Quasar Proximity Zones in a Partially Ionised IGM

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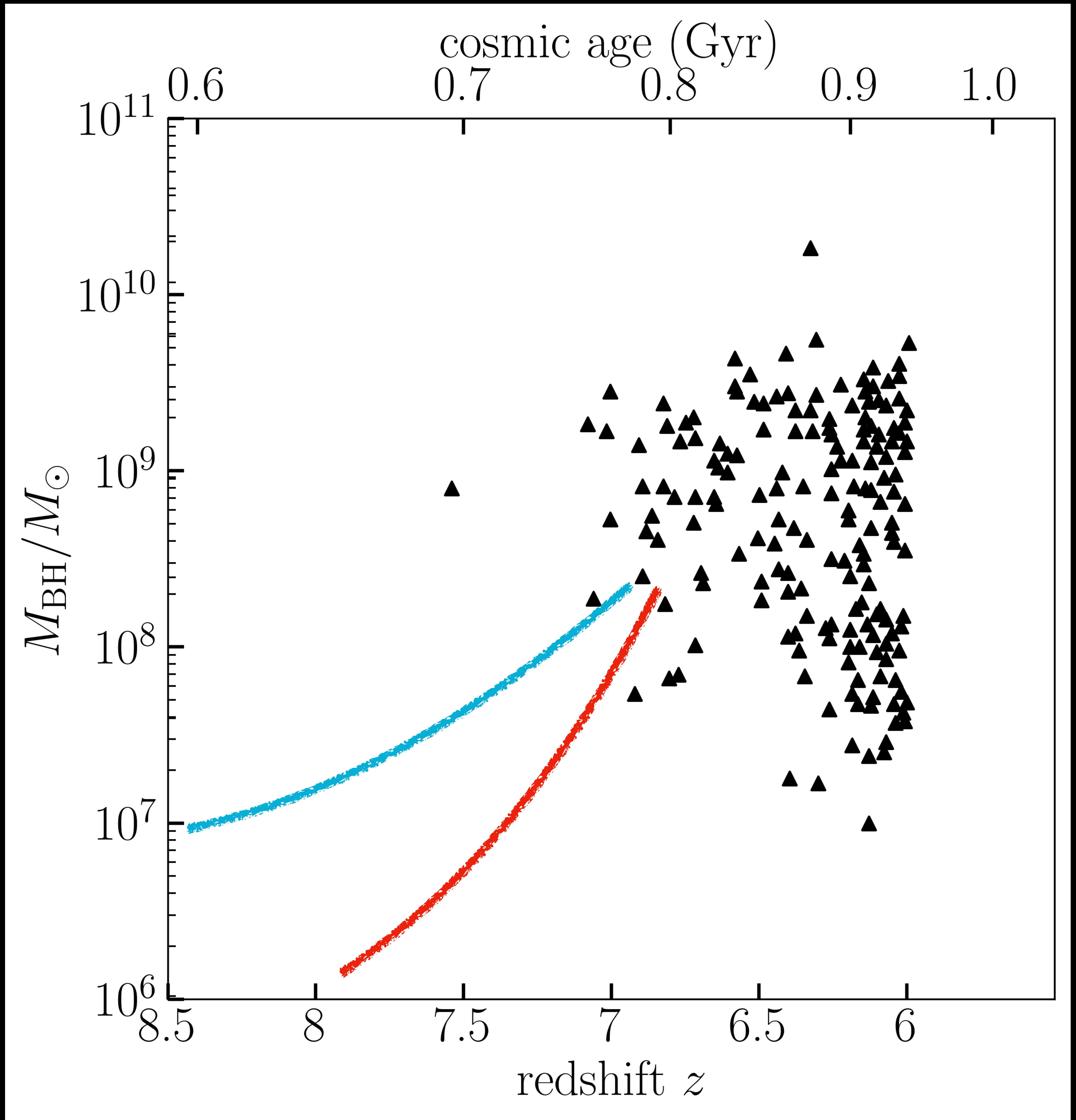
First billion years: intergalactic gas in the Universe was reionized

- The intergalactic medium (IGM), which fills the space between galaxies, is composed of mostly neutral hydrogen (HI), which later became ionized (HII)

- Details of reionization are yet to be understood: How long did it last? What caused it? How did it occur?

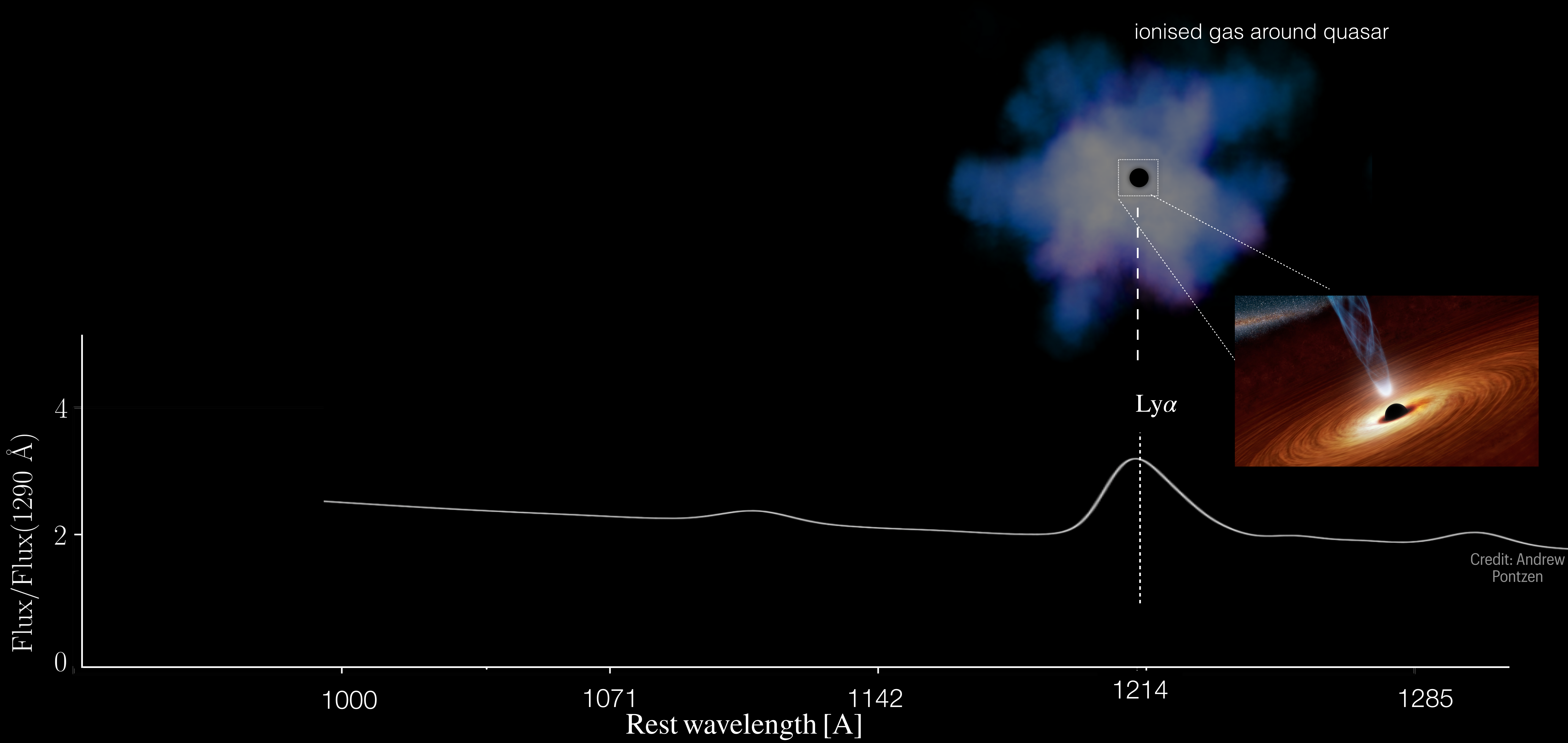
First billion years: too early for Supermassive Black holes?

- Supermassive black holes (SMBHs) are present almost in all massive galaxies today
- However, some of the most massive SMBHs have been found to already exist at $z \sim 6$
- How did these SMBHs form so early?

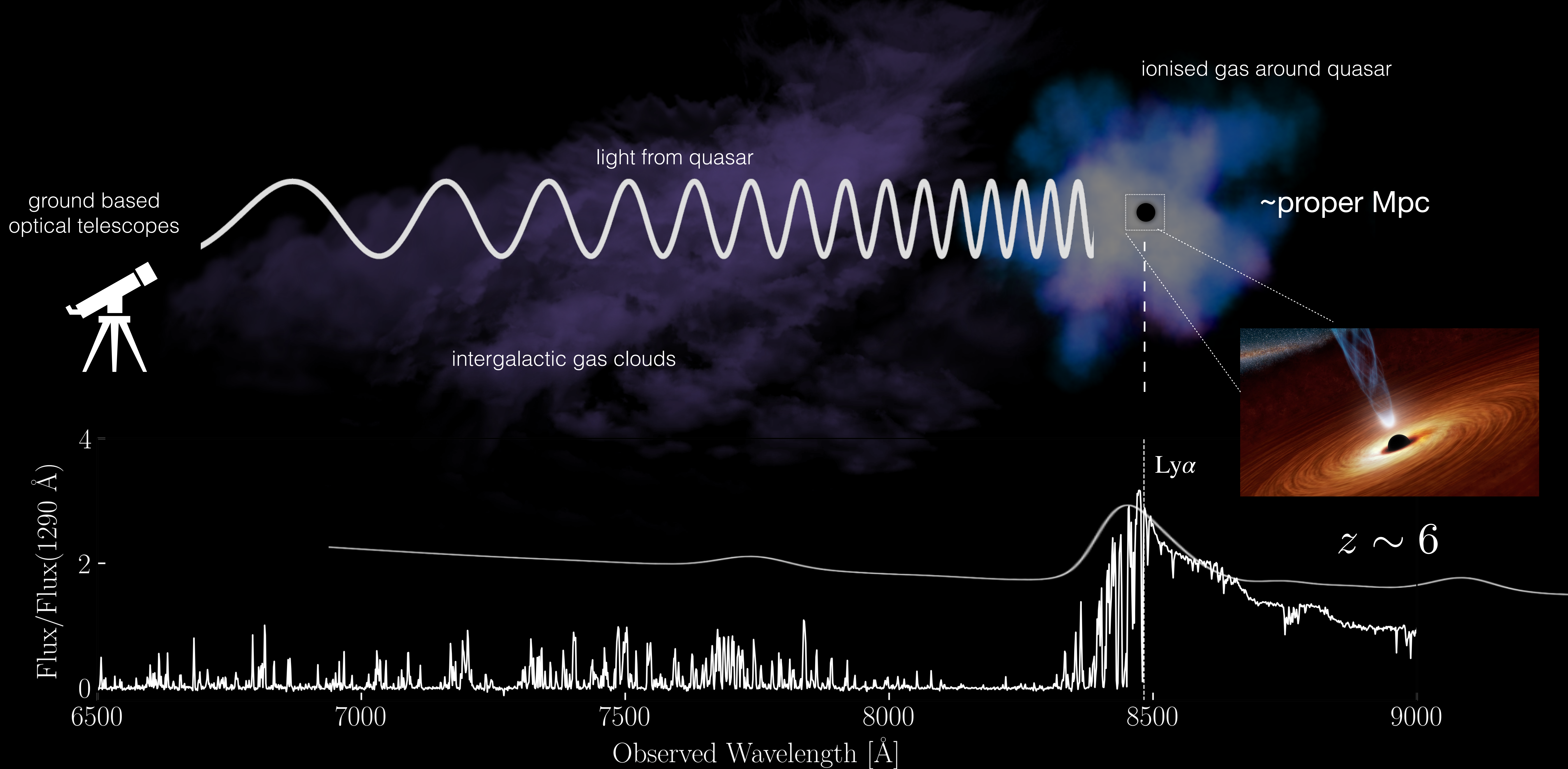


Adapted from Fan et al. 2022

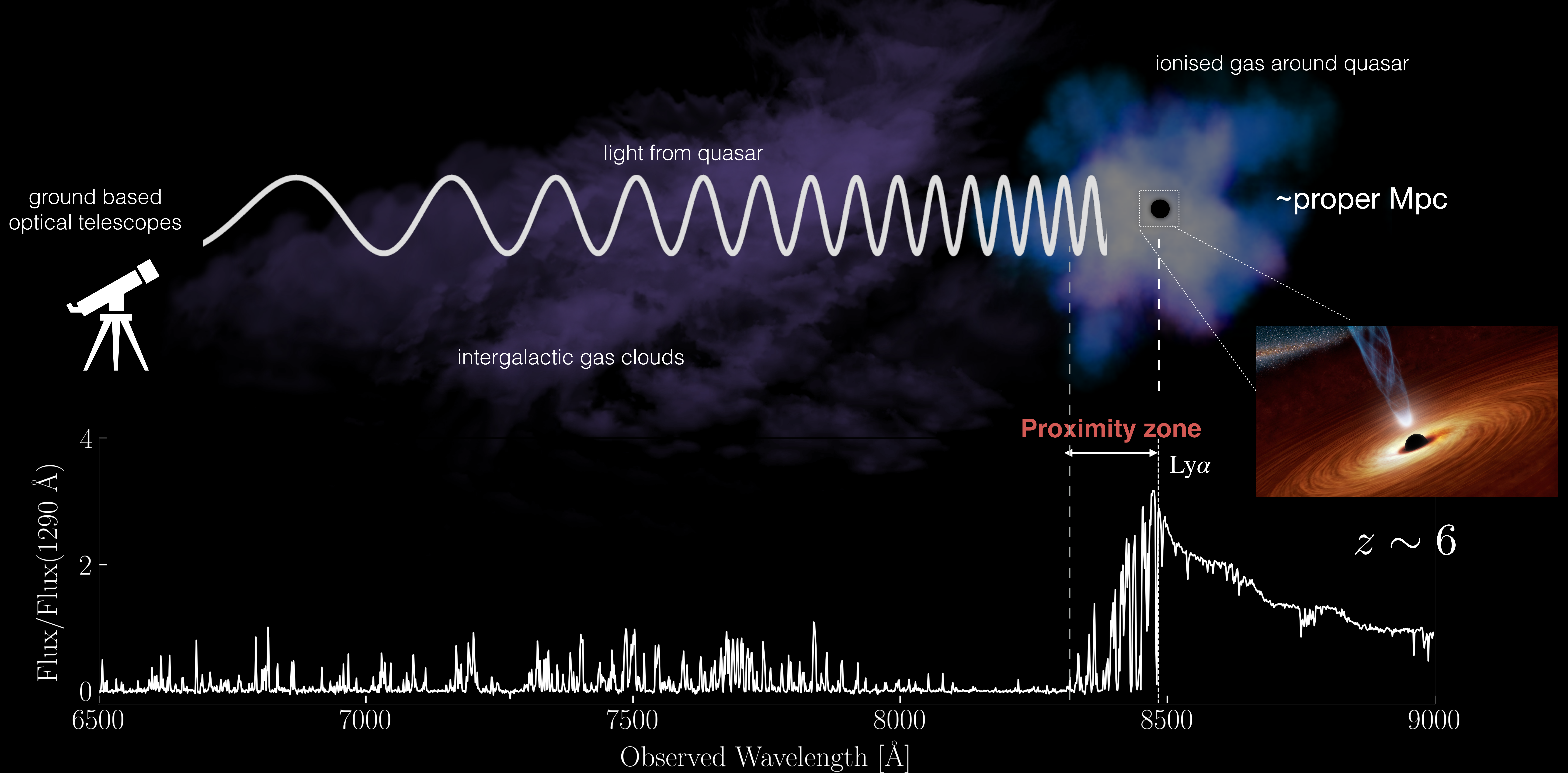
Quasars as a probe of IGM and SMBH growth



Quasars as a probe of IGM and SMBH growth



Quasars proximity zones: transparent regions in the IGM formed by quasars



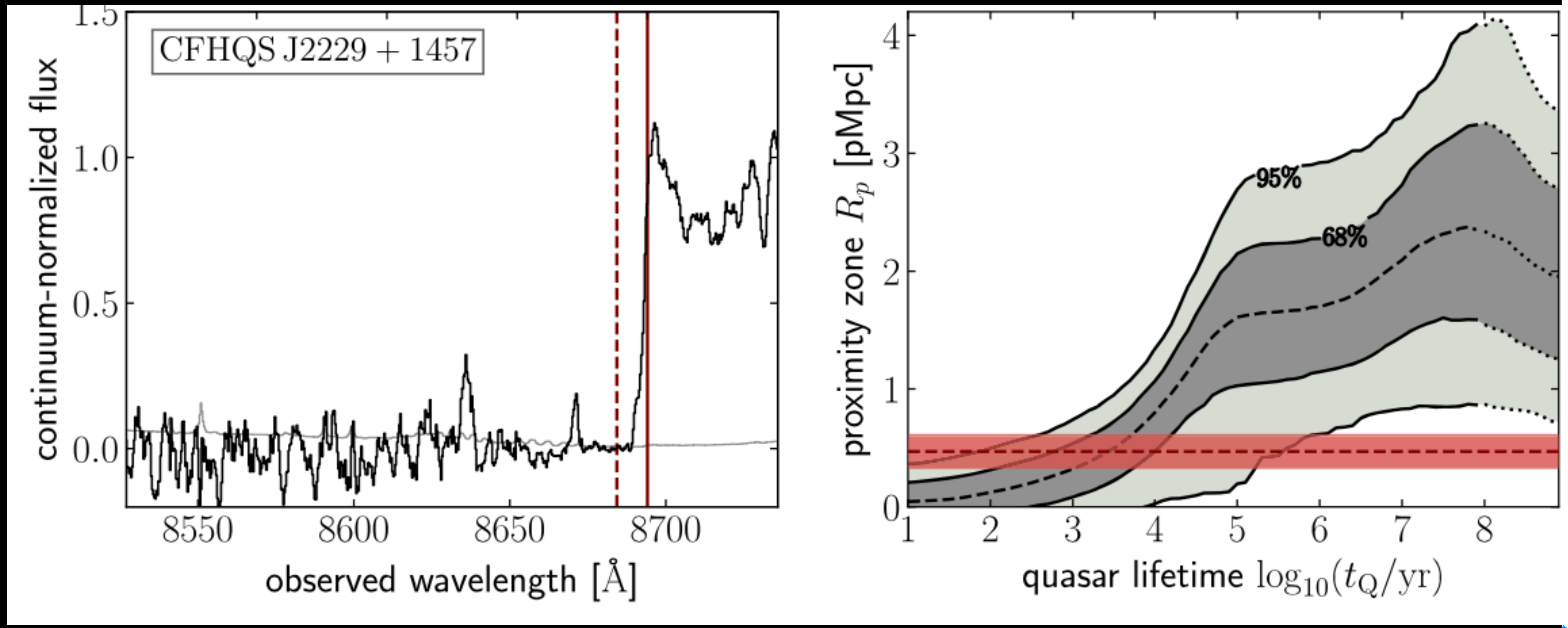
Proximity zones respond promptly to quasars

Proximity zones are also sensitive to the IGM around it

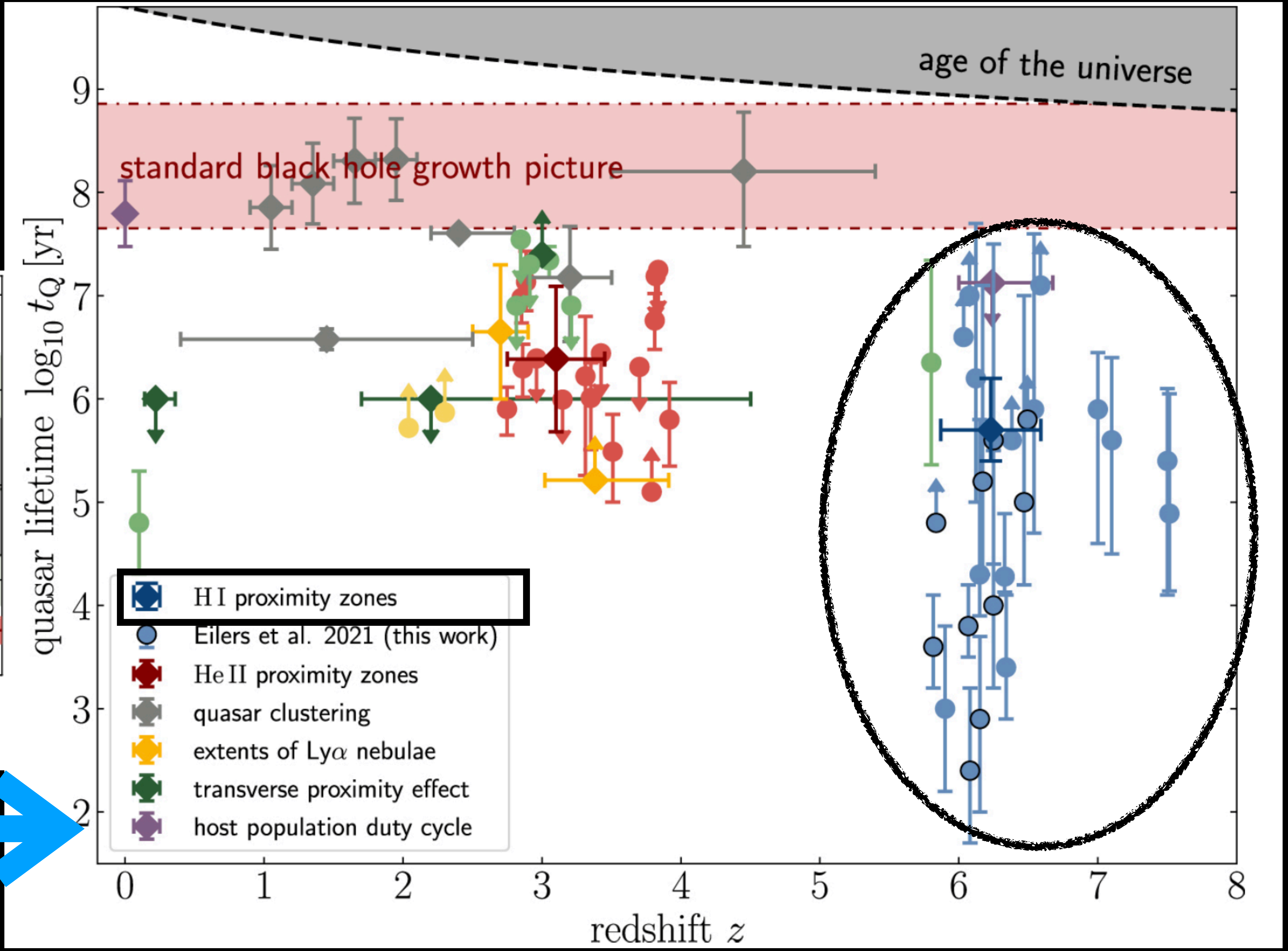
Quasar lifetimes from proximity zones: a crisis?

Proximity zone size $R_{\rm p}$

Eilers et al. 2021



Measurements + Models



Eilers et al. 2021

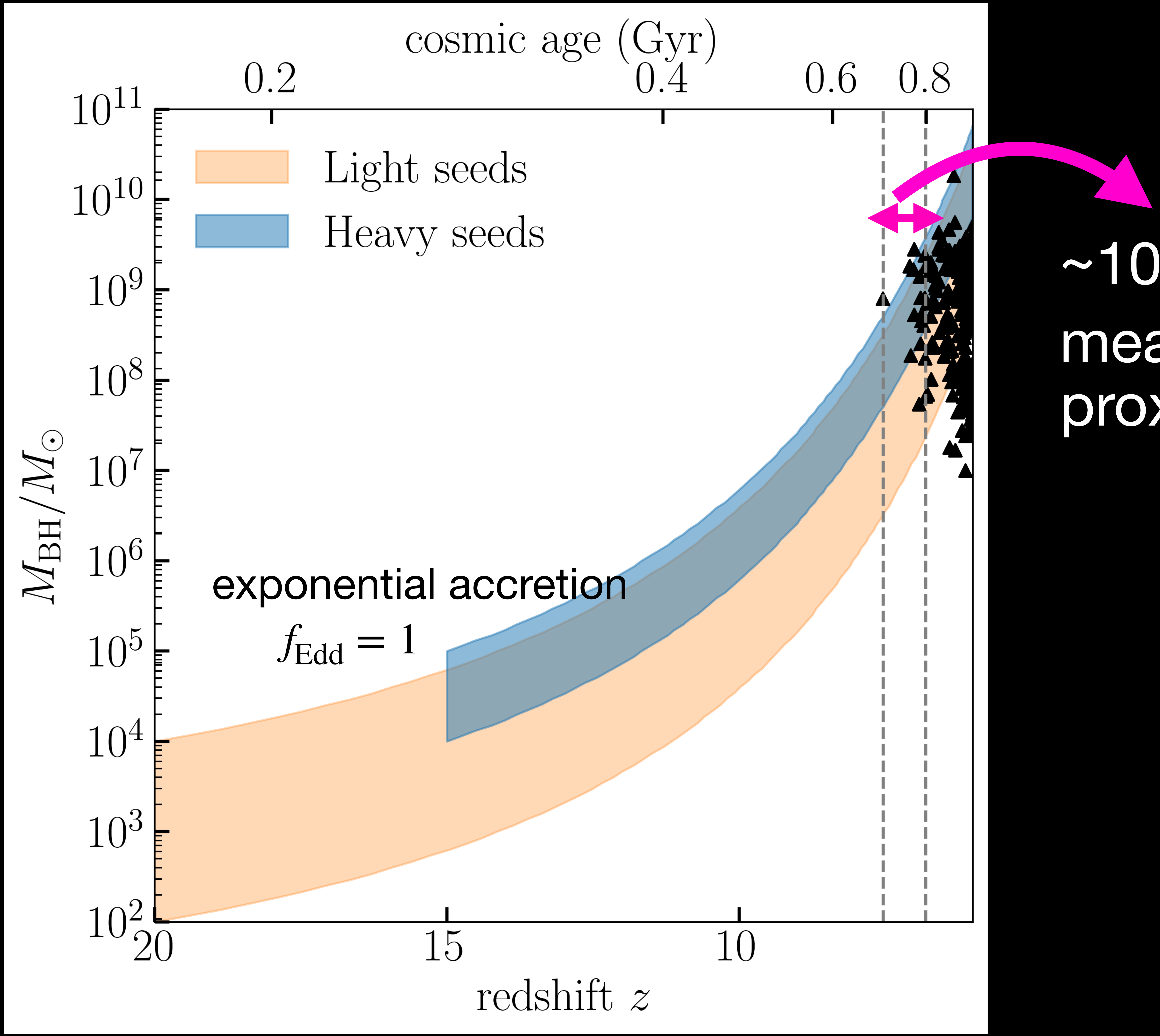
Average lifetimes of quasars inferred using proximity zone sizes is $\sim 10^6$ yr, about 10% with lifetimes $< 10^4$ yr

SMBH masses are too large for measured lifetimes

$M_{\mathrm{BH}} \propto M_{\mathrm{seed}} \exp(t_{\mathrm{q}})$

$f_{\mathrm{Edd}} = L/L_{\mathrm{Edd}}$

L_{edd}: maximum luminosity such that radiation pressure equals to gravitational pressure

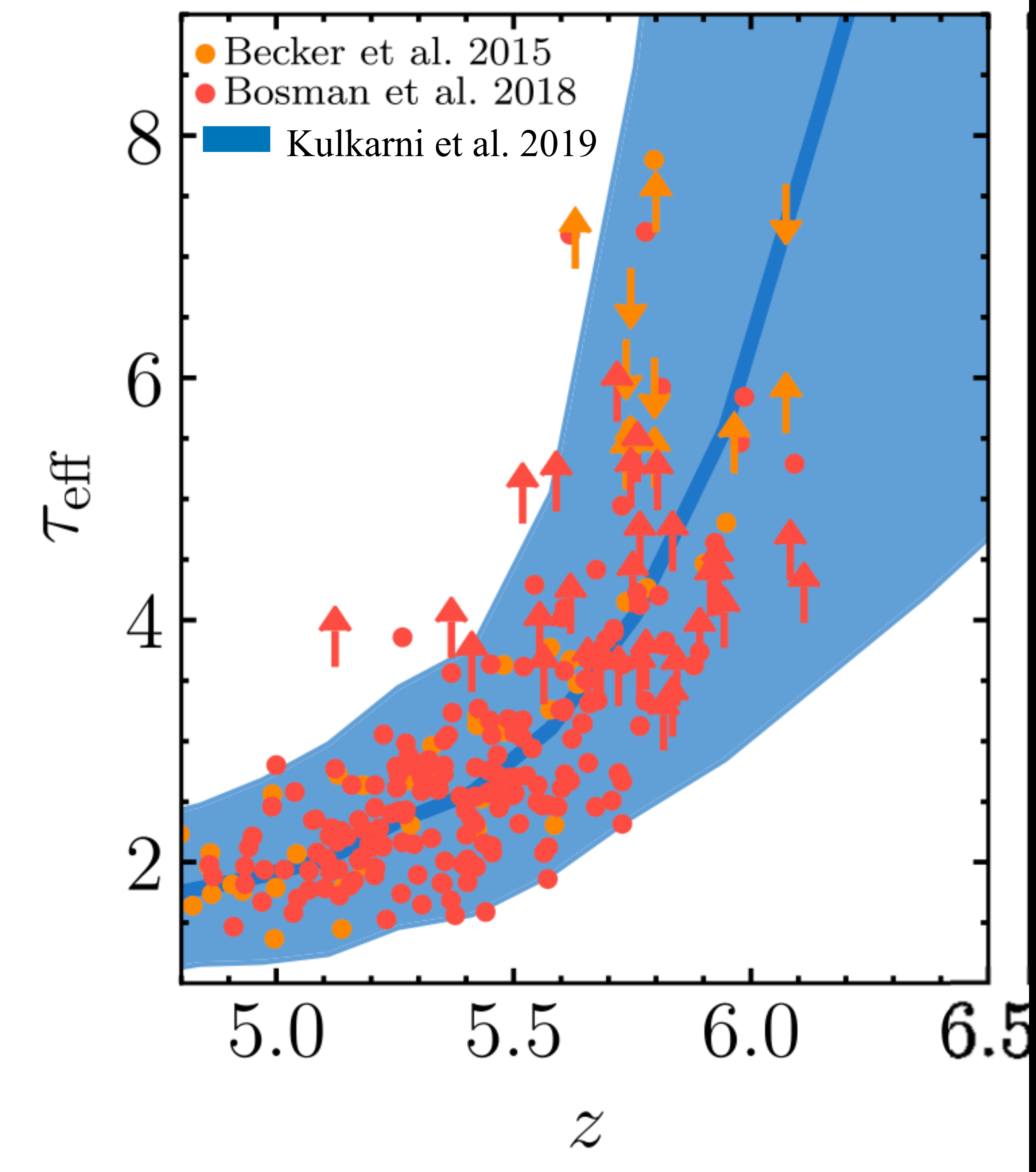


~100 times greater than t_{q} measured from quasar proximity zone sizes

Challenges standard SMBH growth. E.g., require accretion rates $\gtrsim 500$ larger than the maximum theoretical limit ($f_{\mathrm{Edd}} = 1$)

Need for more realistic models of proximity zones

IGM: Increasing evidence that reionization was inhomogeneous and ended late



Kulkarni et al. 2019

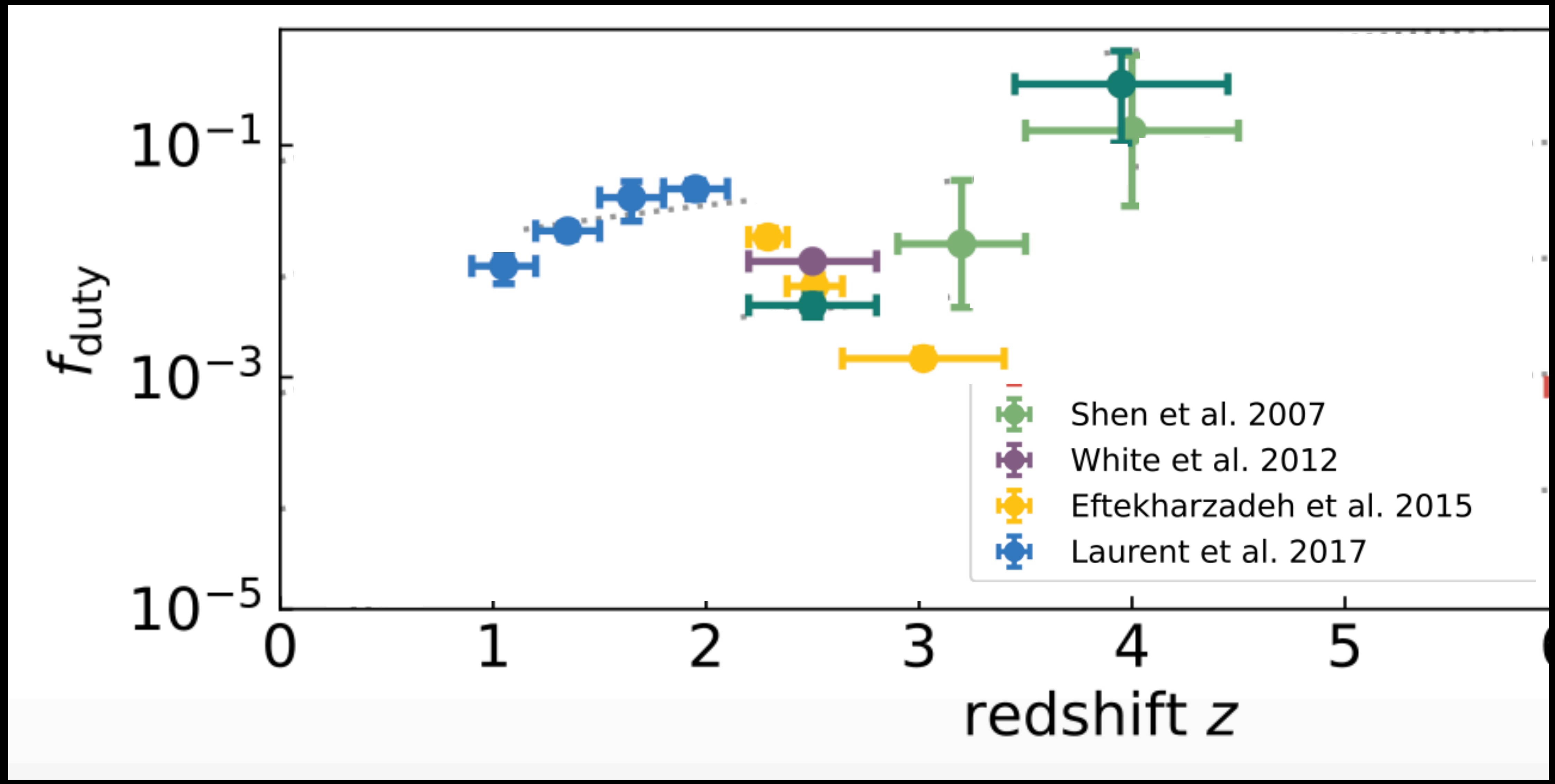
at $z \sim 6$

Large scatter in effective optical depth

Also, direct measurements of $\langle x_{\rm HI} \rangle$ ~ 0.2

Quasar light curves are also understood to be complex: SMBHs having quiescent and active periods

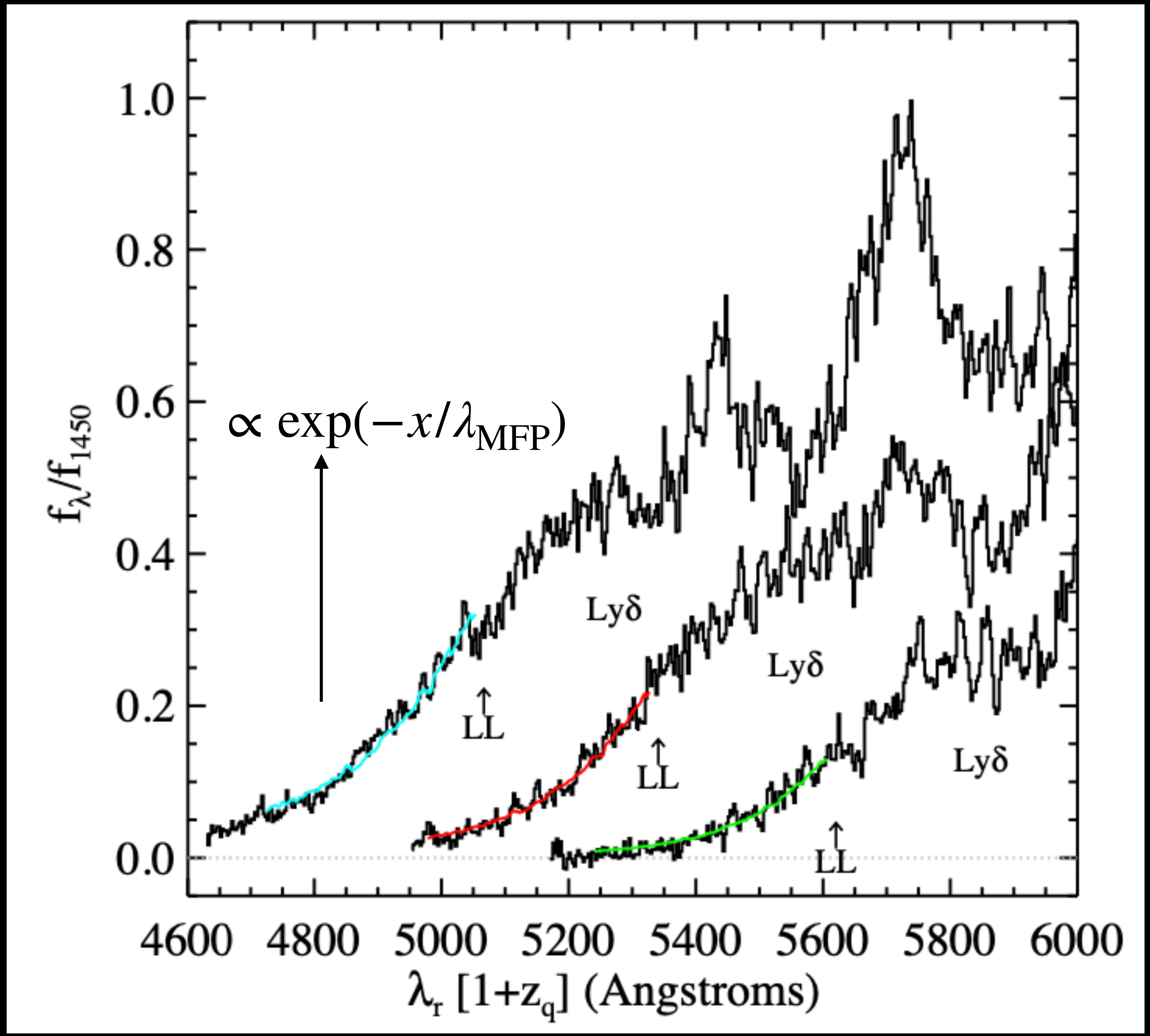
Eilers et al. 2024



Modeling of proximity zones was hindered by simple IGM and quasar models

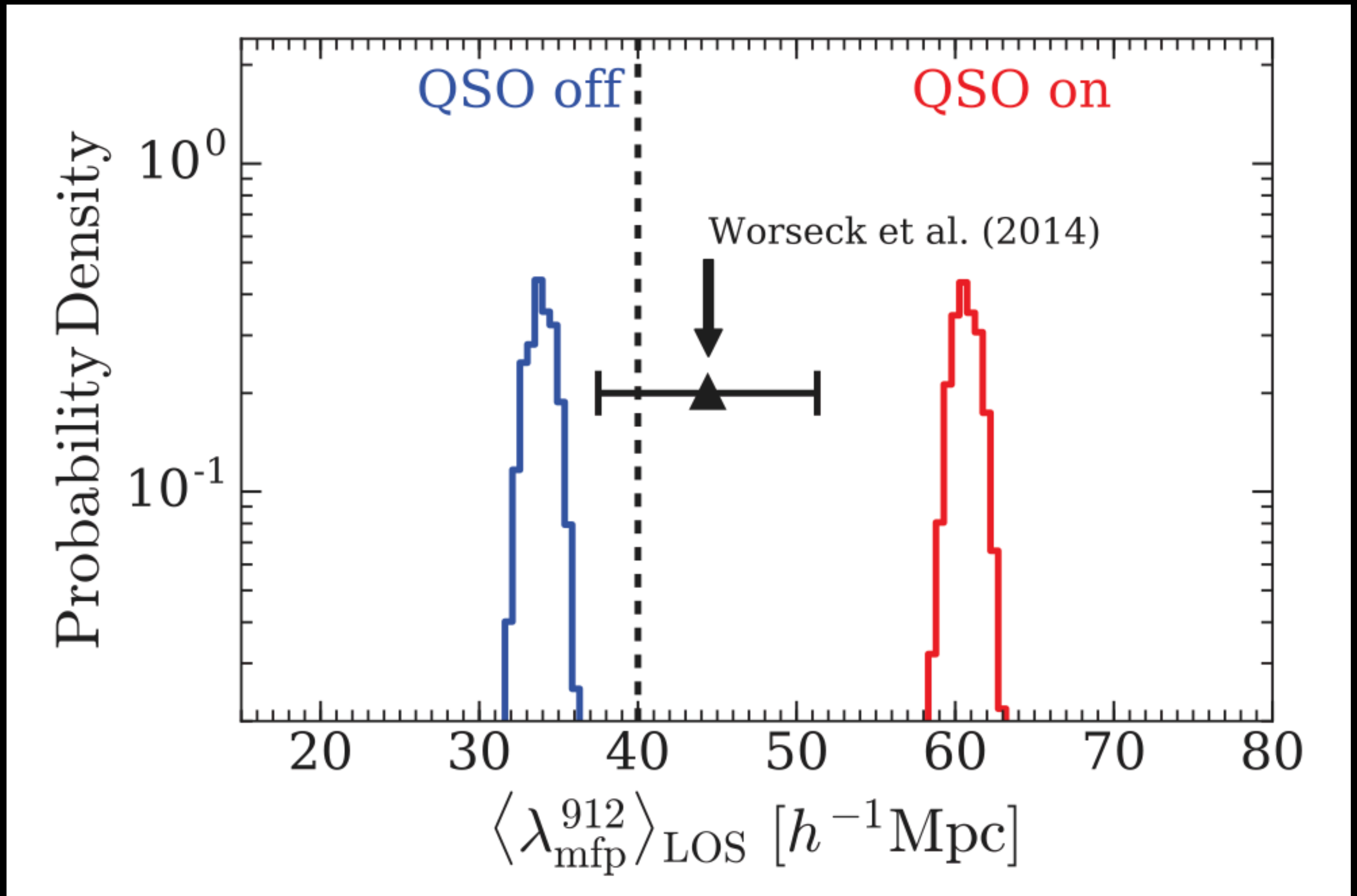
Proximity zones are crucial for MFP measurements

- Mean free path (MFP) of ionising radiation is an important parameter for constraining sources and sinks of radiation during reionization
- Measured from quasar Lyman continuum spectra.
- Defined as the flux attenuation length scale
- Much of this flux is within the quasar proximity zones
- At higher-z, λ_{mfp} can become comparable to proximity zone size



Worseck et al. 2014

Proximity zones bias in mean free path measurements: overestimated?



D'Aloisio et al. 2018

Optically thin simulations with analytic models for proximity zones predict ~50% bias at $z \sim 5.2$

Proximity zones bias in mean free path measurements: overestimated?

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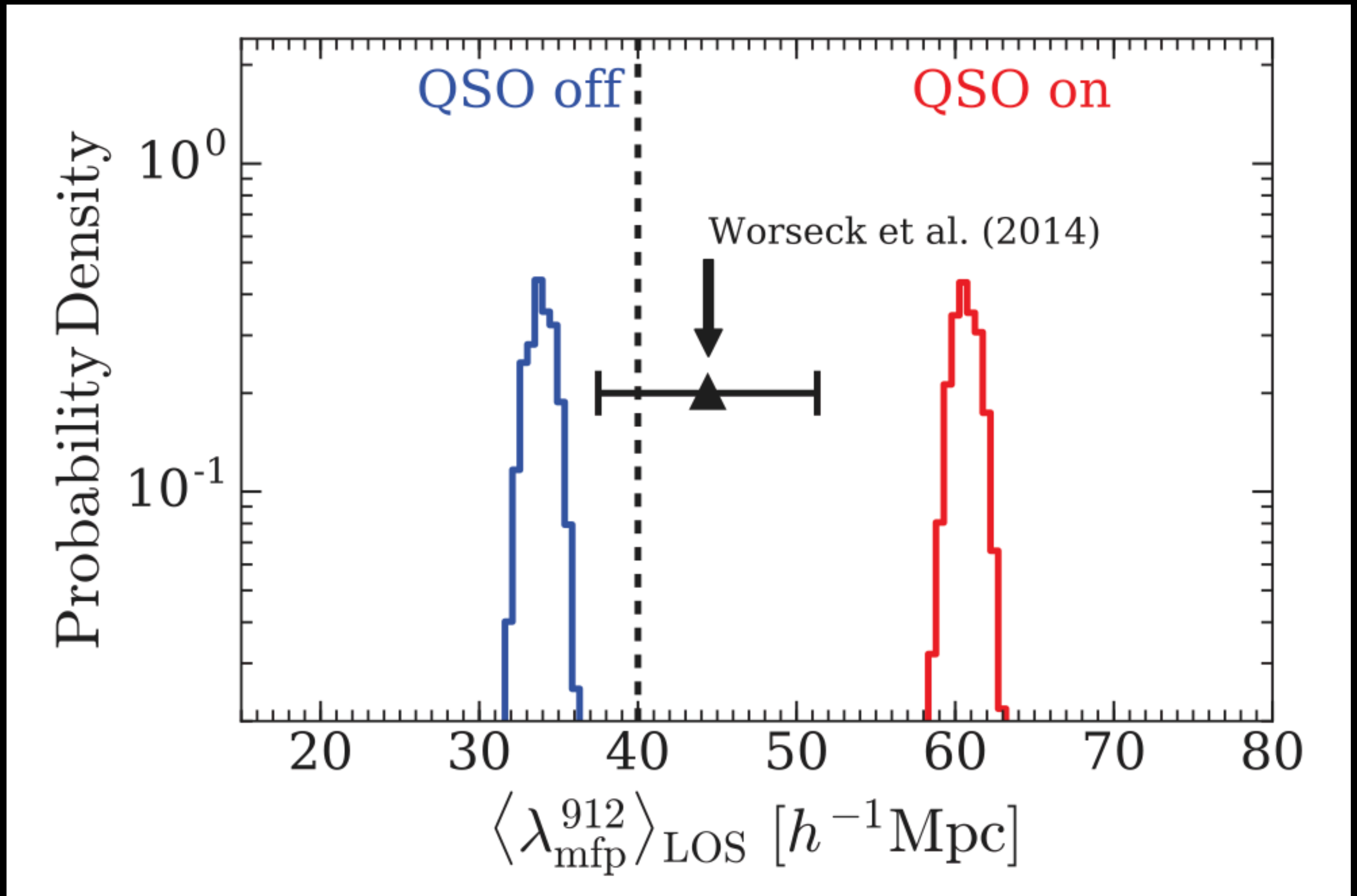

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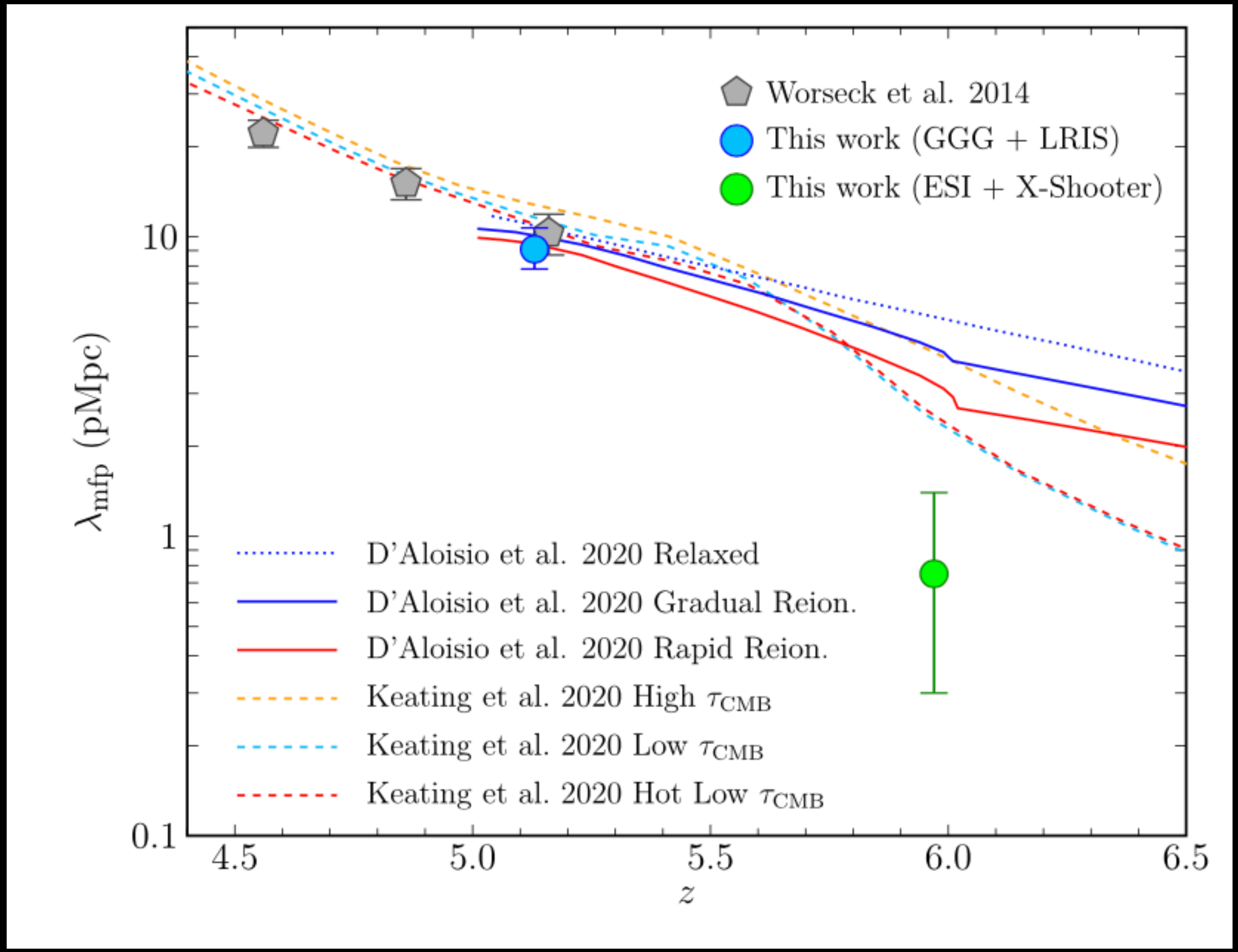
Mean free path



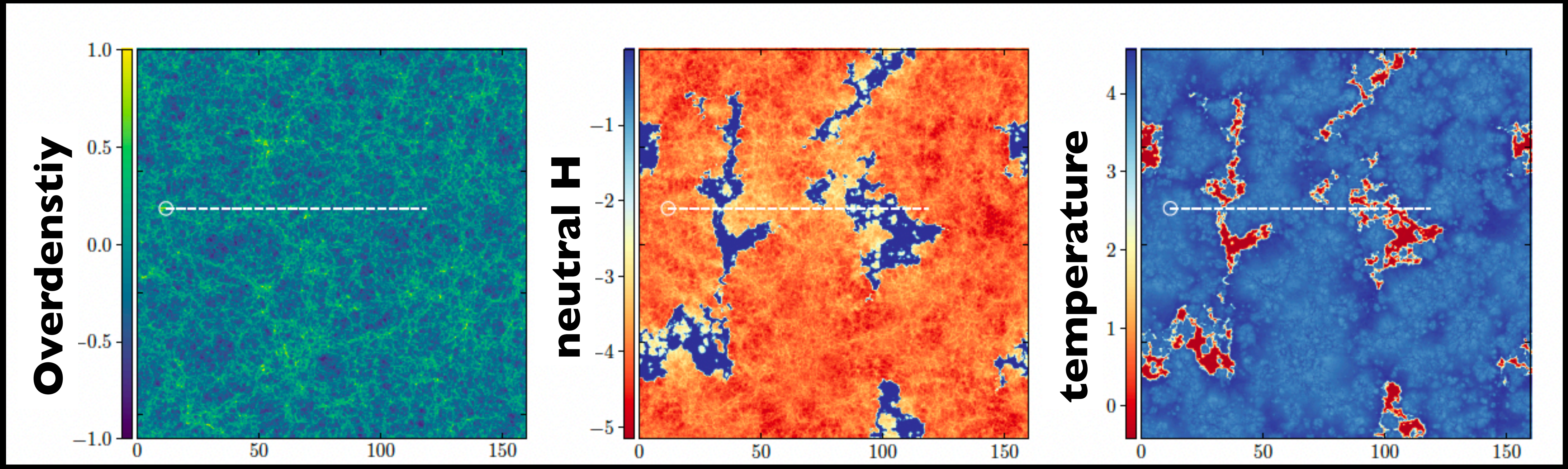
redshift

Becker et al. 2021

Measurements of the MFP using analytic correction for the proximity zone sizes yields an MFP shorter than the theoretical prediction

We look at proximity zones in newer simulations

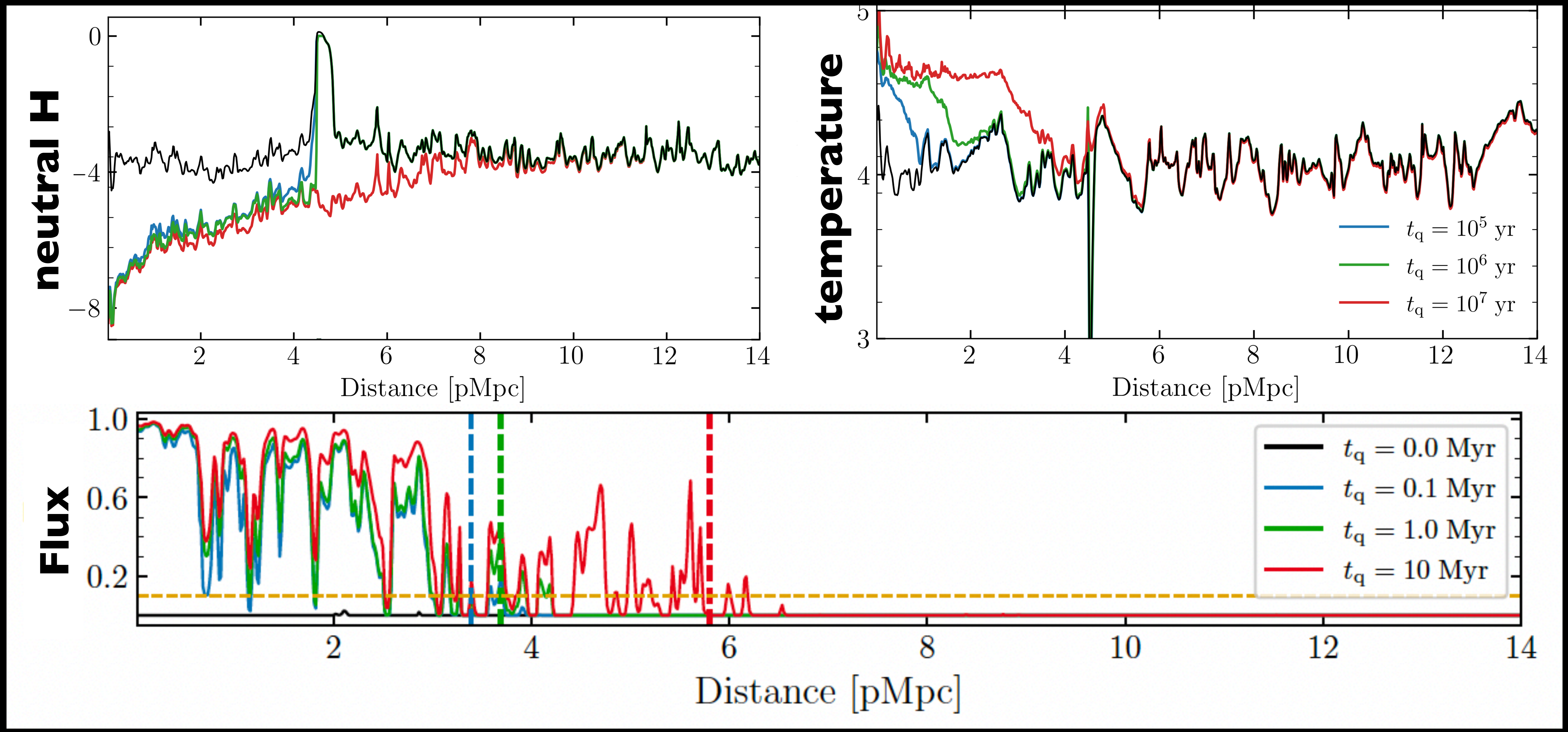
- These simulations match the latest Lya effective optical depth measurements, apart from several other observables
- Large dynamic range of halo masses
- Inhomogeneous reionization with large residual neutral islands even at $z \sim 5.5$
- Reionisation ends as late as $z \sim 5.3$
- Quasars added in post-processing (Satyavolu et al. 2023)



Kulkarni et al. 2019

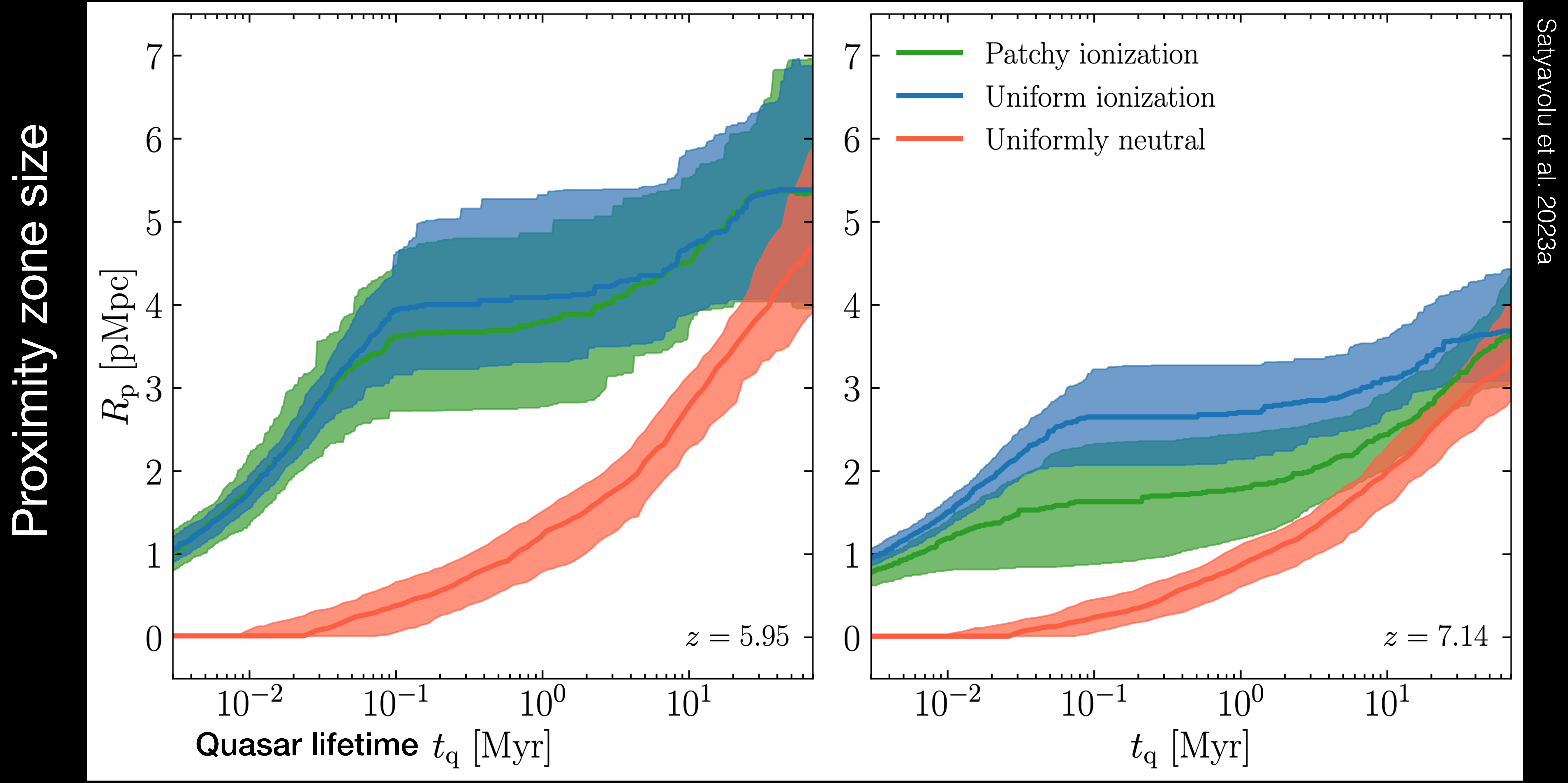
Distance (cMpc/h)

Post-processed to include quasars



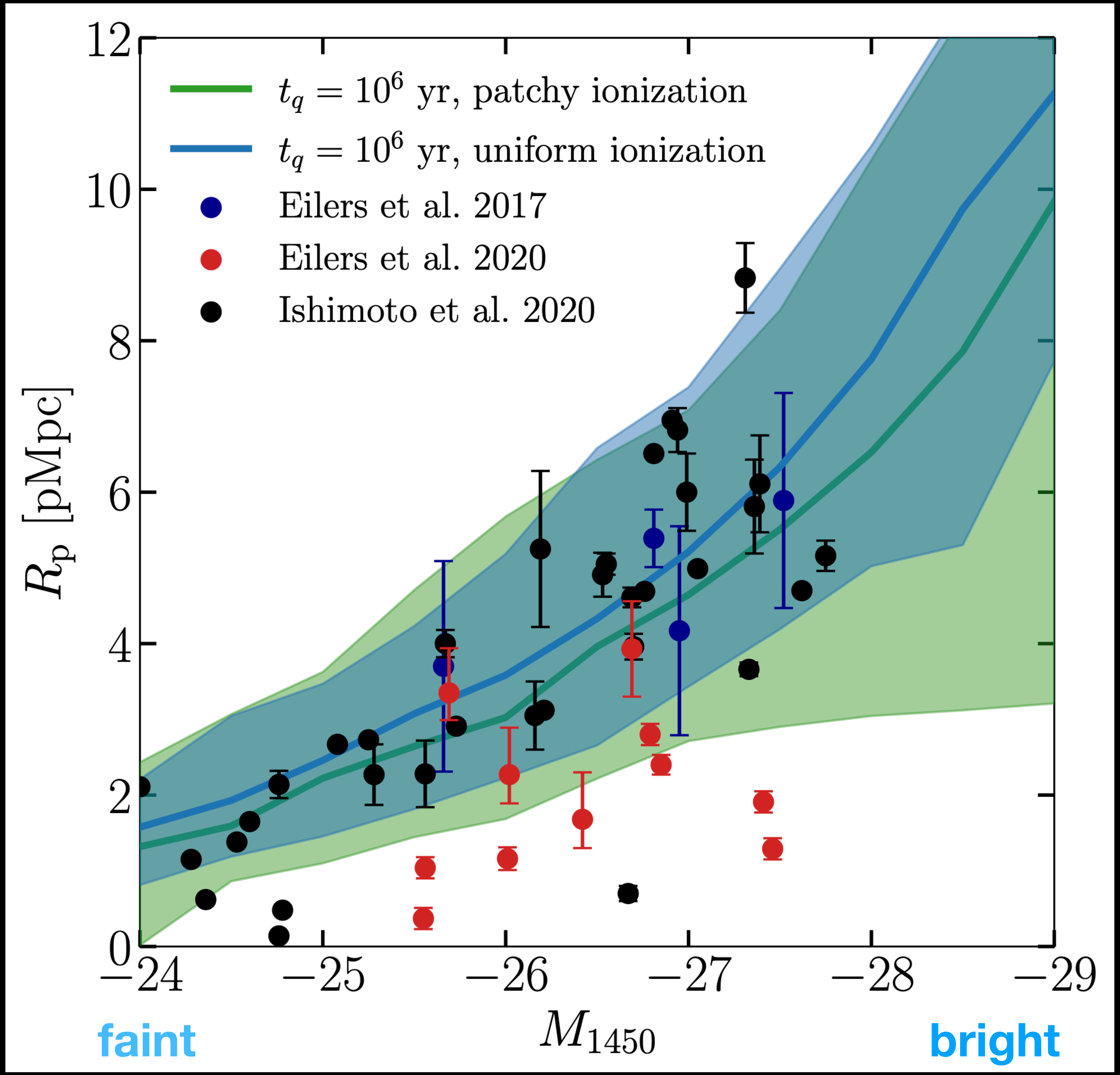
These simulations help bring realistic IGM to models.

Incomplete reionization impedes proximity zone growth

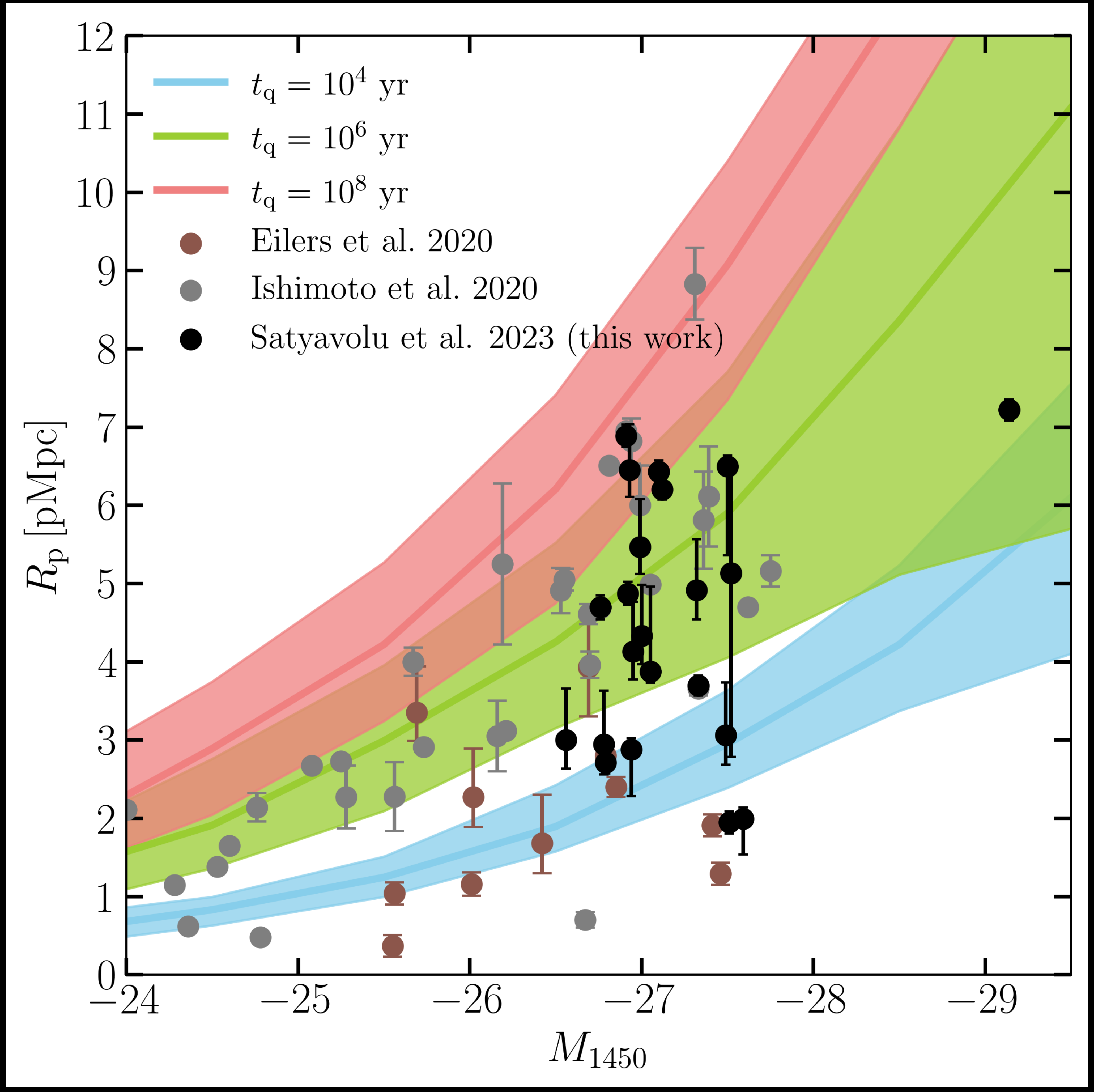


The topology of reionization reduces proximity zone sizes by up to 30%

Patchy reionization can not fully resolve quasar lifetime-SMBH growth tension



Satyavolu et al. 2023a

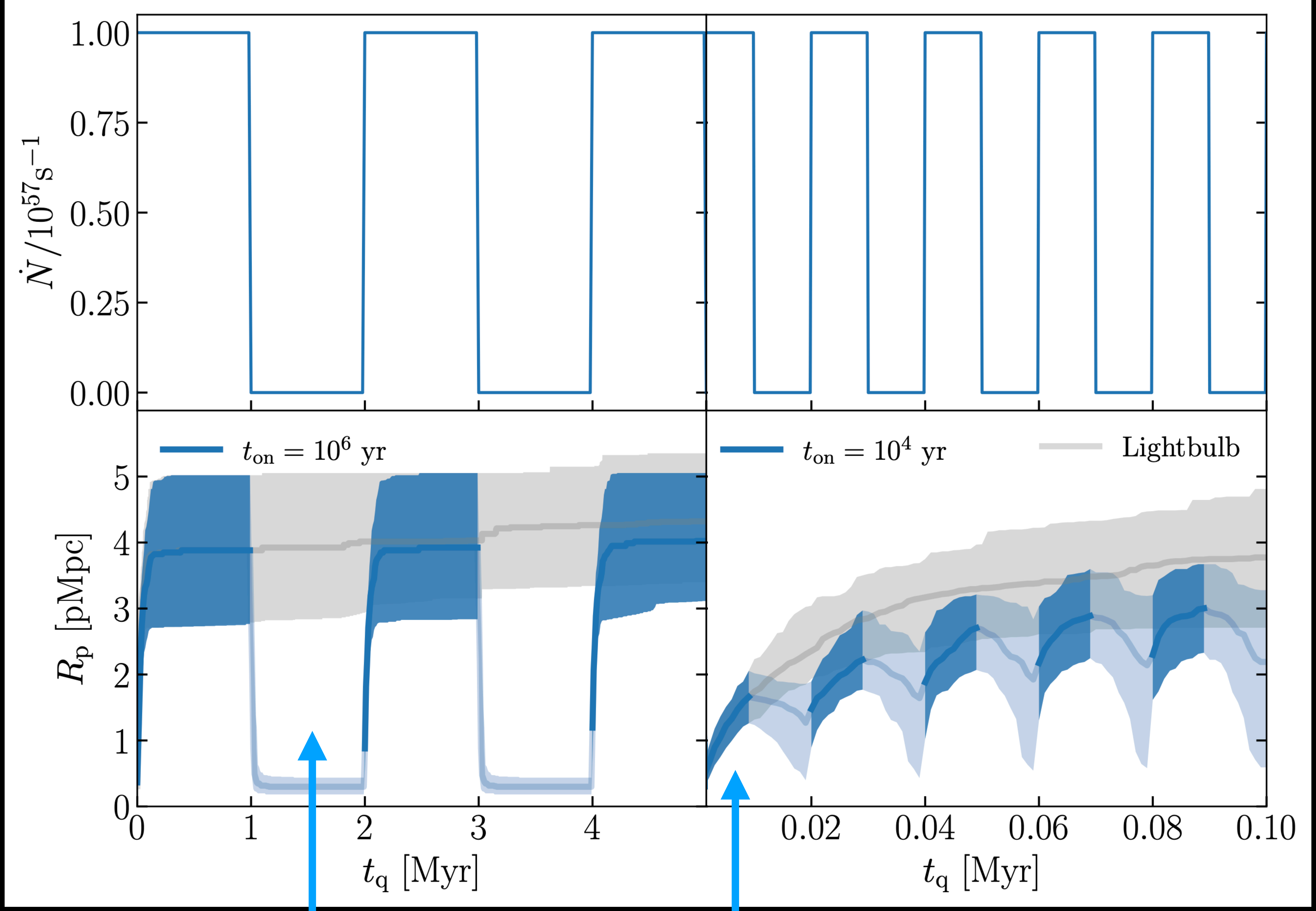


Despite increase in scatter, few proximity zone sizes suggest a $t_q < 10^4$ even in these models

Quasar variability allows us to increase lifetime

$$f_{\mathrm{duty}} = \frac{t_{\mathrm{on}}}{t_{\mathrm{on}} + t_{\mathrm{off}}}$$

- Quasar lifetimes measured from proximity zone sizes: given a sufficiently large recombination time, correspond to integrated lifetimes
- Otherwise, we are susceptible to episodic lifetimes
- At a fixed duty cycle, as t_{on} increases, R_{p} reaches lightbulb value
- For small t_{on}, R_{p} remains small even at large lifetimes if duty cycle is such that $t_{\mathrm{off}} > t_{\mathrm{vanish}}$

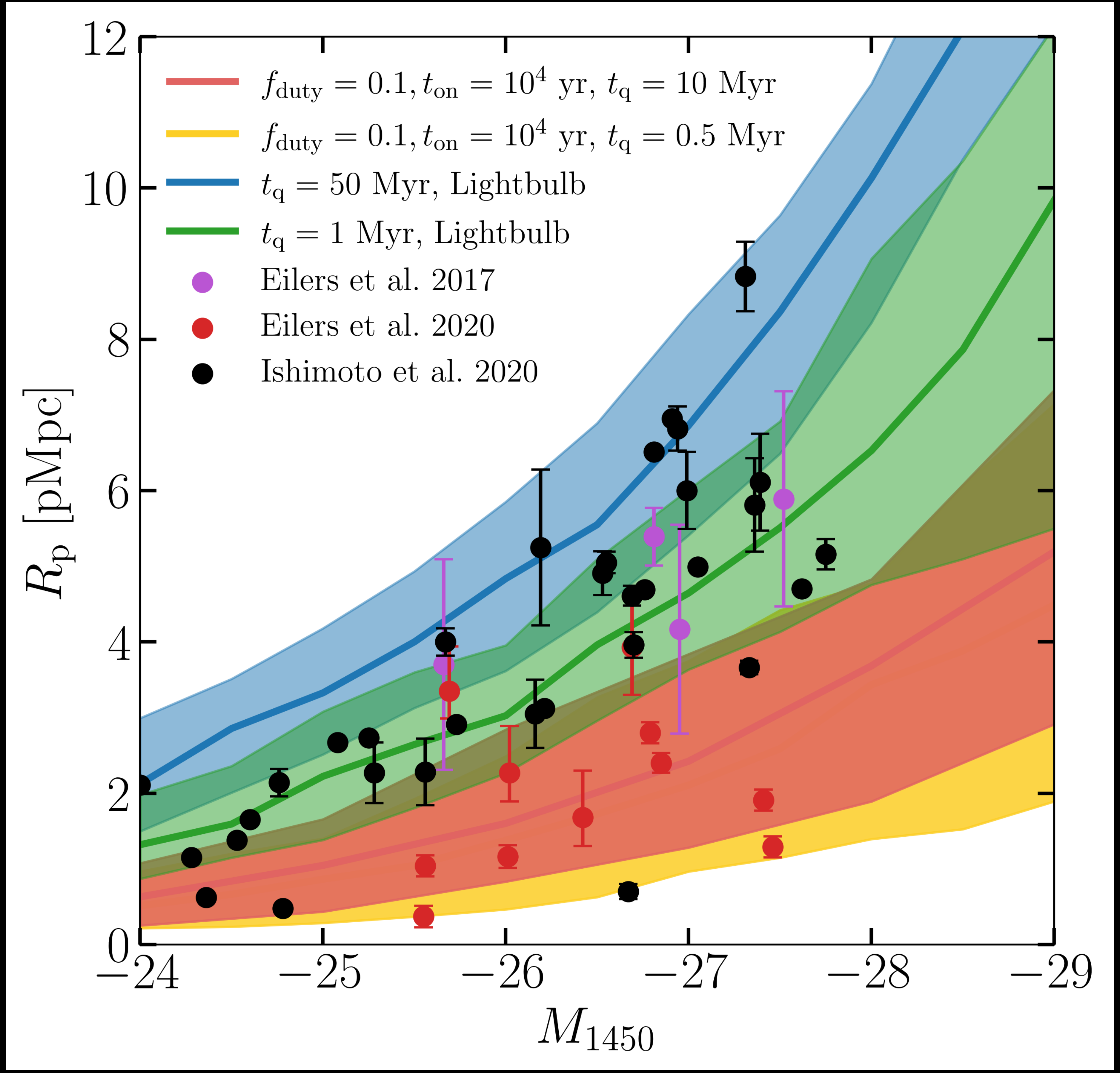


gas recombines at a rate $\propto 1/(n_{\mathrm{HII}}\alpha)$

$t_{\mathrm{vanish}} \sim 0.01 - 0.1\,\mathrm{Myr}$

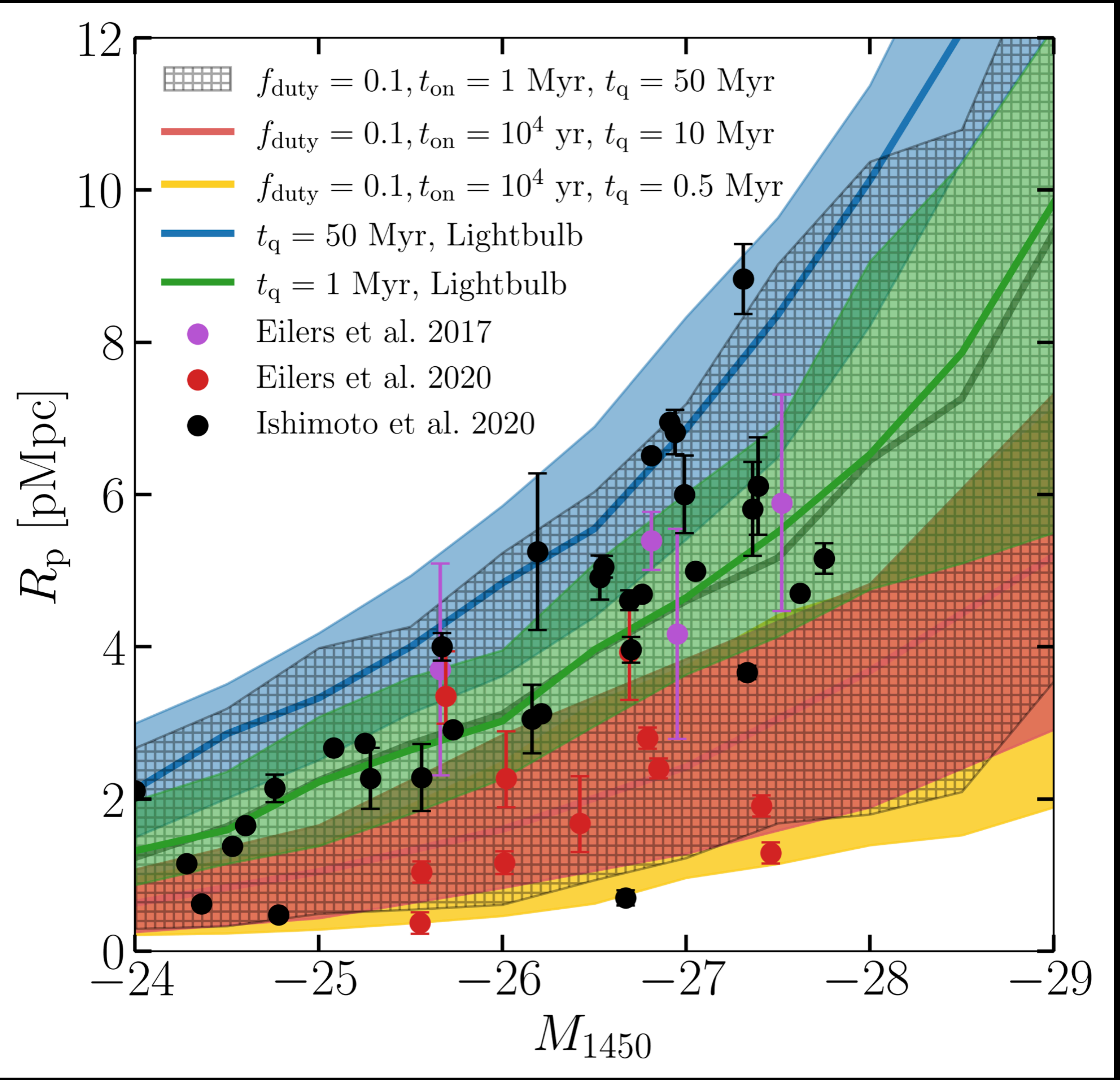
$t_{\mathrm{eq}} >> 1/\Gamma \sim 0.1\ \mathrm{Myr}$

Small duty-cycle and short episodic quasars can explain small $R_{\rm p}$



Model however inconsistent with large proximity zone sizes

A consistent model for all observed proximity zone sizes for the first time



A short duty cycle with large on-time can fit the distribution of all $R_{\rm p}$ for large lifetimes

Is the new model consistent with SMBH growth?

$$M_{\rm BH}(z) = M_{\rm seed}(z_0)\ \exp\left(\frac{f_{\rm duty} t_q}{t_{\rm S}}\right) \Longrightarrow$$

For $f_{\rm duty}$ ~ 0.3, required $t_{\rm q}$ exceeds 2 Gyr with $10^3 M_\odot$ seed!

Rather, define: $M_{\rm BH}(z) = M_{\rm seed}(z_0)\ \exp\left(\frac{f_{\rm acc} t_q}{t_{\rm S}}\right)$

$$f_{\rm acc} = \frac{t_{\rm on} + t_{\rm obsc}}{t_{\rm on} + t_{\rm off,acc,lum+t_{obsc}}} = f_{\rm duty,lum} + f_{\rm obsc}$$

Accretion duty cycle defines the period when black hole is accreting, which includes the luminous phase (proximity zones are visible to us) and the obscured phase

Obscuration could explain high-z SMBH growth

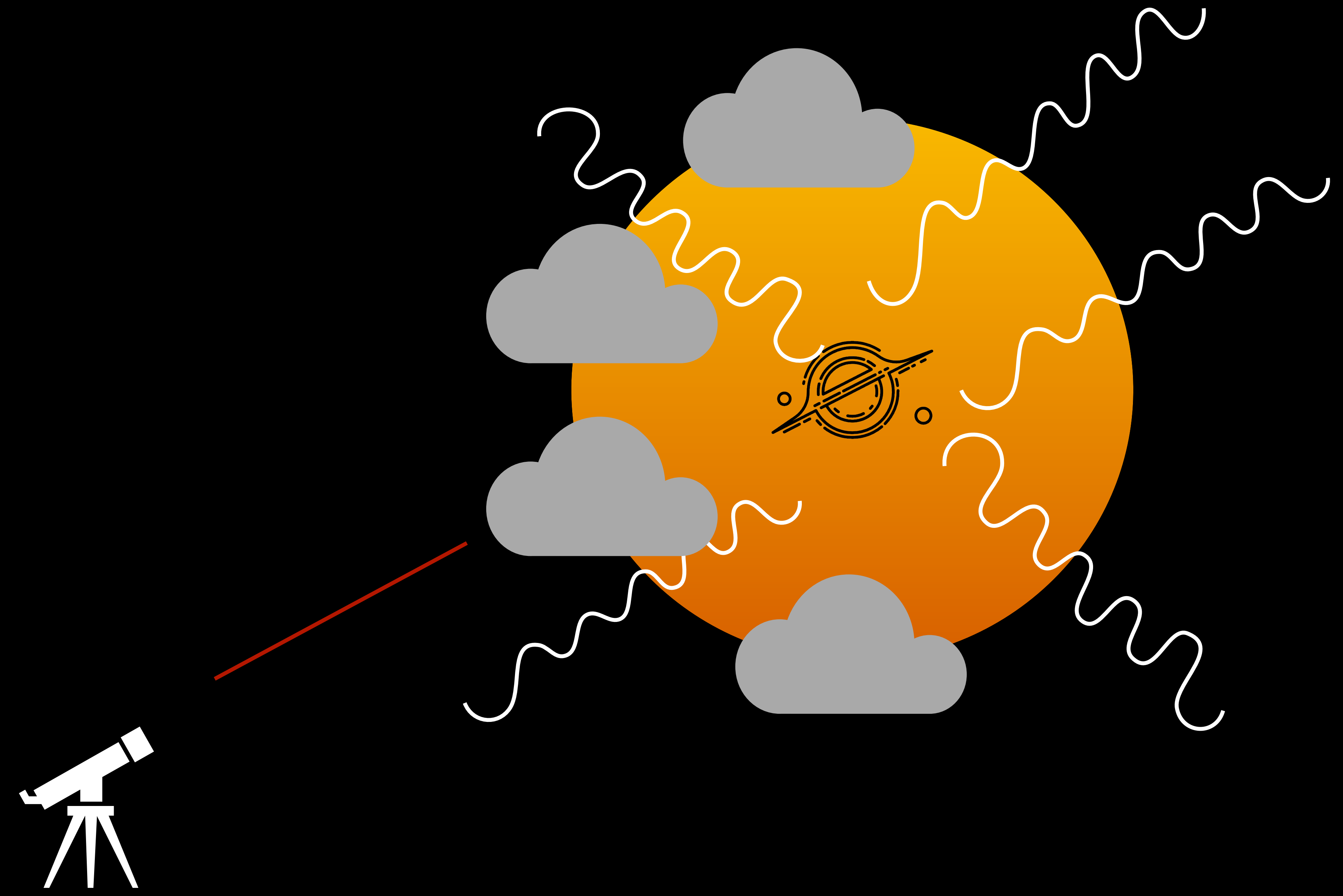
$$M_{\rm BH}(z) \propto M_{\rm seed}(z_0)\ \exp\left(f_{\rm acc} t_q\right)$$

$$f_{\rm acc} = f_{\rm duty,lum} + f_{\rm obsc}$$

$$f_{\rm acc} = 0.7, z = 15, M_{\rm seed} = 10^3\,{\rm M_\odot}, f_{\rm Edd} = 1$$

$$\implies M_{\rm BH}(z=6) \sim 10^9\,{\rm M_\odot}$$

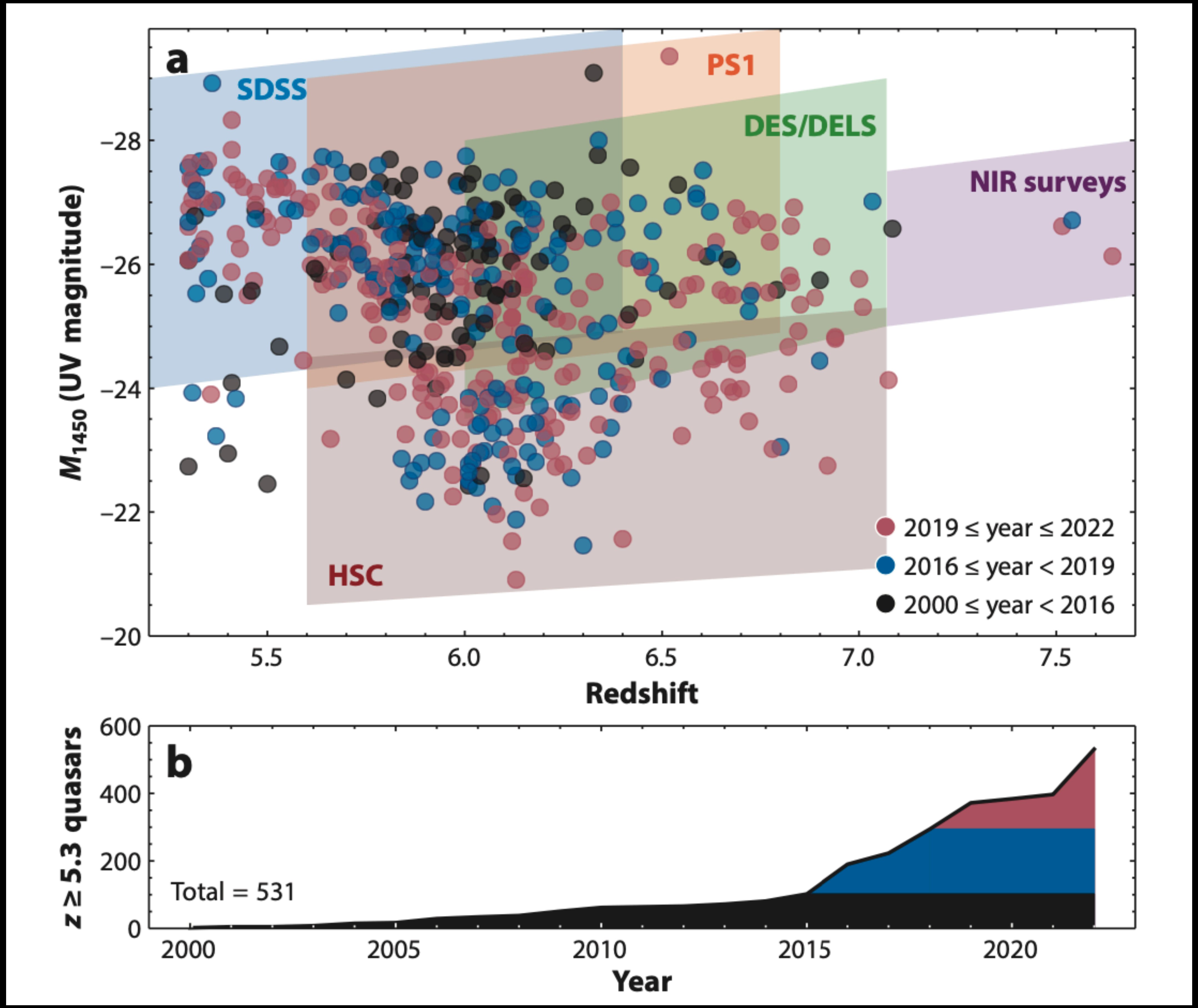
With an obscuration fraction of 60%, a $10^3\,{\rm M_\odot}$ seed can grow into a billion solar mass black hole, and have proximity zone sizes that are consistent with measurements



JWST large program (~265 hrs) to measure $f_{\rm obsc}$ (COSMOS-3D, Cycle 3 program, P.I Kakiichi)

High-redshift quasars: A new dawn

- By 2021, More than ~ 200 quasars at $z > 6$ are known.
- Only a fraction (< 20) of them had high quality spectra (SNR $\gtrsim 10$) that can enable science across the entire NIR-VIS part of the quasar spectrum.



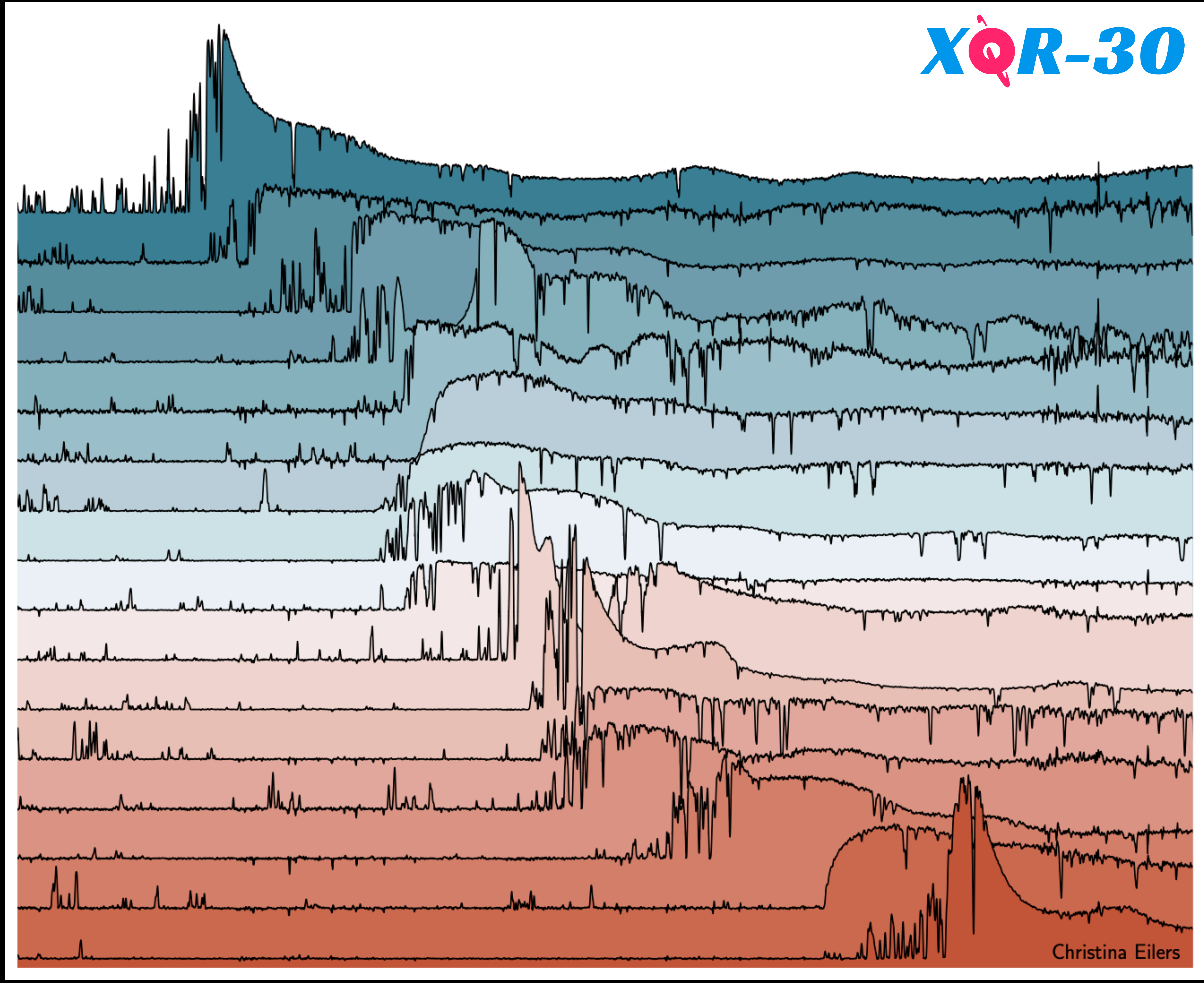
Fan et al. 2022

New large volume surveys, improved selection techniques and multi-wavelength data accelerated discovery of quasars in the last decade

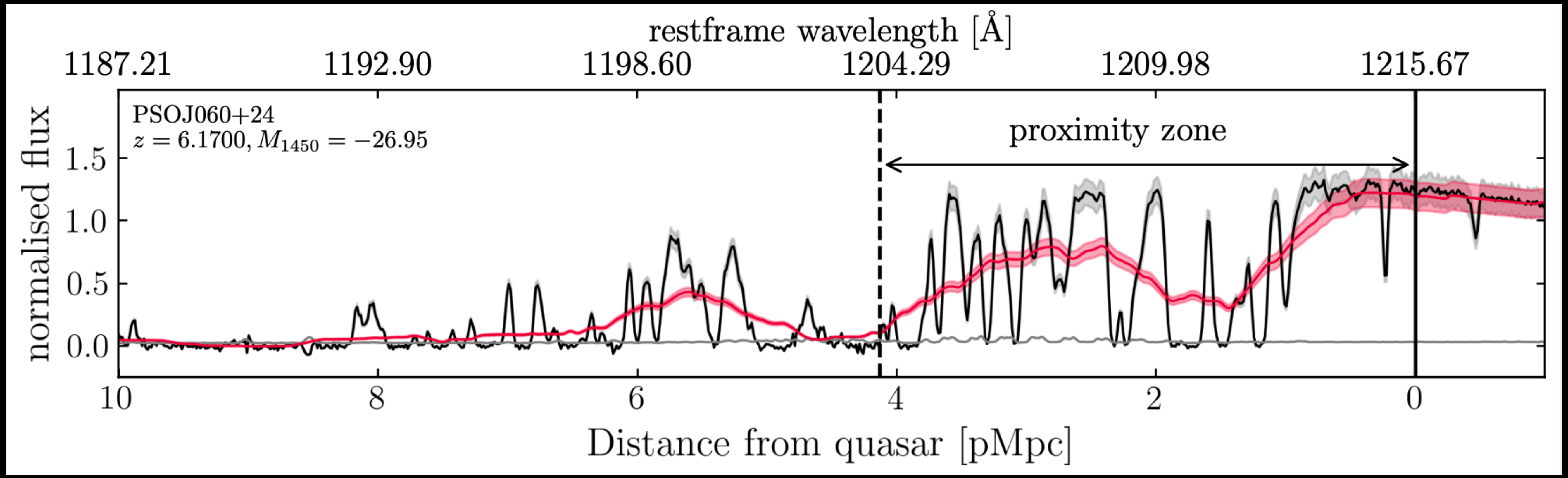
The XQR-30 survey

- Observing program to do high-SNR Optical and Near Infrared spectroscopy of 30 bright ($M_{1450} < -26.5$) quasars at high redshifts $5.8 < z < 6.5$ using X-SHOOTER spectrograph on the Very Large Telescope (VLT)

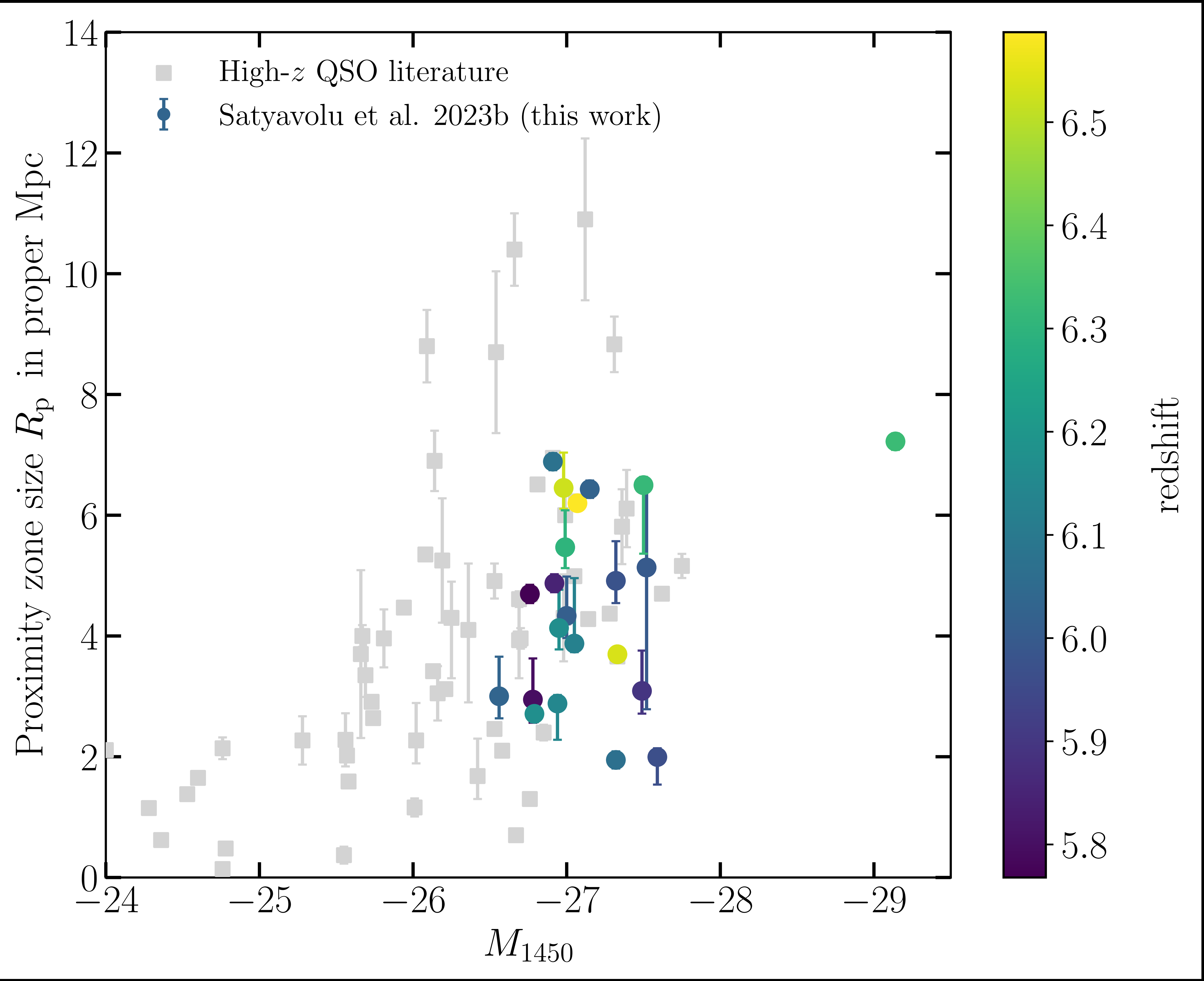
- Major science goals:
  - timing and morphology of Reionization
  - constraining early galaxy and SMBH formation
  - high-z stellar population.



New measurements of proximity zone sizes



- Measured proximity zone sizes of 22 quasars, including updated measurements of 10 quasars
- Folded in continuum errors as well as redshift errors
- Two quasars have $R_p < 2$ pMpc. One of them has a metal absorption system. The other shows features that could potentially originate from absorption due to neutral island in the IGM.



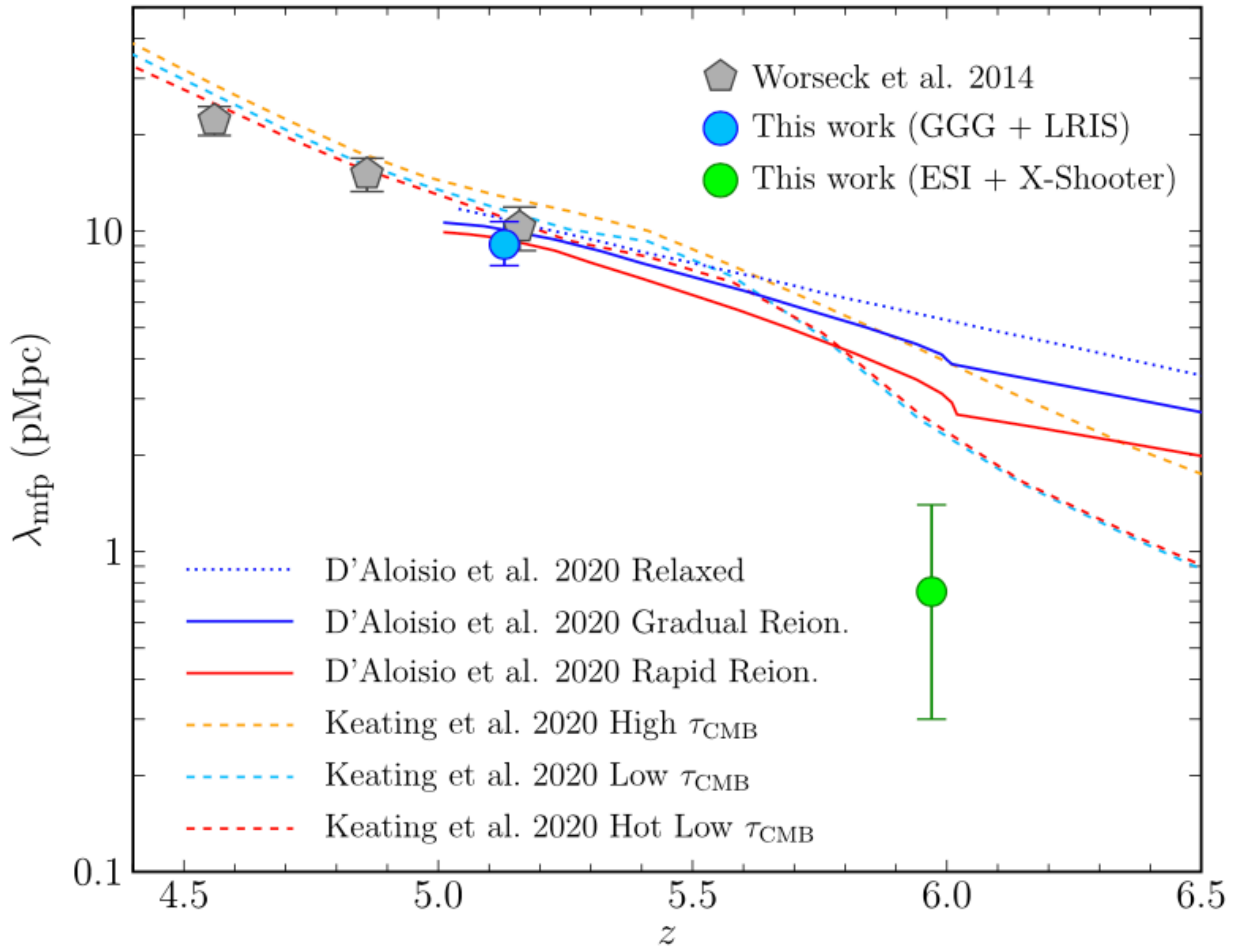
Increased the total number of R_p measurements above $z \gtrsim 5.5$ to 87

Robustness of high-z measurements of the mean free path

- Recent discrepancy leaves us with a couple of unanswered questions about the B21 measurements—

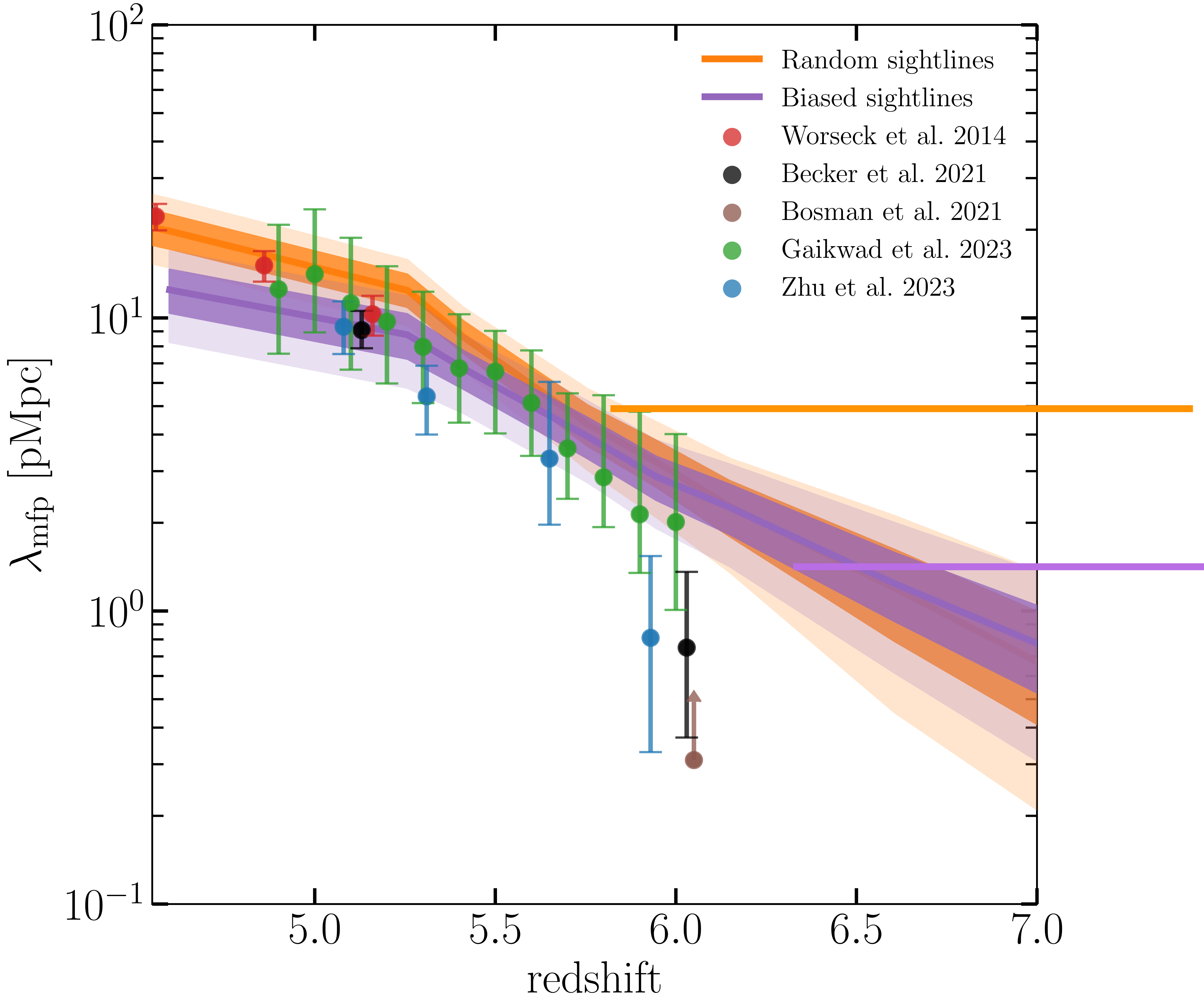
(1) Do higher cosmological densities around quasars bias the MFP?

(2) Proximity zones around quasars in a partially ionized IGM: the analytic model vs RT



Becker et al. 2021

Bias due to overdensity is not important

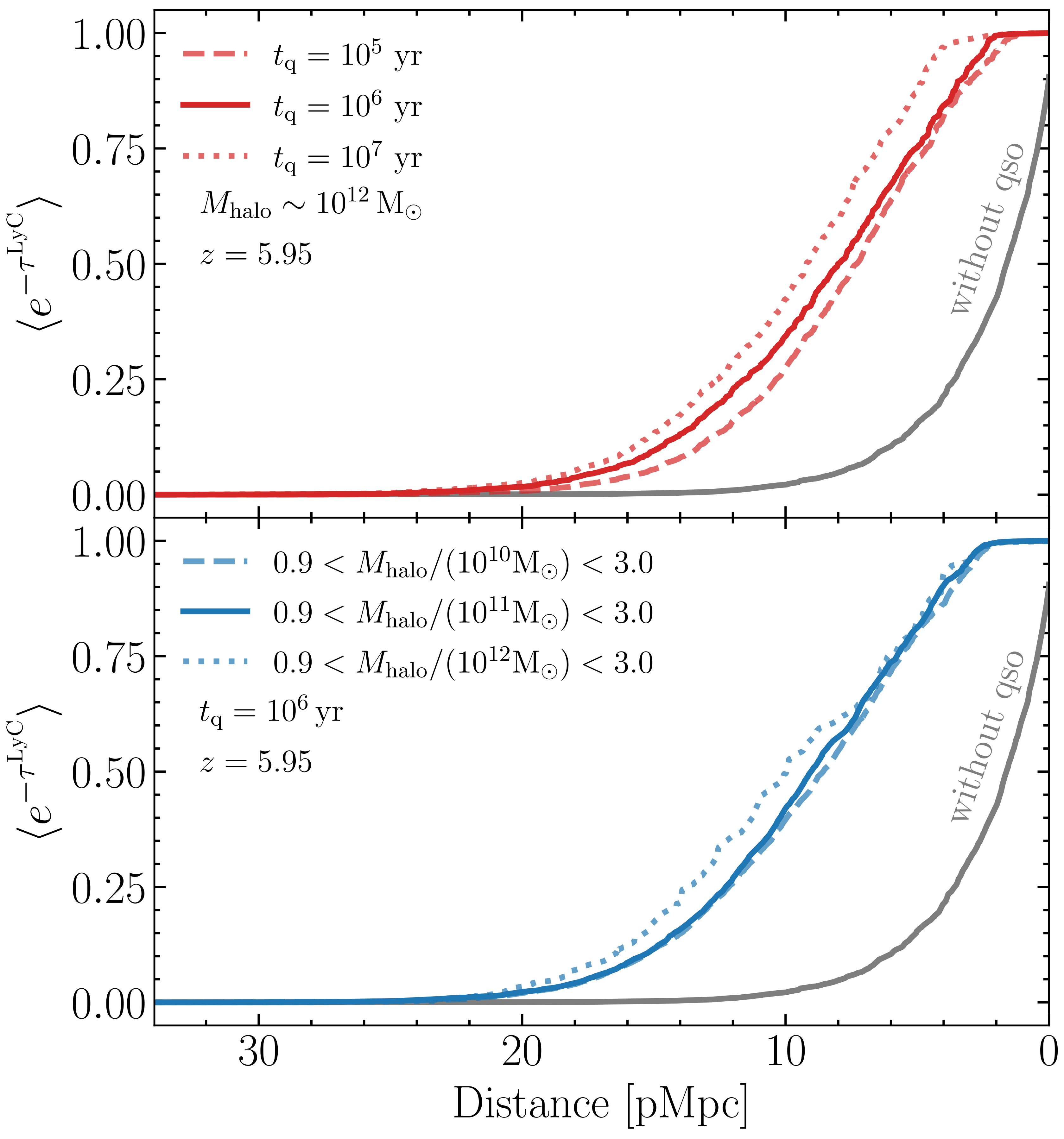


Measured along random directions

Measured along sightlines originating in halos of mass $\sim 10^{12} M_\odot$

Bias increases towards low redshift as the medium is homogeneously ionized

Applying B21 method to model spectra



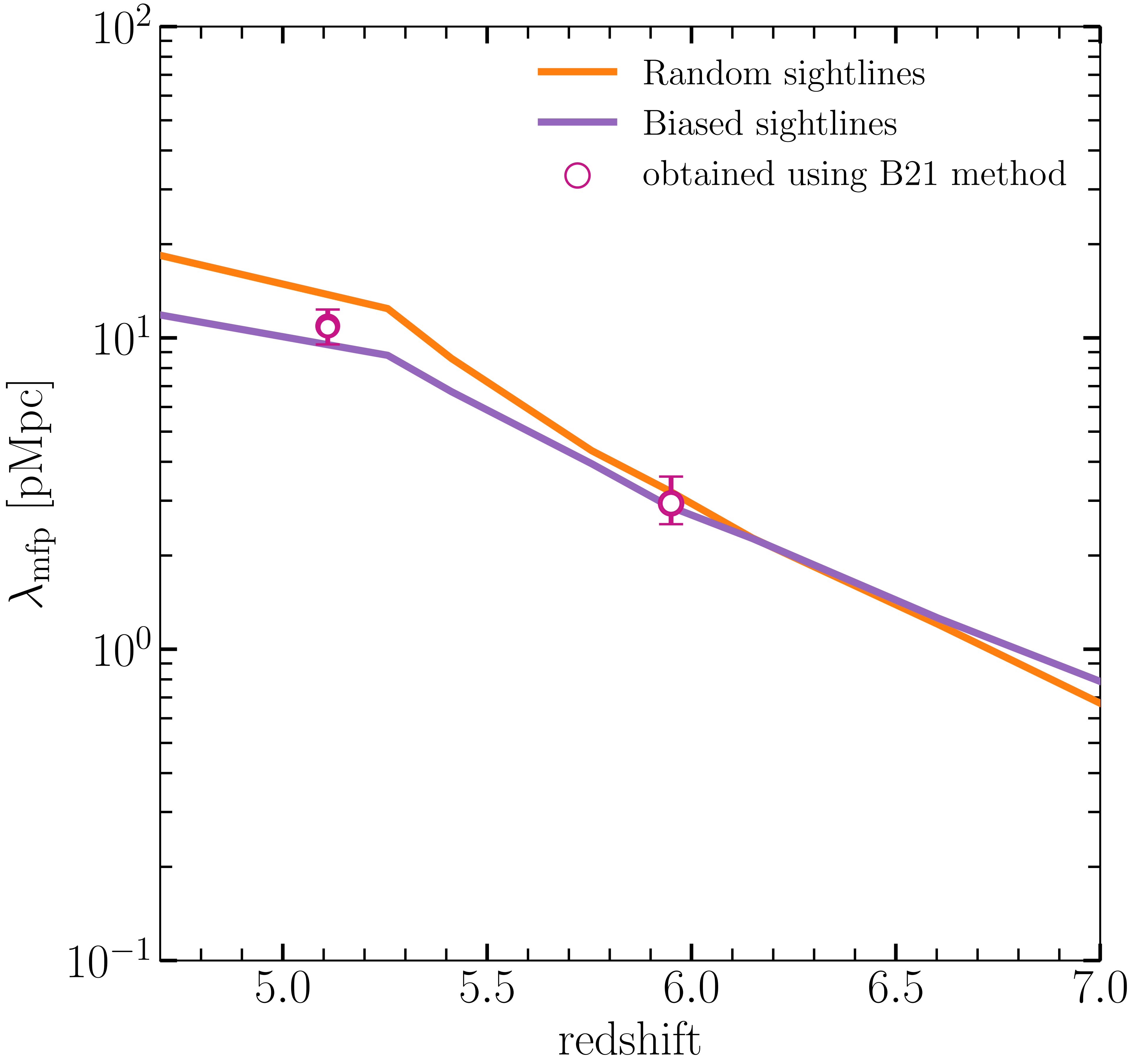
1 Simulated stacks with different quasar properties

$$\tau_{LL} \propto \int \kappa_{912}(r)dr$$

$$\kappa_{912}(r) = \kappa_{912}^{bg}\left(1 + \frac{\Gamma_{qso}}{\Gamma_{bg}}\right)^{-\xi}$$

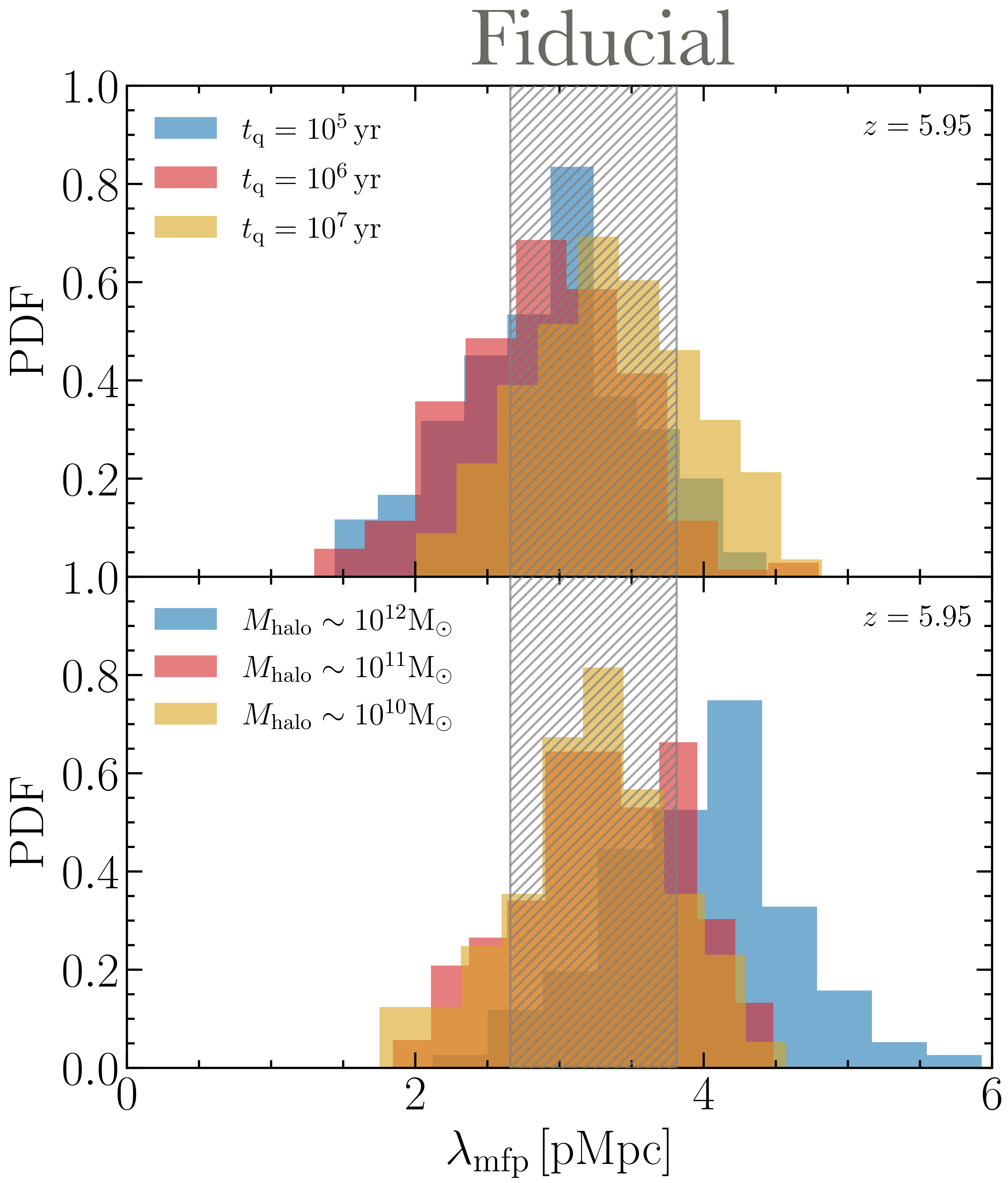
$$\Gamma_{qso} \propto e^{-\kappa_{912}(r)}/r^2$$

2 B21 model

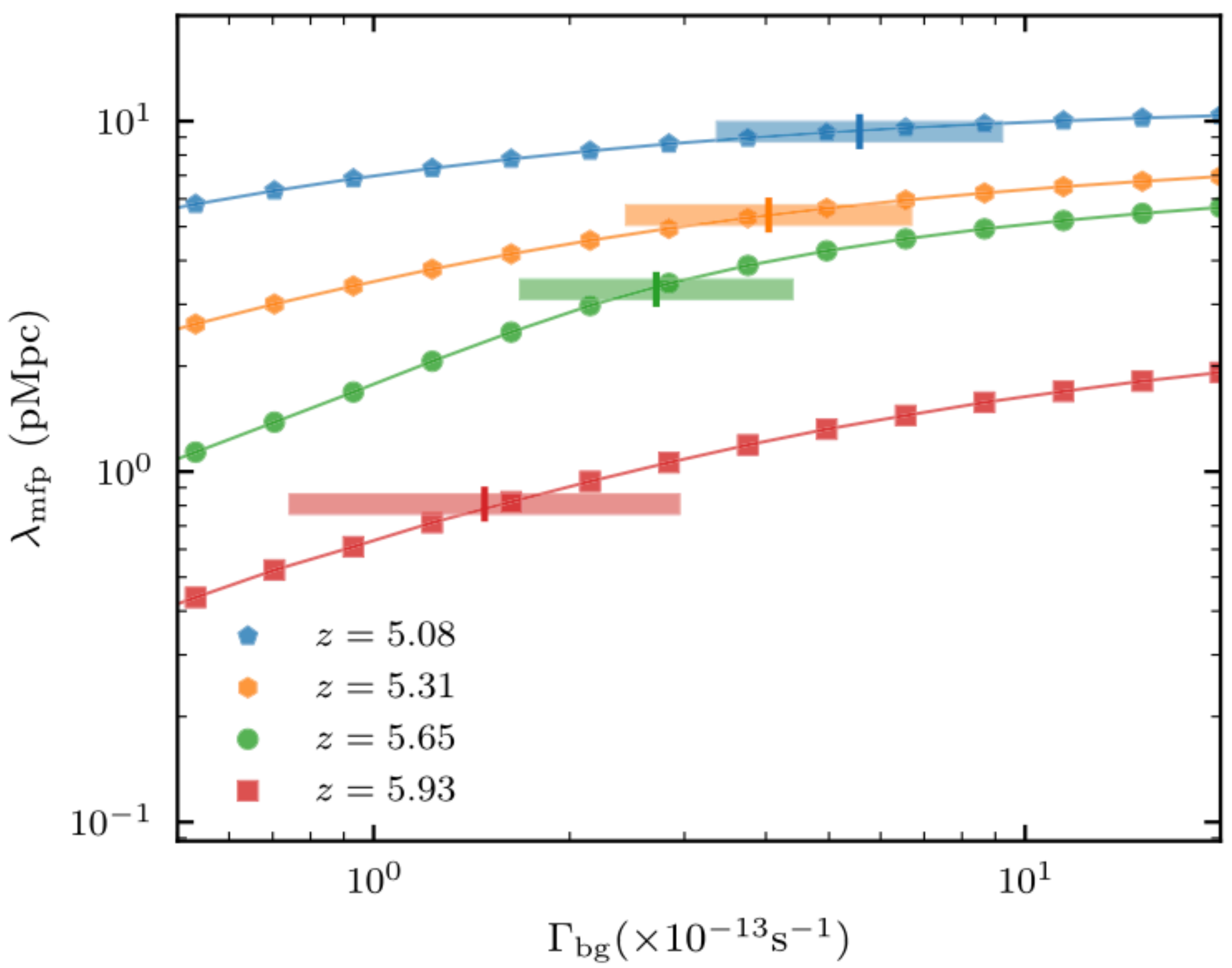


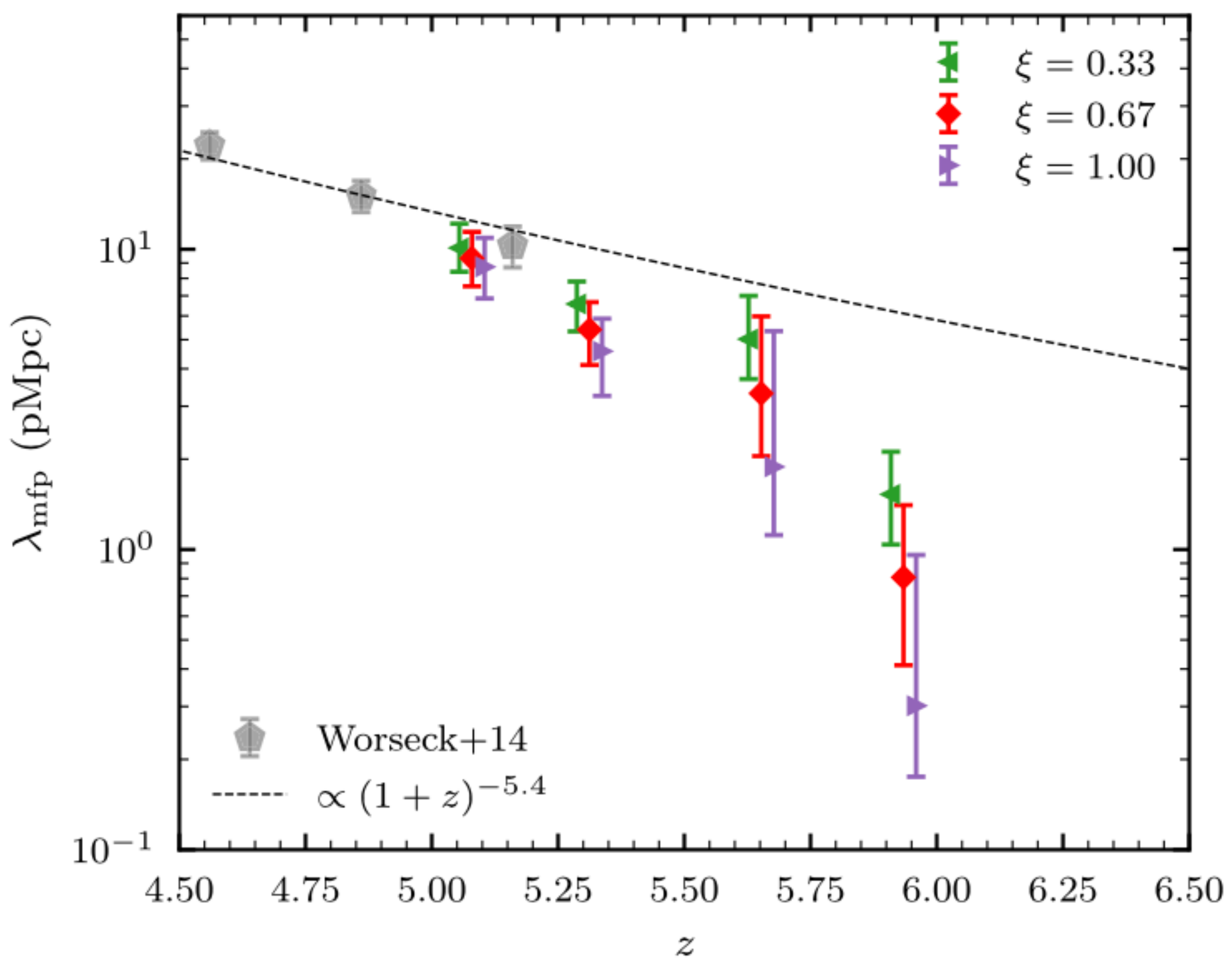
3 Mock measurements are consistent with simulations

Systematic errors can be large



Bias due to quasar parameters upto 25%



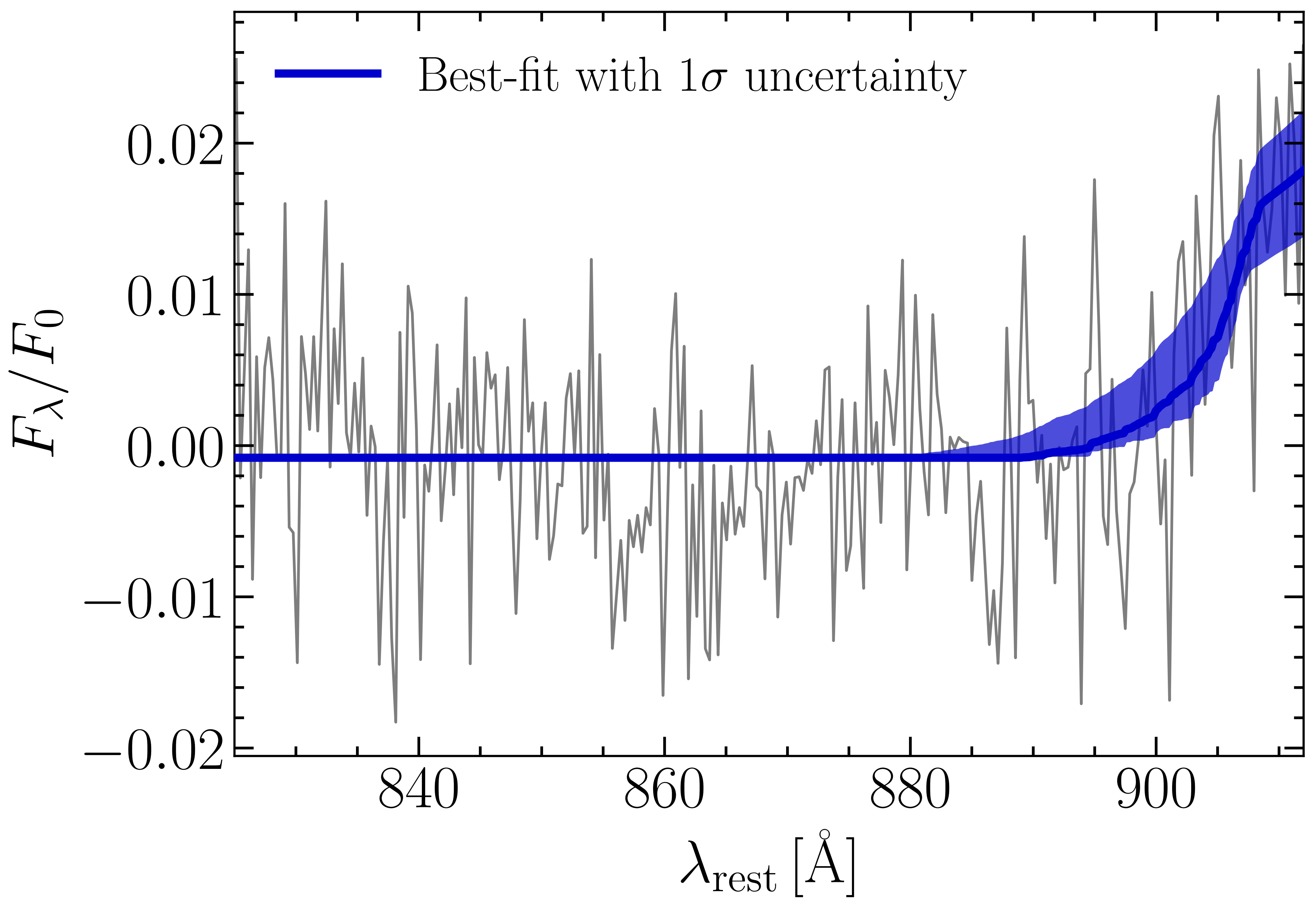


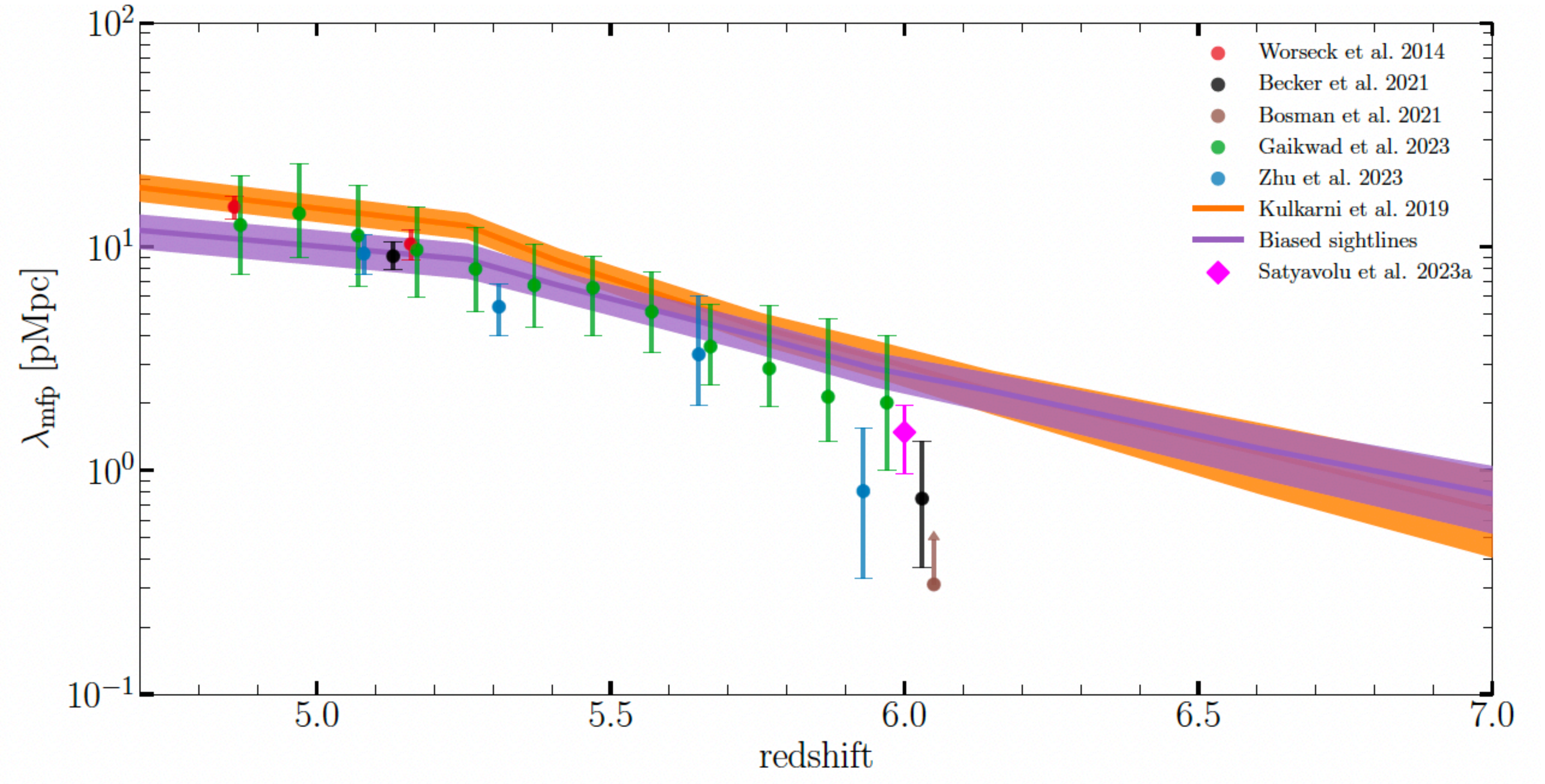
Zhu et al. 2023

Bias due to explicit model parameters upto 50%

Prompted us to attempt measuring the MFP by forward modeling the quasar instead

Measurements with RT models consistent with analytic fitting





Re-evaluation of MFP with B21 stack using simulations gives a similar result, confirming the bias of direct measurements towards a lower MFP at high-z

Summary

- Quasar proximity zones are ionized regions in the IGM around the quasar.
- Limitations of proximity zone modelling challenged our understanding of SMBH growth and reionization.
- We give a model for all observed proximity zone sizes using realistic simulations of reionisation. We show that this model necessitates obscured growth of SMBHs at high redshifts.
- We increase the number of proximity zone sizes measured at high redshifts to 87 using high quality spectra.
- We test the robustness of the direct measurements of the mean free path of hydrogen ionising photons in the epoch of reionization.