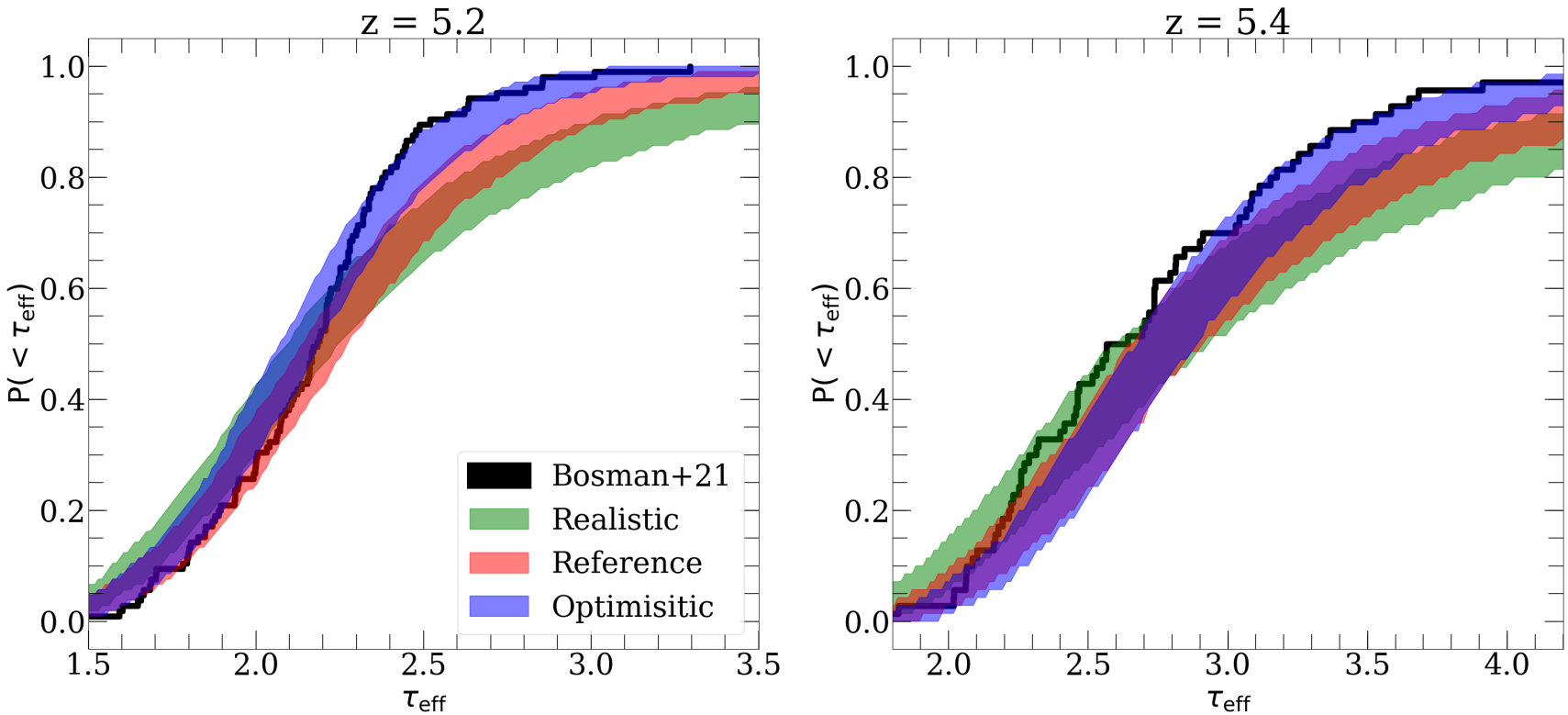
$\tau_{\rm eff}$ fluctuations: Lyα forest convergence

- Less converged forest $\rightarrow$ earlier reionization history $\rightarrow$ spuriously better agreement



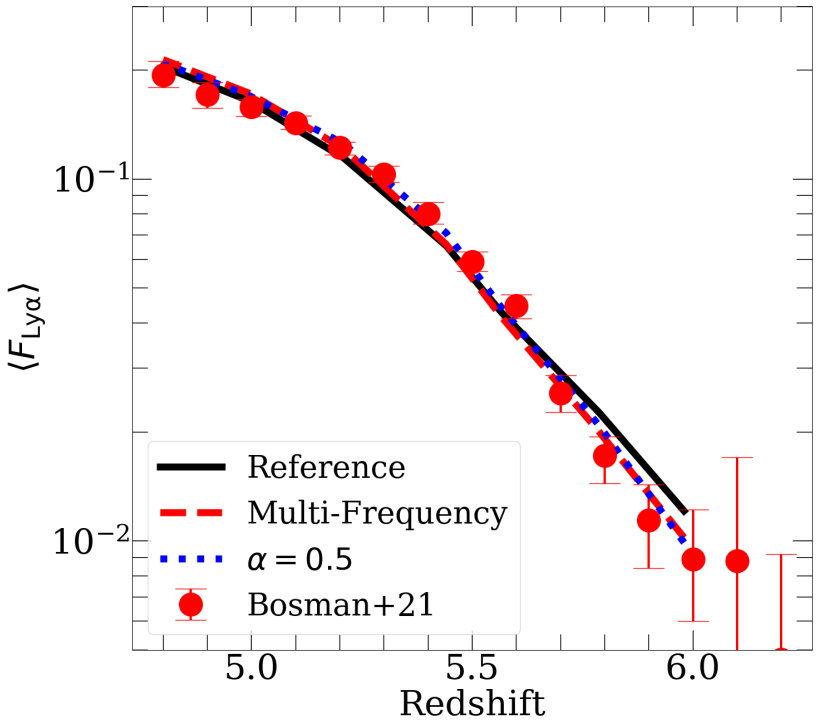
$\tau_{\rm eff}$ fluctuations: Realistic & Optimistic Scenarios

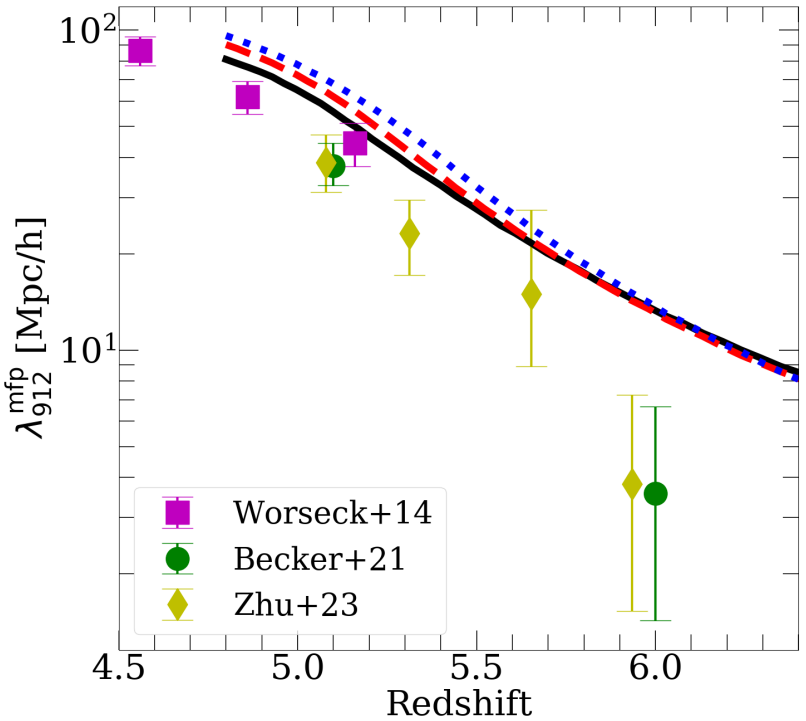
- Optimistic (Realistic) models agree better (worse) due to earlier (later) reionization histories



Forest transmission/MFP: Ionizing Spectrum

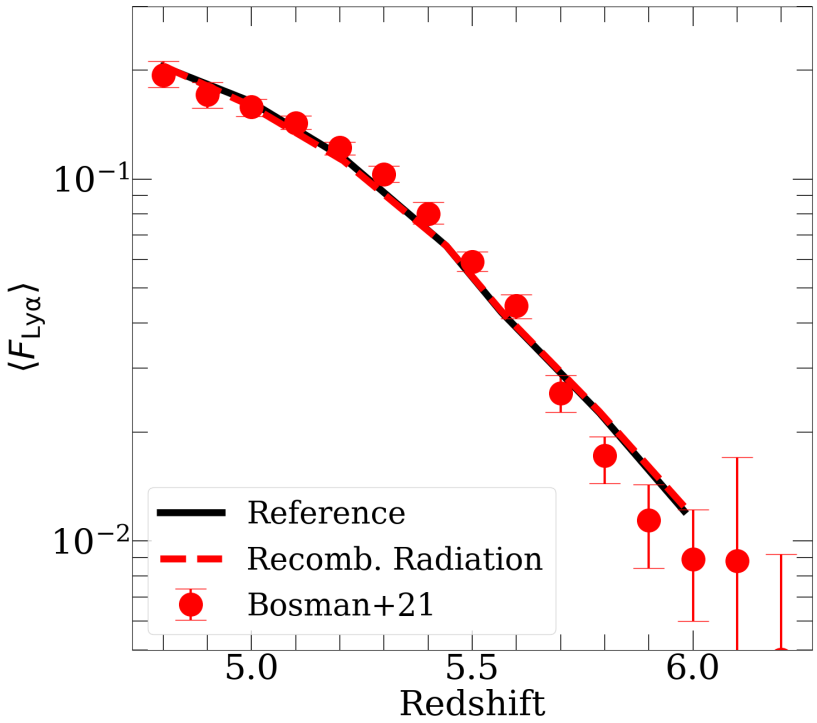
- Harder spectra produce slightly worse agreement with MFP measurements

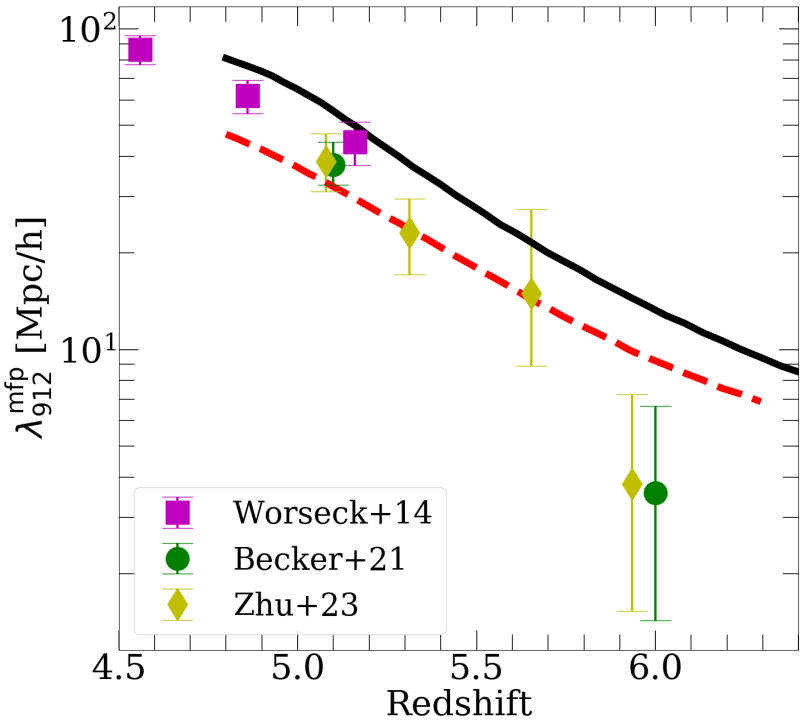




Forest transmission/MFP: Recombination Radiation

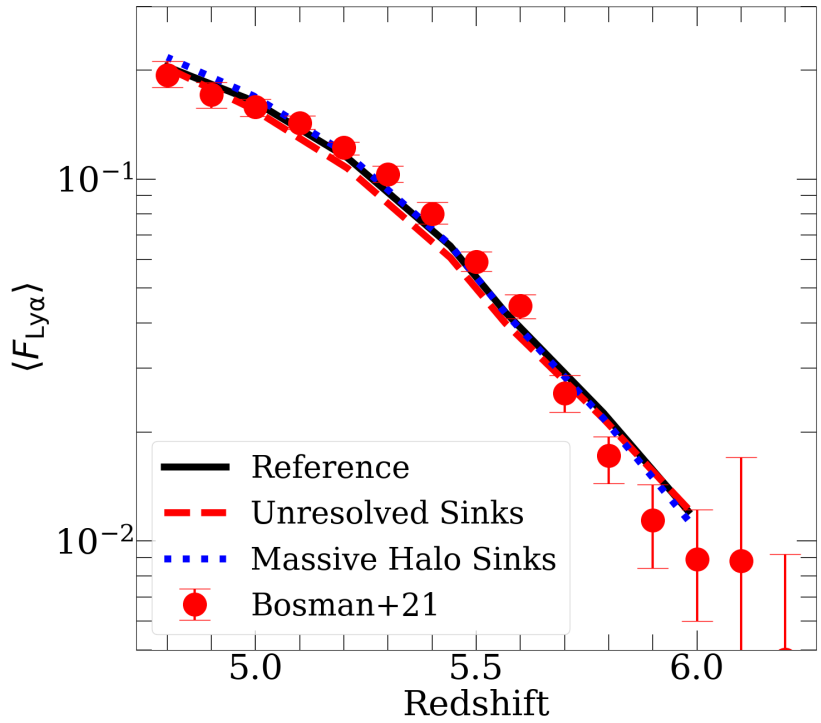
- Recombination radiation shortens the MFP significantly if most of it escapes the dense clumps that produce it

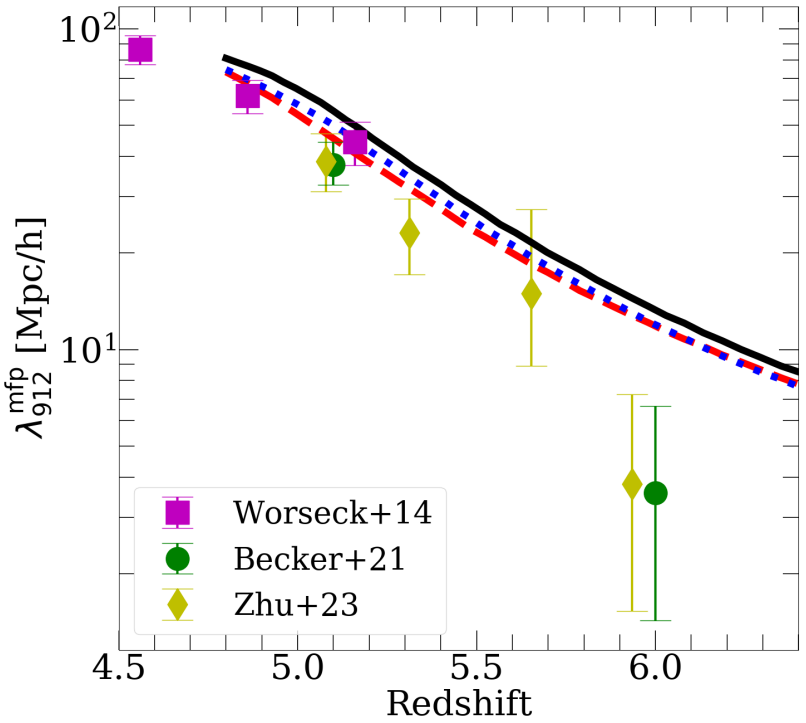




Forest transmission/MFP: Missing Sinks

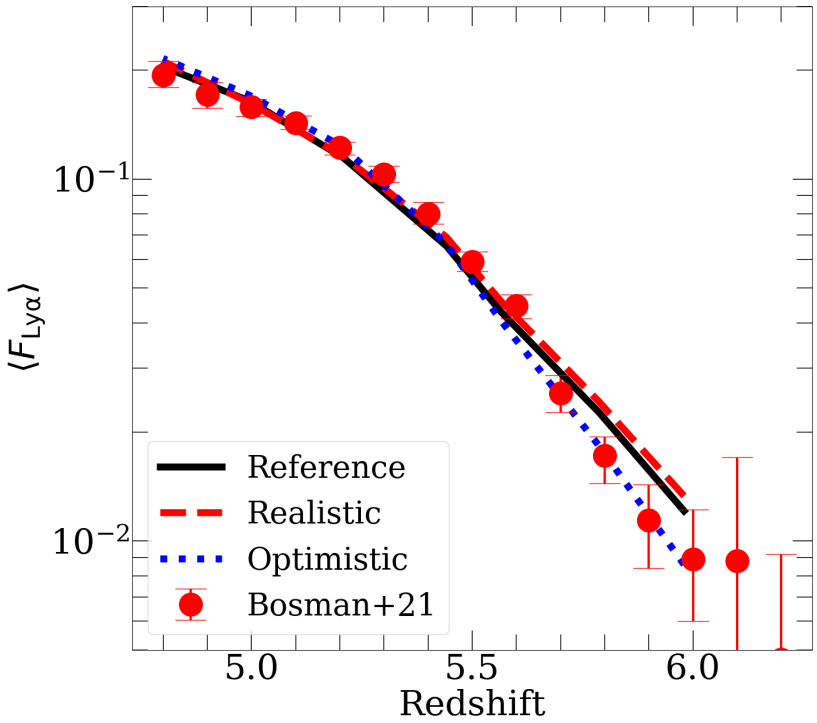
- Both models with extra sinks produce slightly better agreement with MFP measurements, but still miss $z = 6$

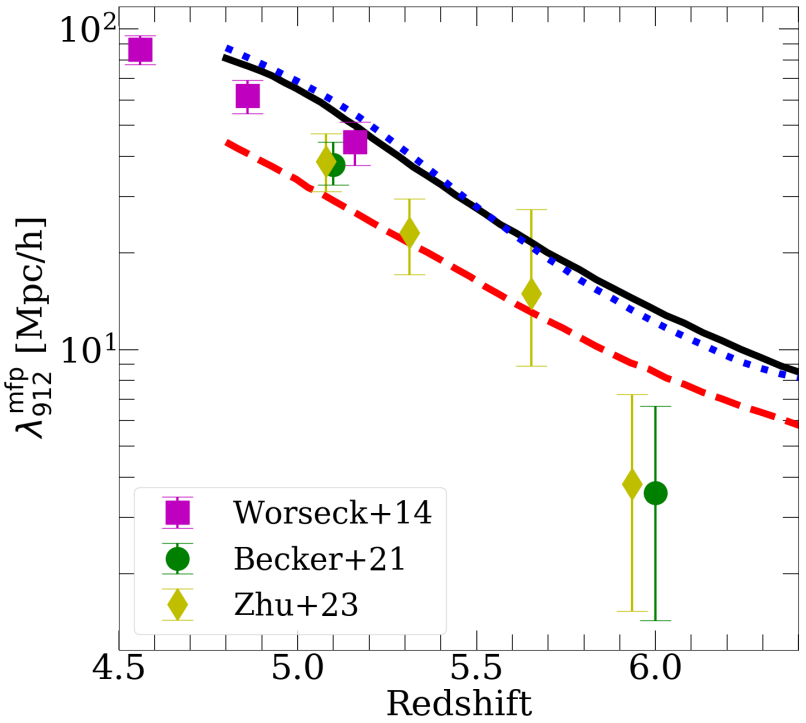




Forest transmission/MFP: Optimistic & Realistic Models

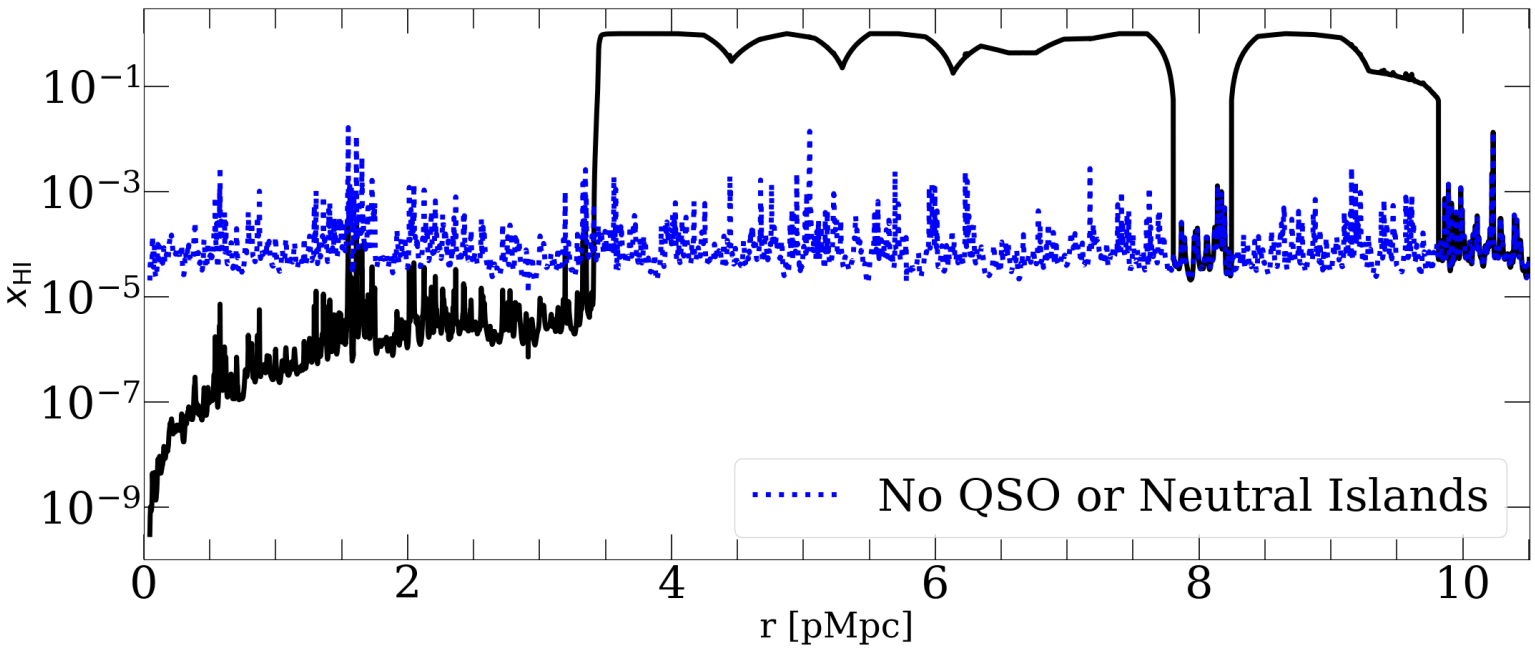
- Reference and Optimistic models have slightly high MFP, Realistic has slightly low





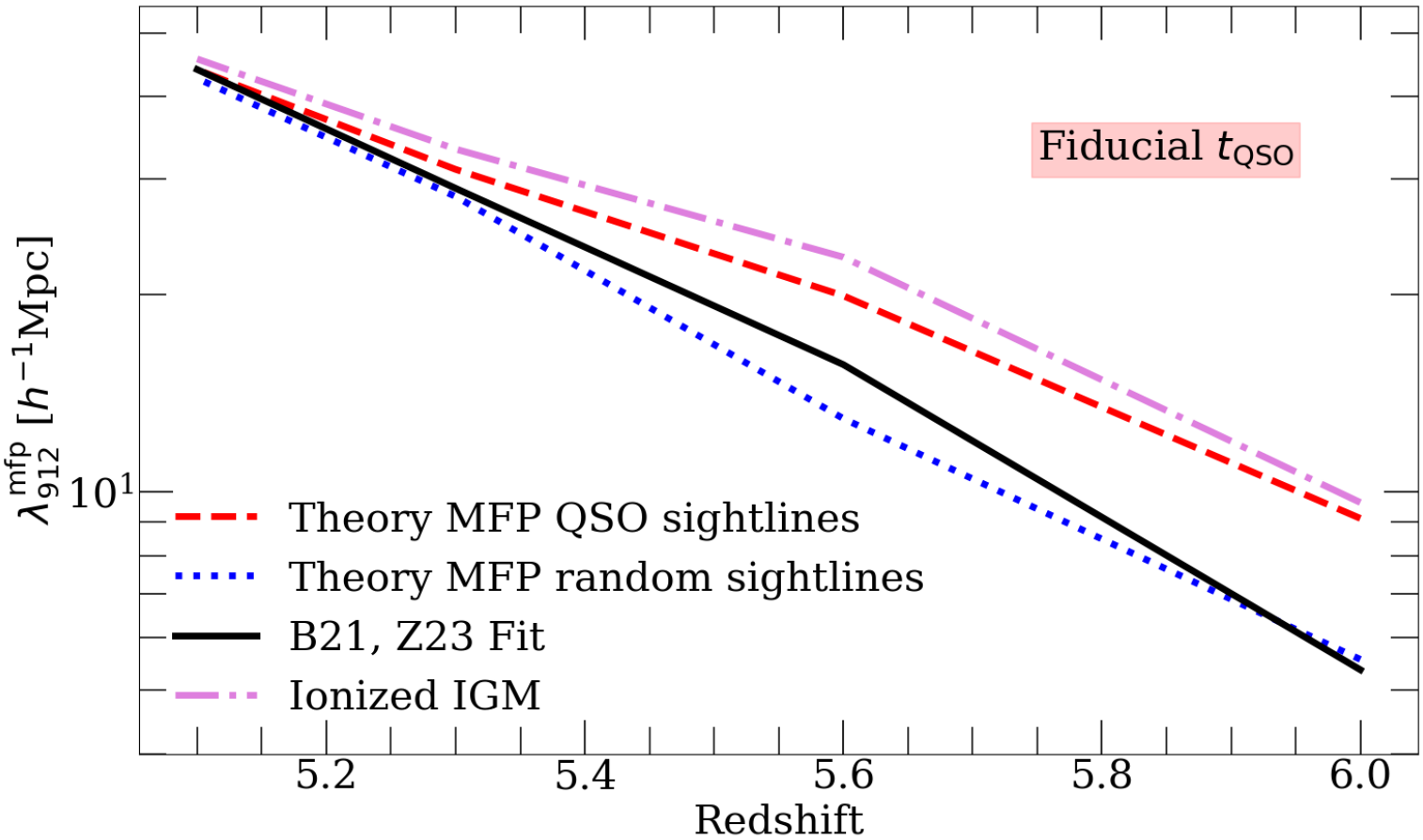
Methods

- 1D RT on sightlines taken from a hydro simulation
- Neutral islands extracted from 3D RT simulations
- We require the Becker 2021 method to recover the correct MFP without neutral islands (by choosing ξ)



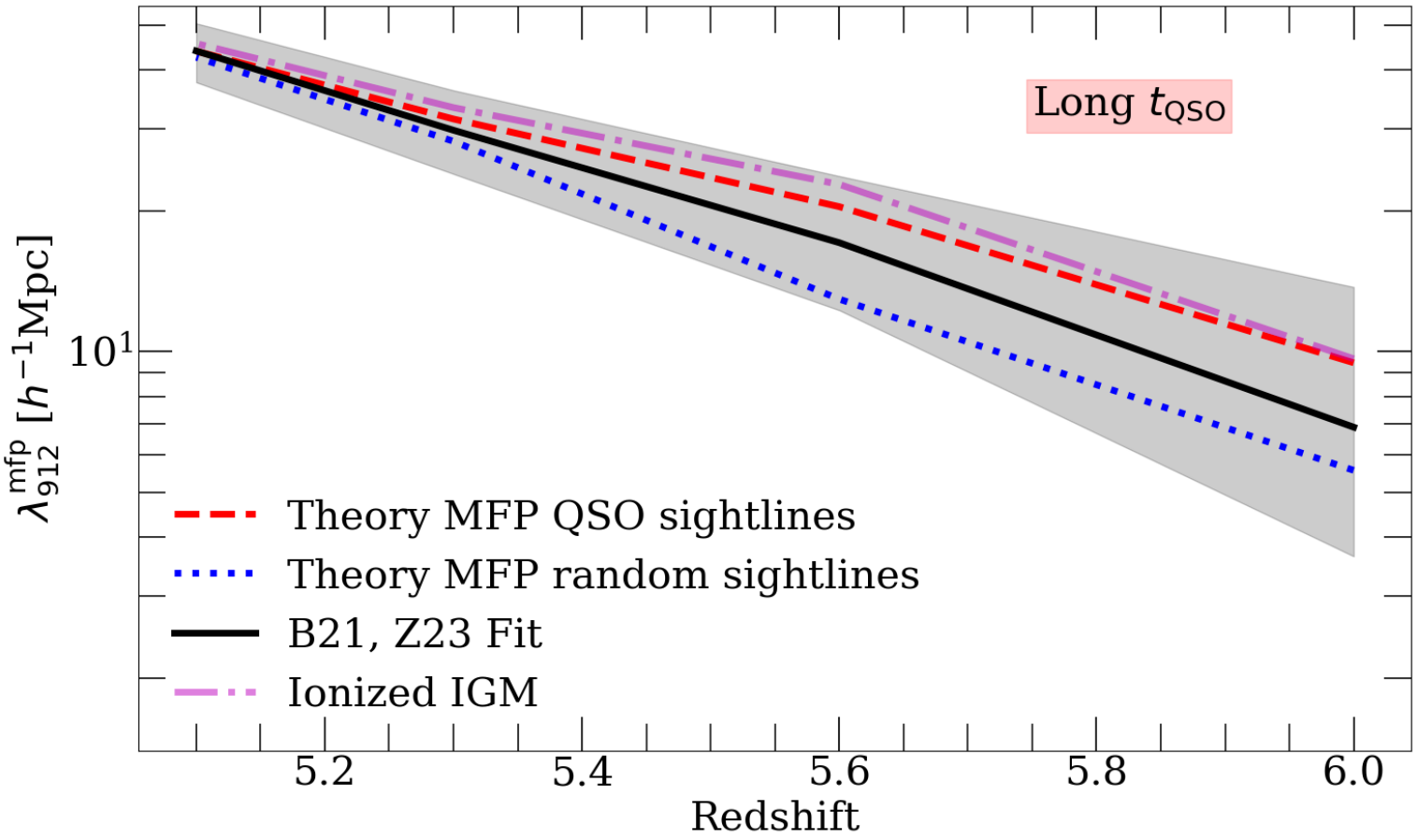
Fiducial Model

- The fit with neutral islands in the spectra agrees remarkably well with the unbiased MFP!



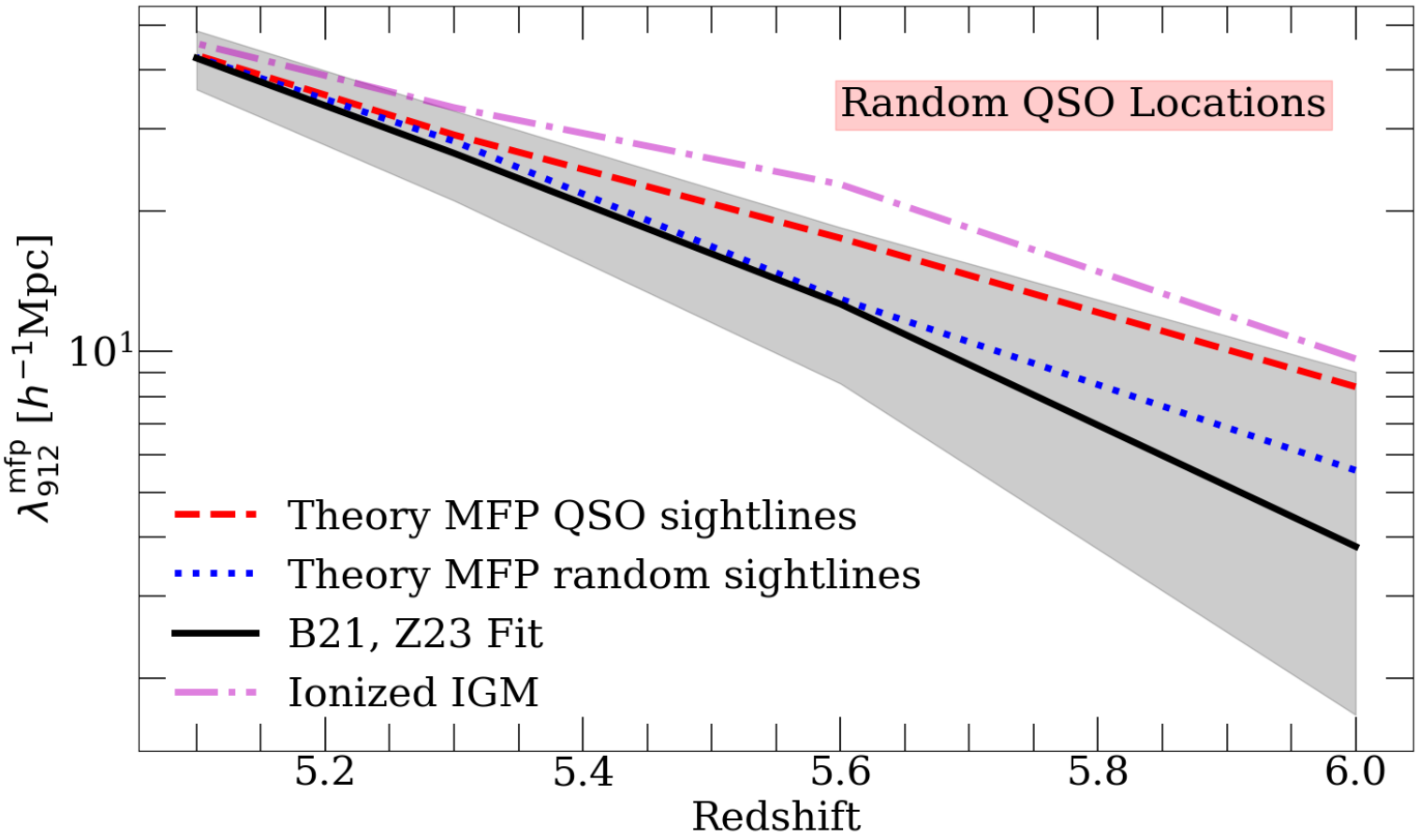
Long $t_{\rm QSO}$ Model

- Longer QSO lifetimes reduces the MFP bias effect



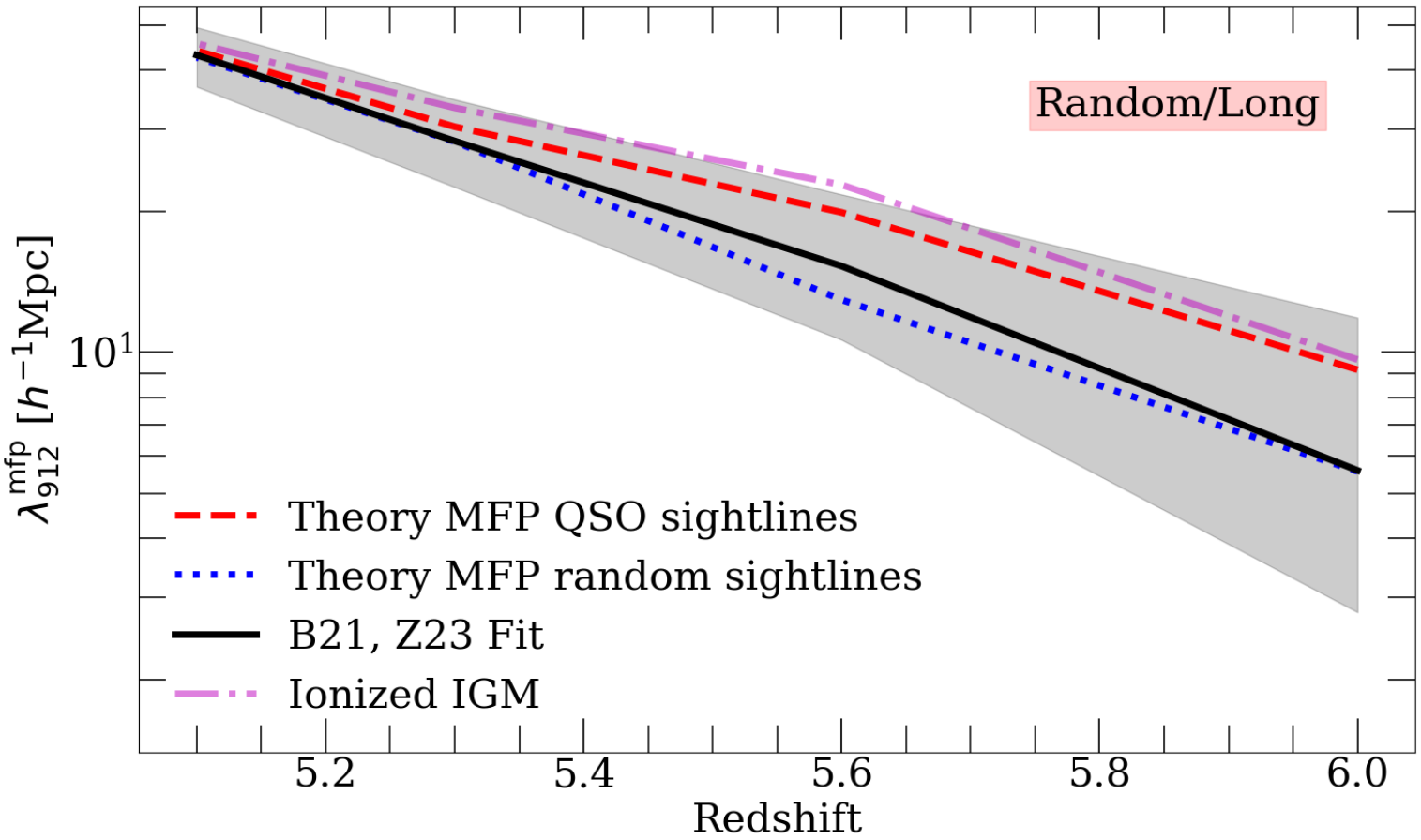
Random QSO Model

- Placing the QSOs randomly instead of in massive halos increases the bias



Random/Long Model

- Doing both gives results similar to the fiducial case



$\Gamma_{\rm HI}$ Dependence

- Agreement holds across a wide range of IGM $\Gamma_{\rm HI}$