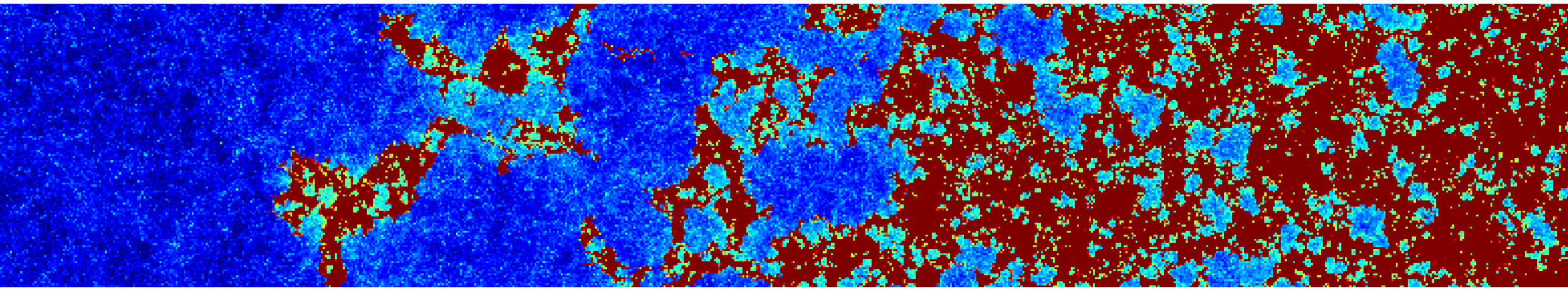
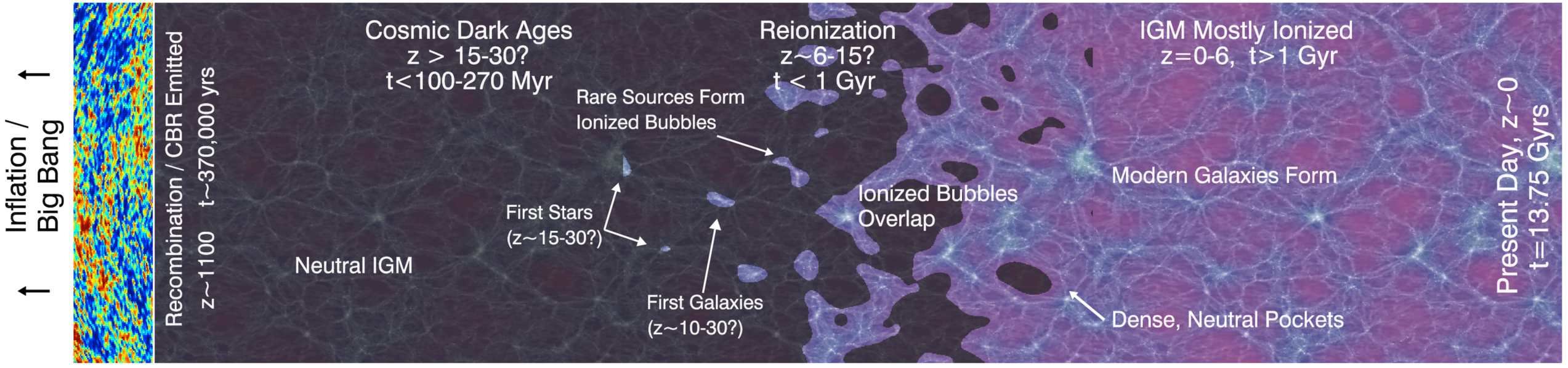
Charting the progress of reionization with quasars and galaxies



Laura Keating
(she/her)

Elizabeth Gardner fellow
Institute for Astronomy, University of Edinburgh

THE UNIVERSITY of EDINBURGH



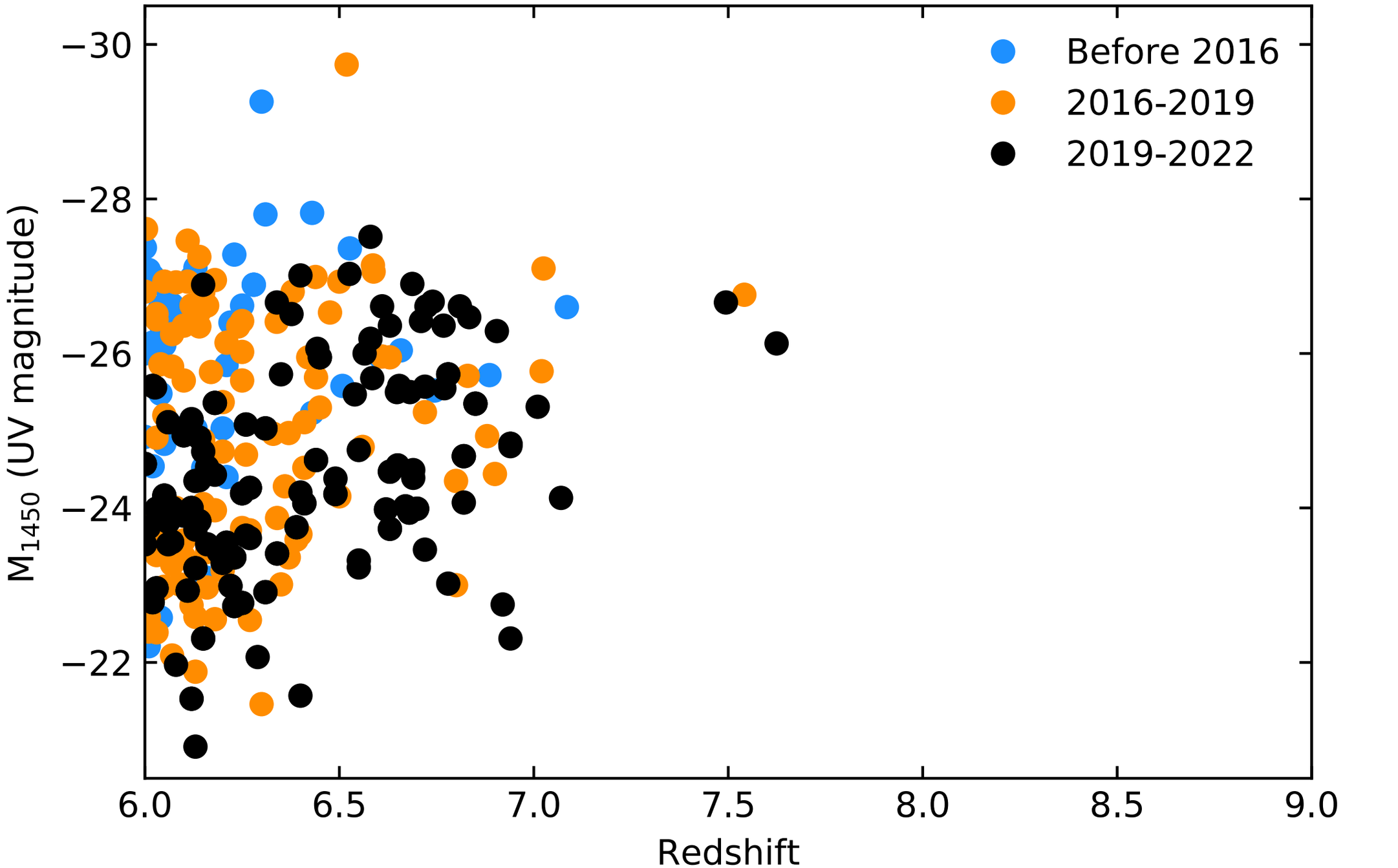
Robertson+10

when? (the timing of reionization)

who? (the sources that ionized the universe)

how? (the shapes/sizes of the ionized regions)

There are now hundreds of quasars known above redshift 6



Based on Fan+23

XQR-30

XQR-30: the ultimate XSHOOTER quasar sample at the reionization epoch

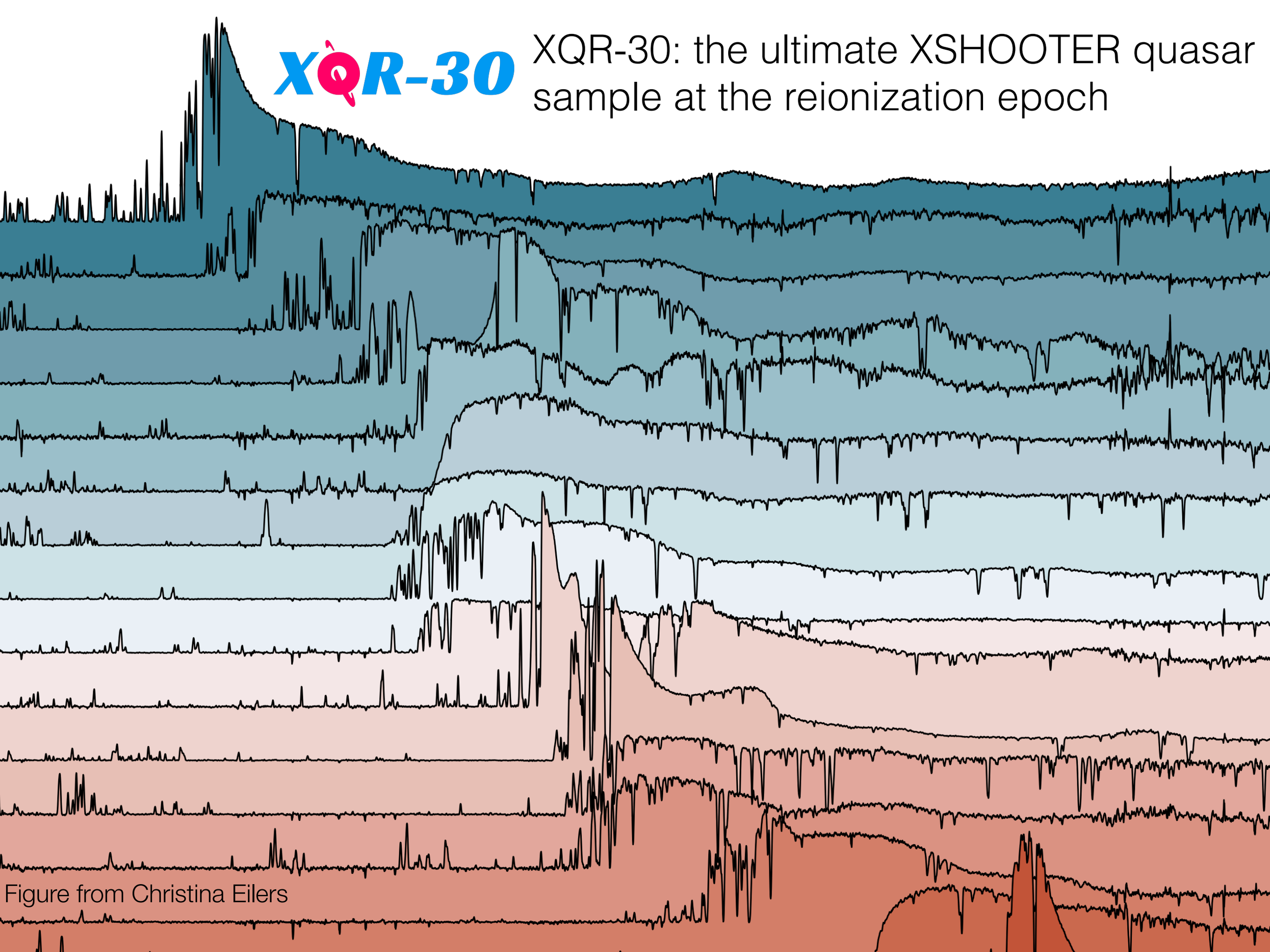
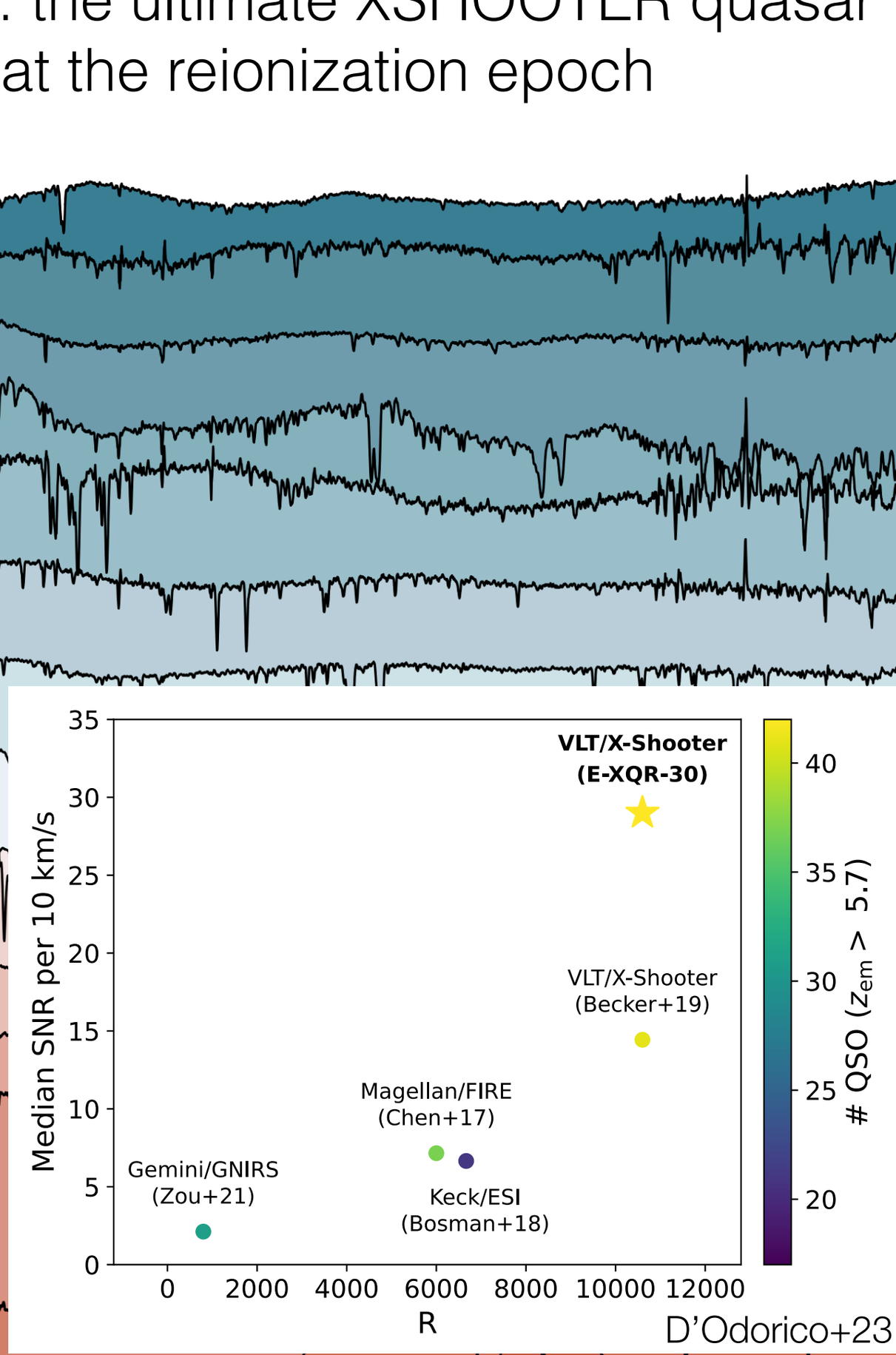


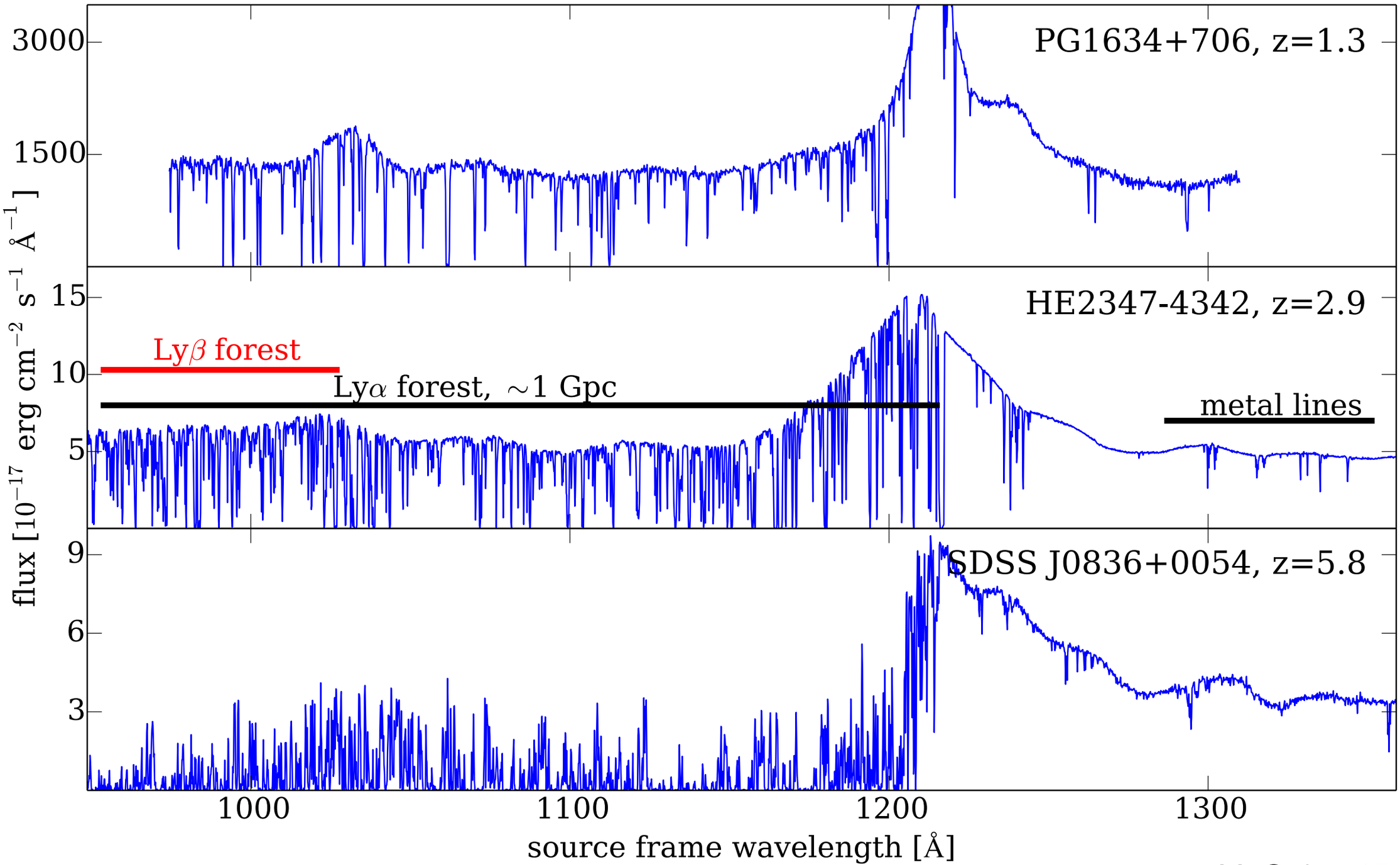
Figure from Christina Eilers

XQR-30: the ultimate XSHOOTER quasar sample at the reionization epoch

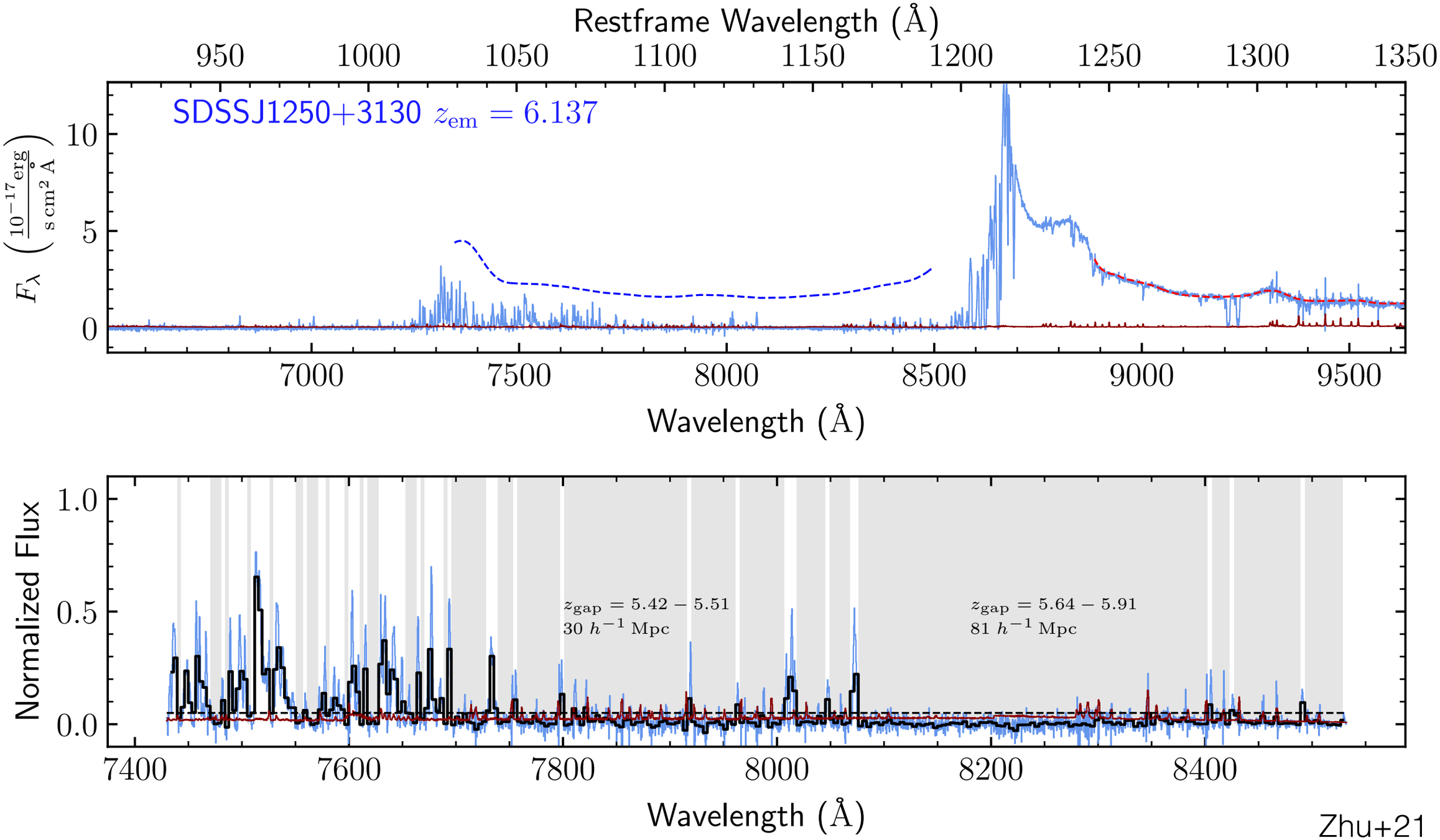
Figure from Christina Eilers



The mean flux of the Lyα forest is evolving with redshift

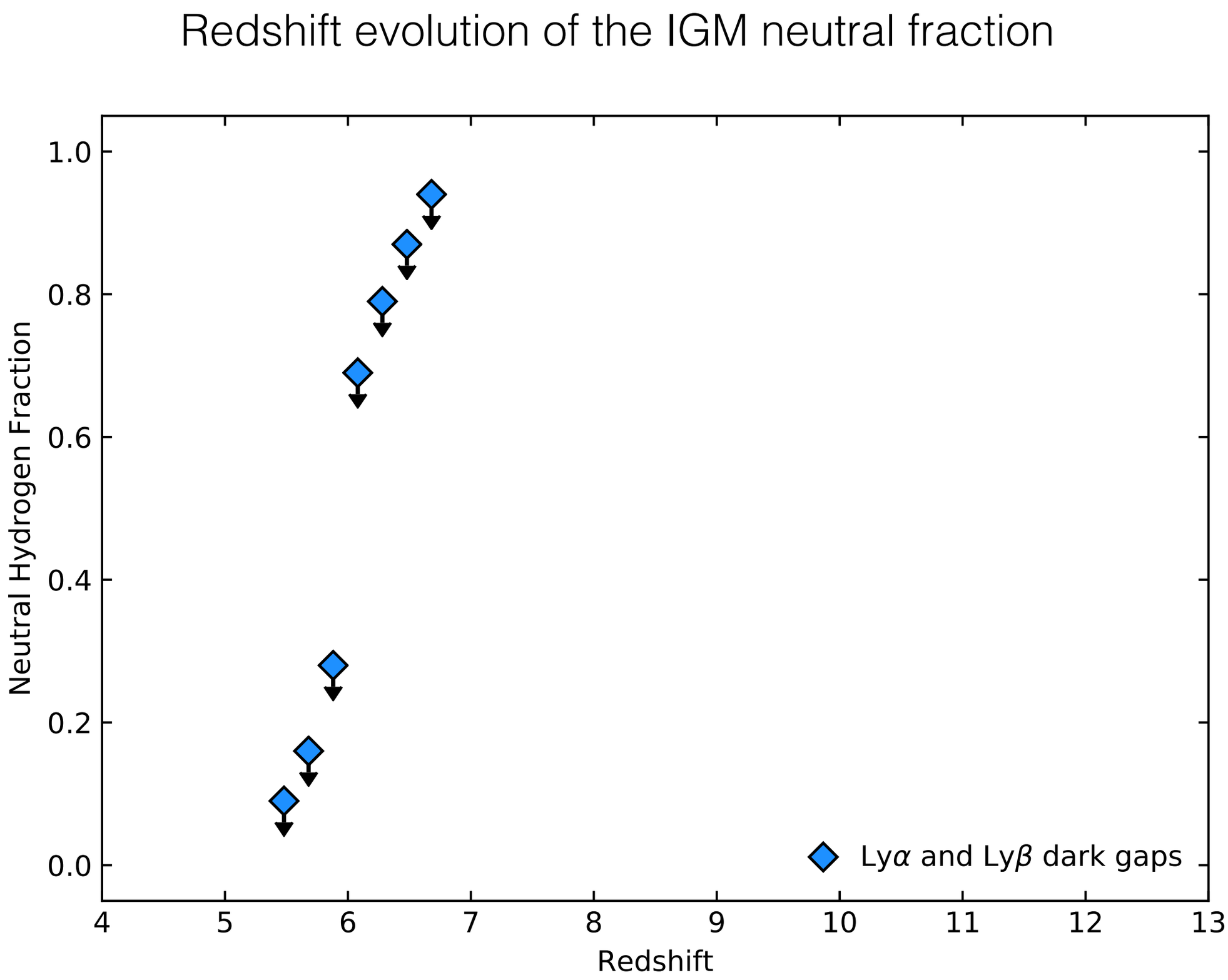


McQuinn 15



What if every dark gap was an island of neutral gas?

Conservative, since Lyα forest saturates at $x_{HI} \sim 10^{-5}$



Jin+23

see also: Mesinger 01, McGreer+11,15, Zhu+22

At the same redshift, the Lyα forest looks very different along different sightlines

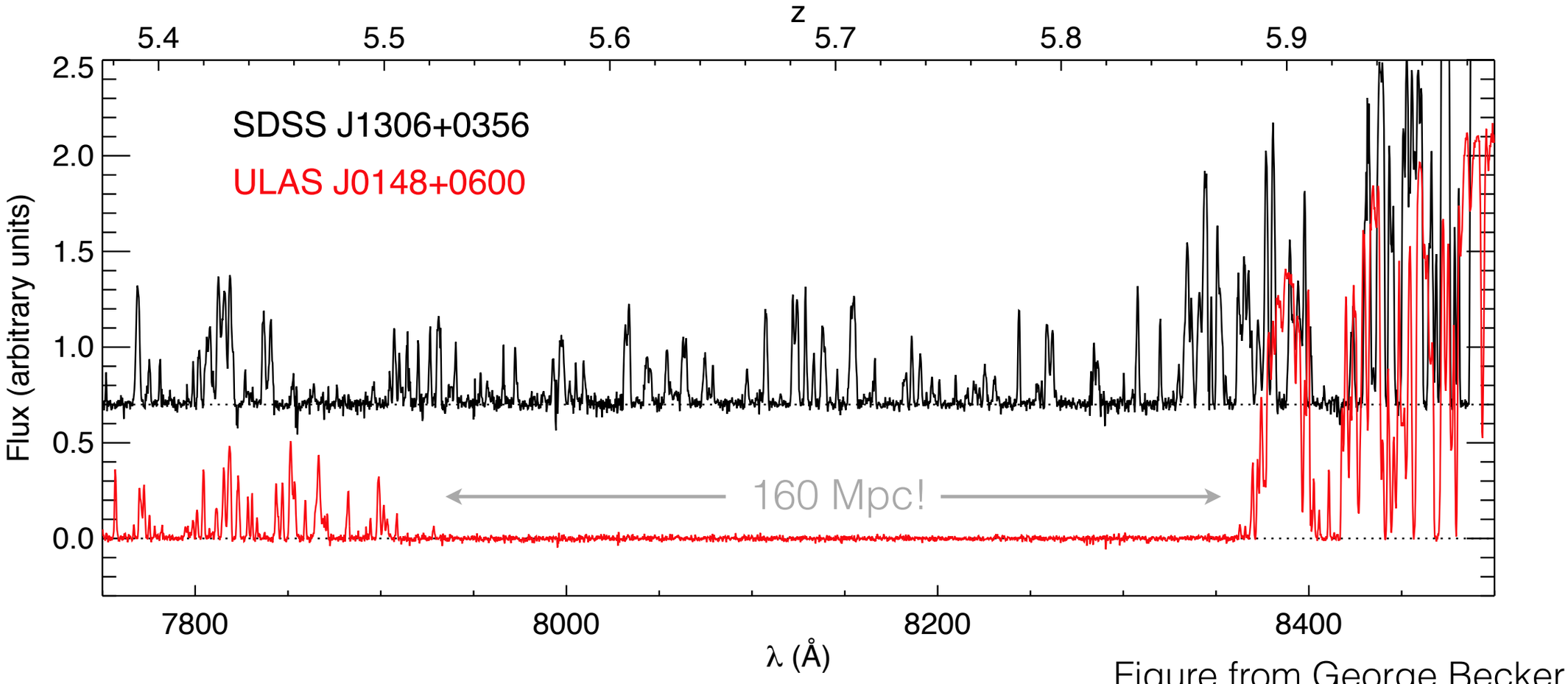
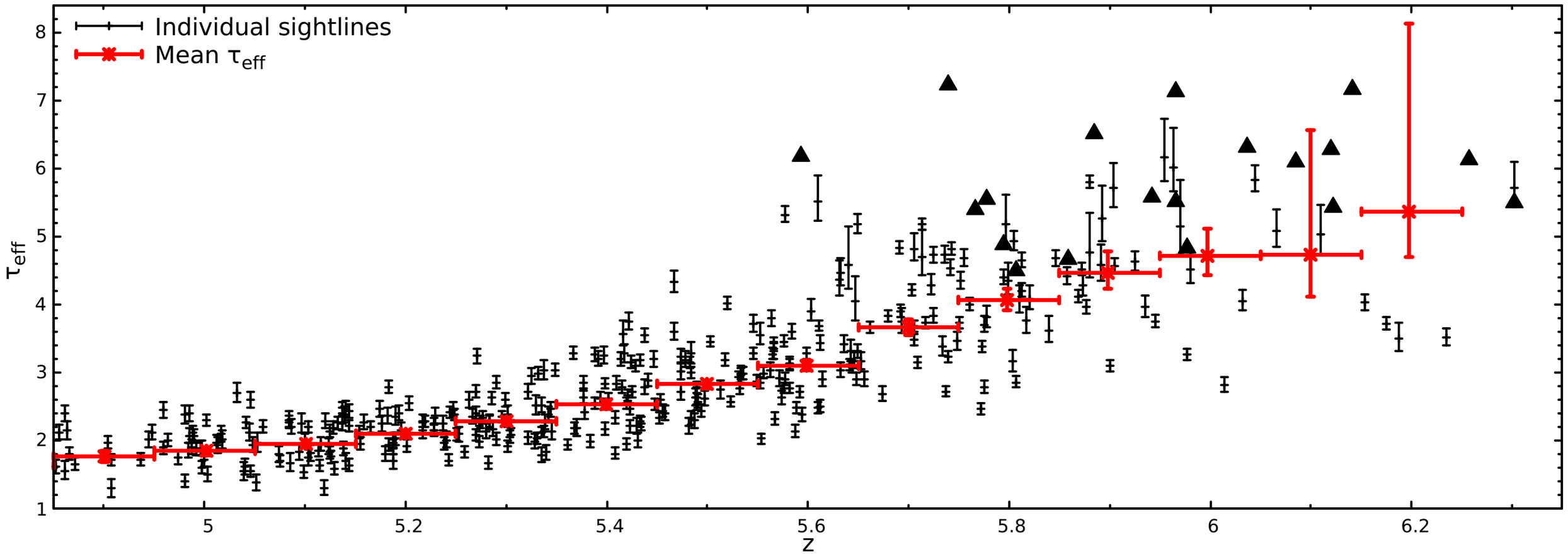


Figure from George Becker

This can be quantified by measuring the evolution of the mean flux of the Lyα forest with redshift

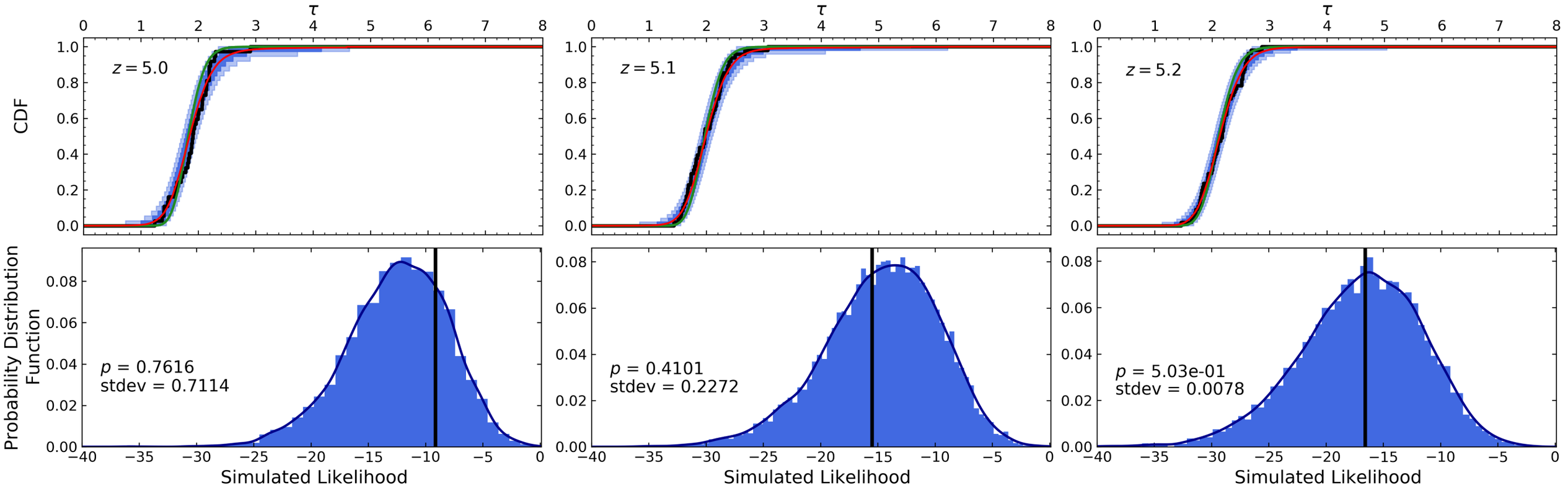


Bosman+22

$$\langle F \rangle = \exp(-\tau_{\rm eff})$$

measured in 50 Mpc/h segments

Some of the scatter can be explained by the density field, but this is not enough to explain the distribution towards higher redshift



Bosman+22

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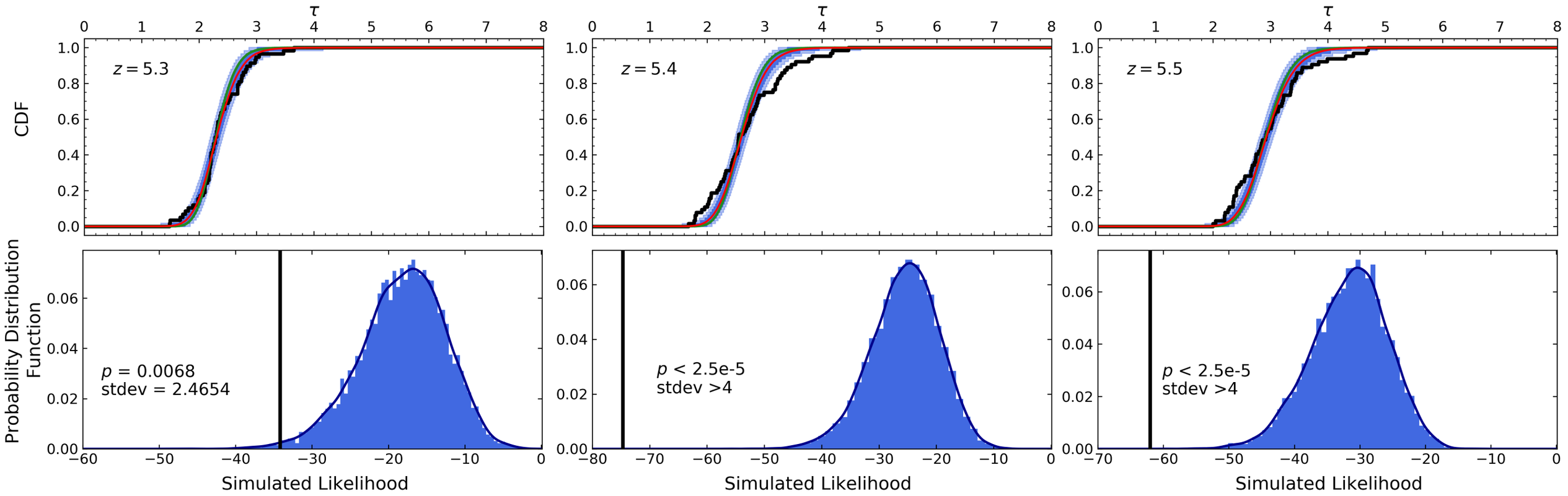

Bosman+22

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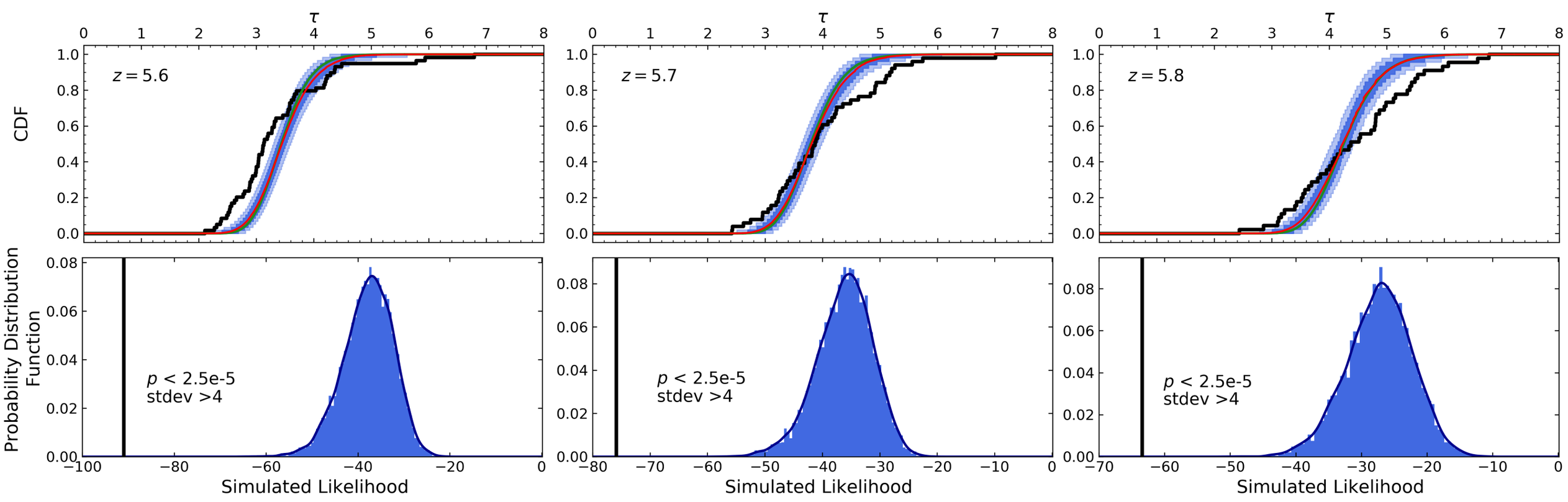
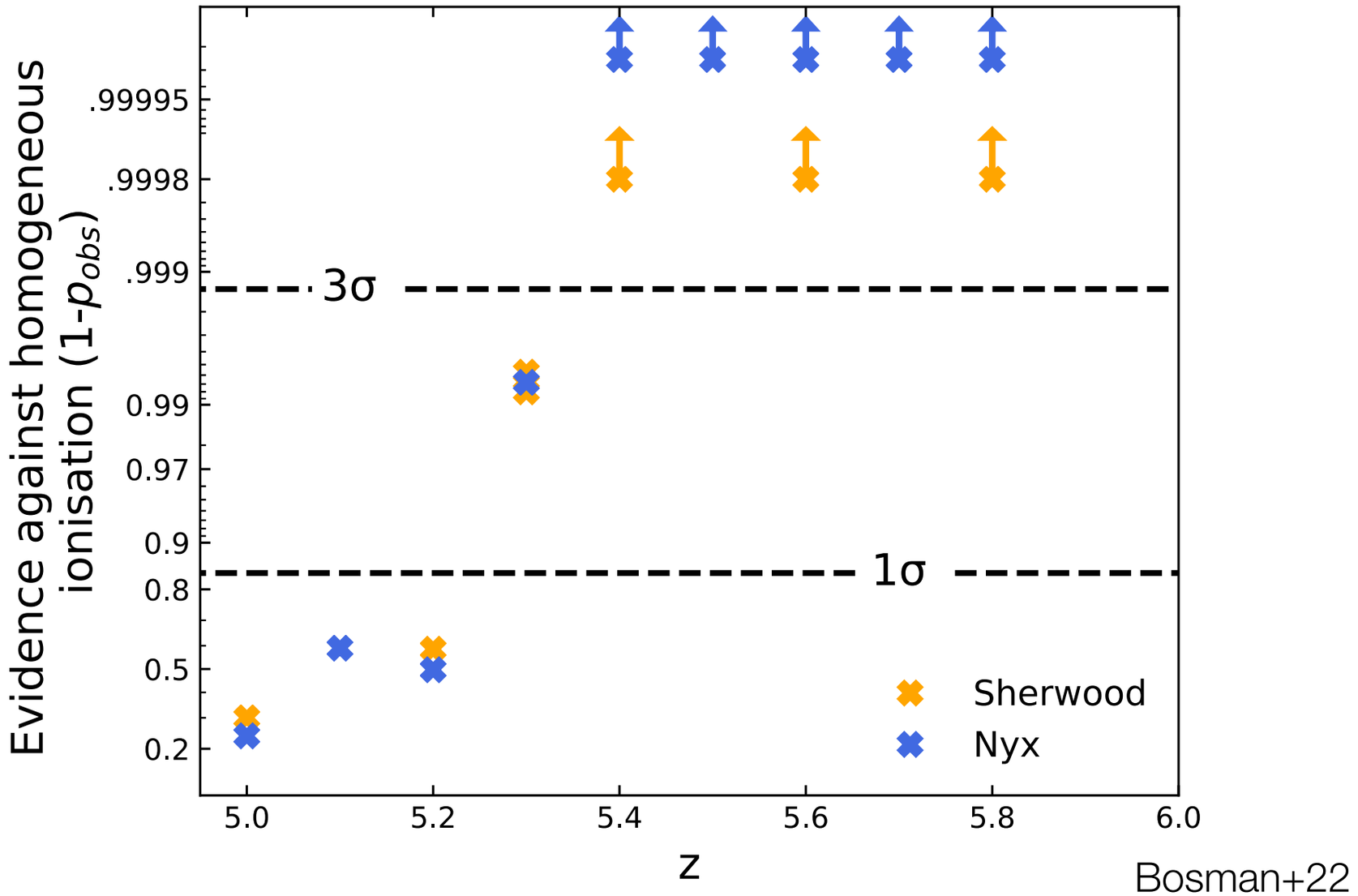
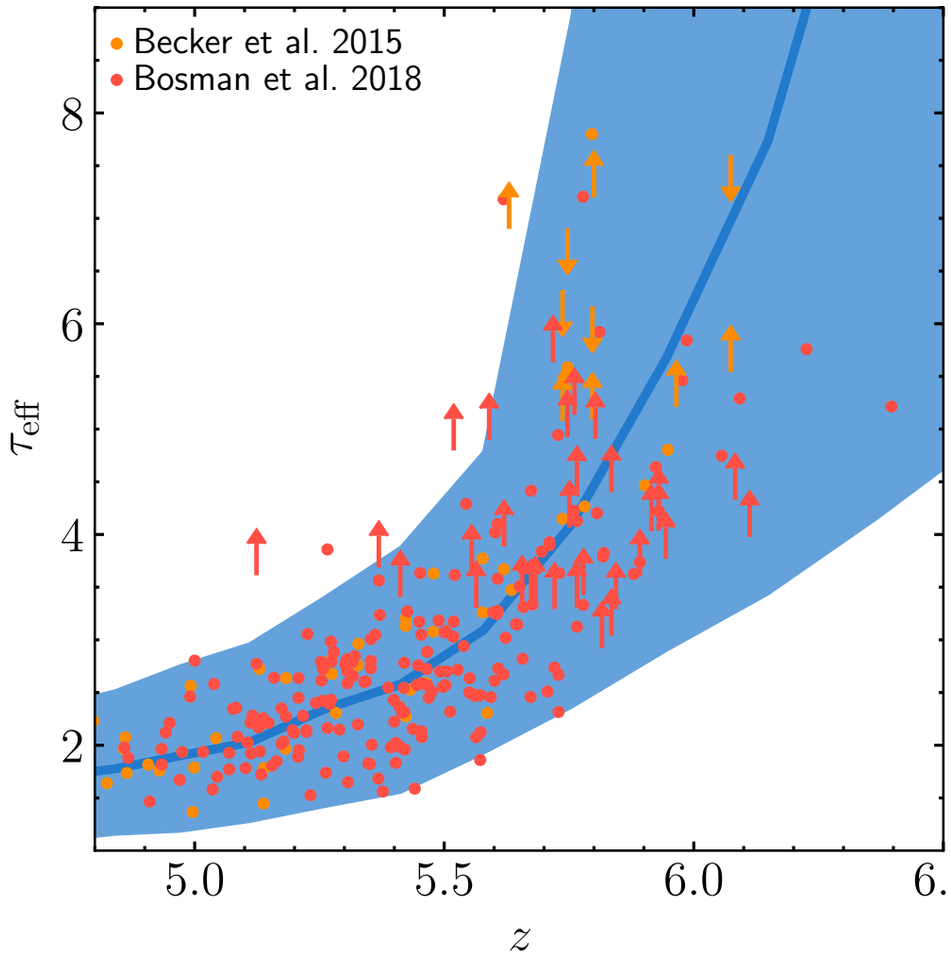


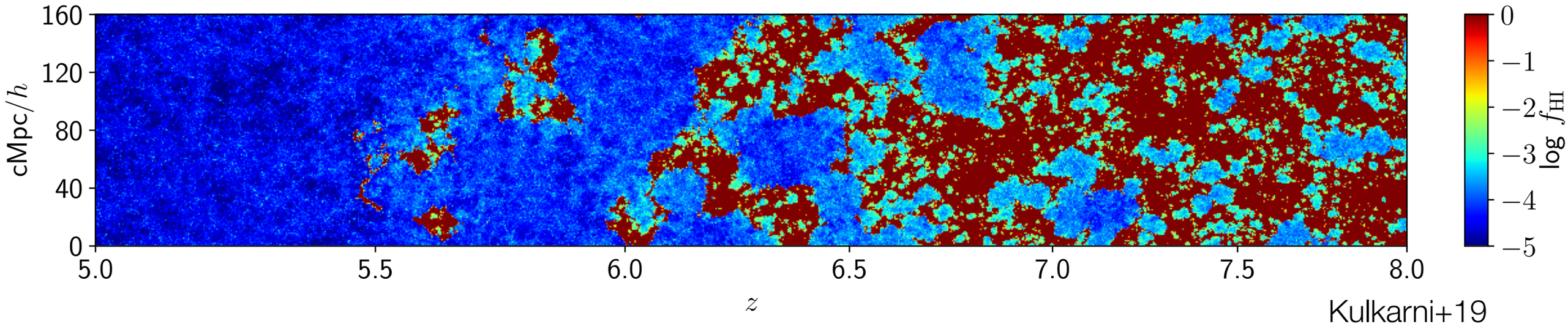
Bosman+22

The role of density fluctuations alone can be ruled out at 3.5σ by redshift 5.4



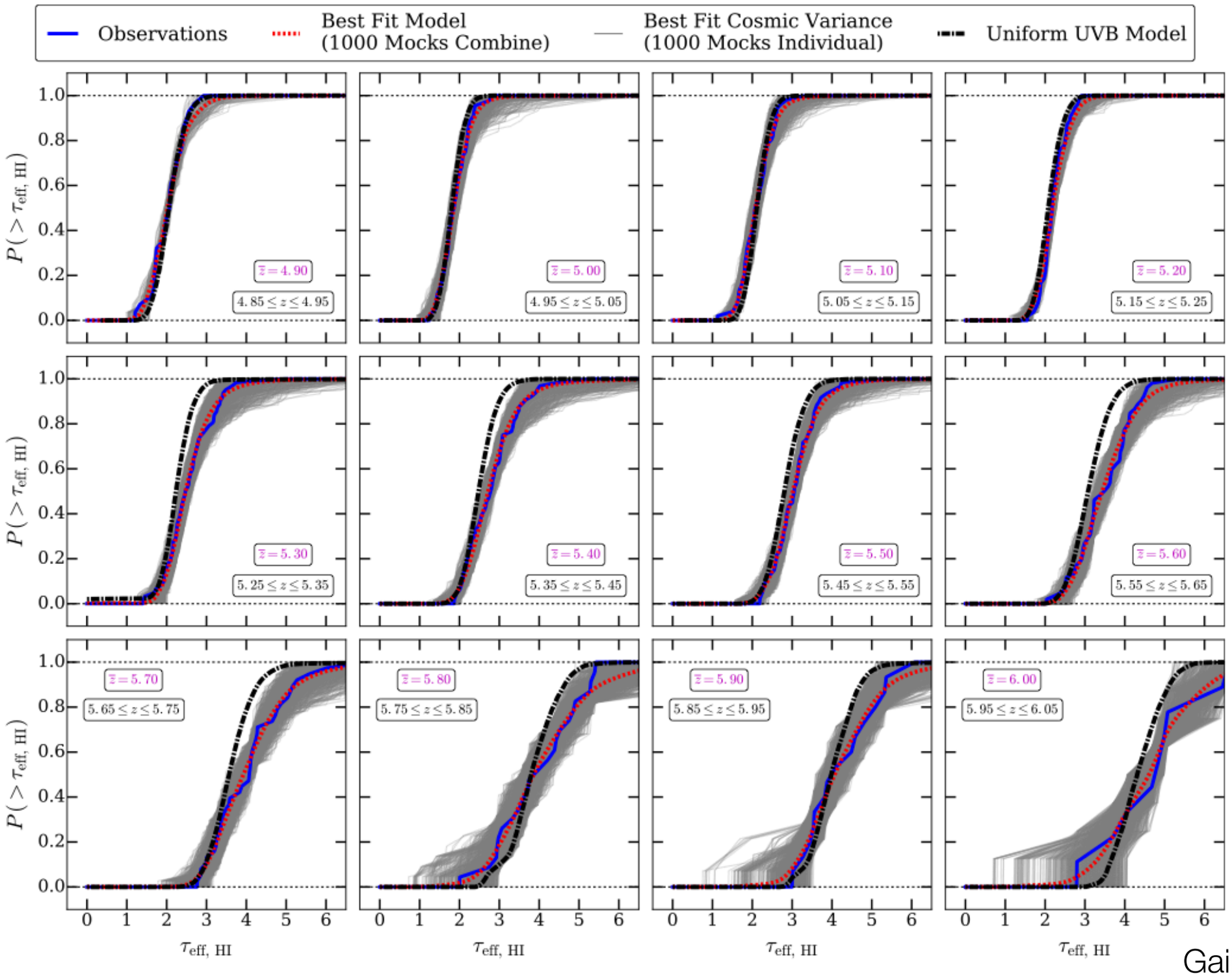


The increasing scatter in the effective optical depth above z = 5.5 can be driven by large islands of neutral gas in the IGM

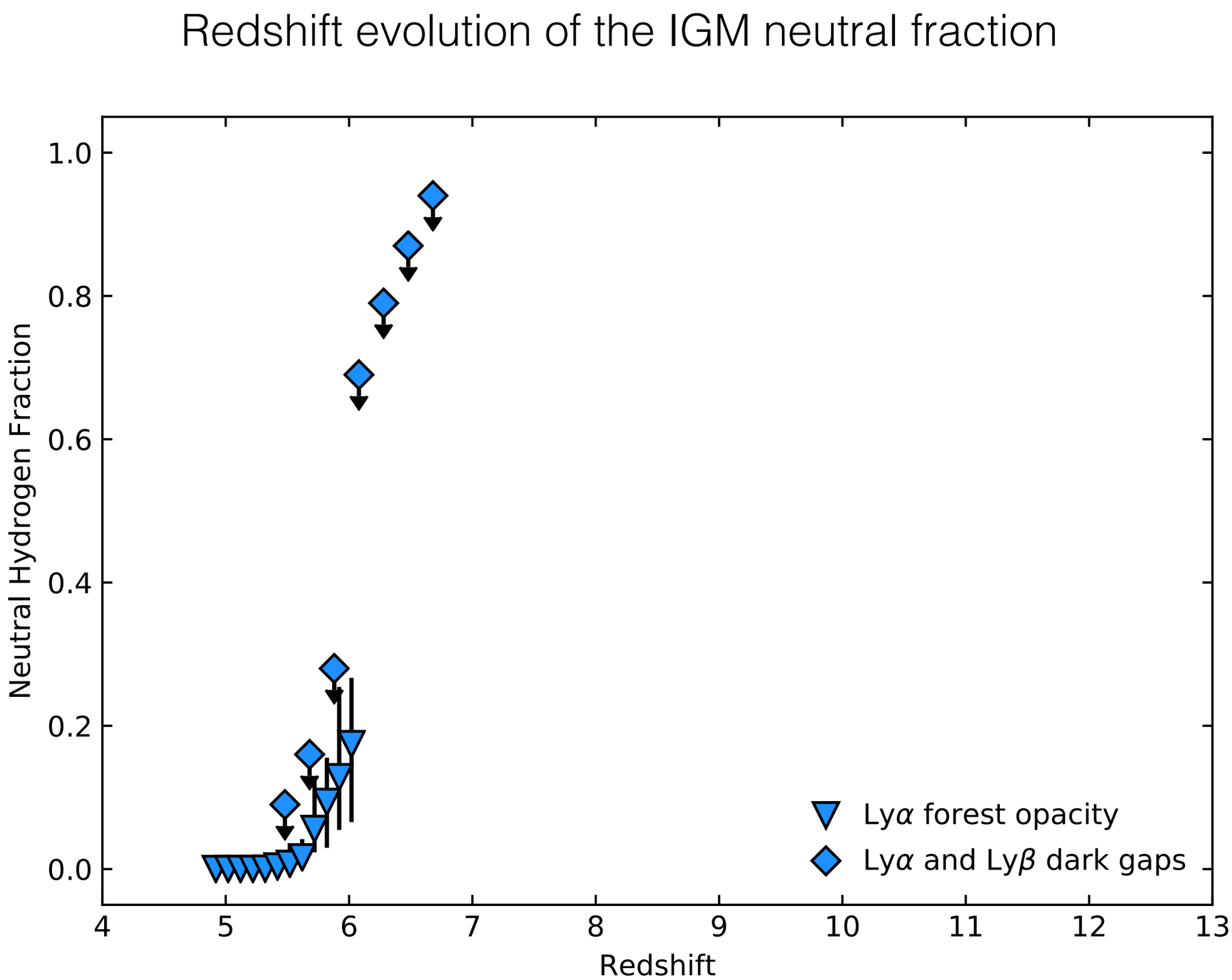


Kulkarni+19

Fitting for the evolution of the Lyα forest opacities tightly constrains the end of reionization

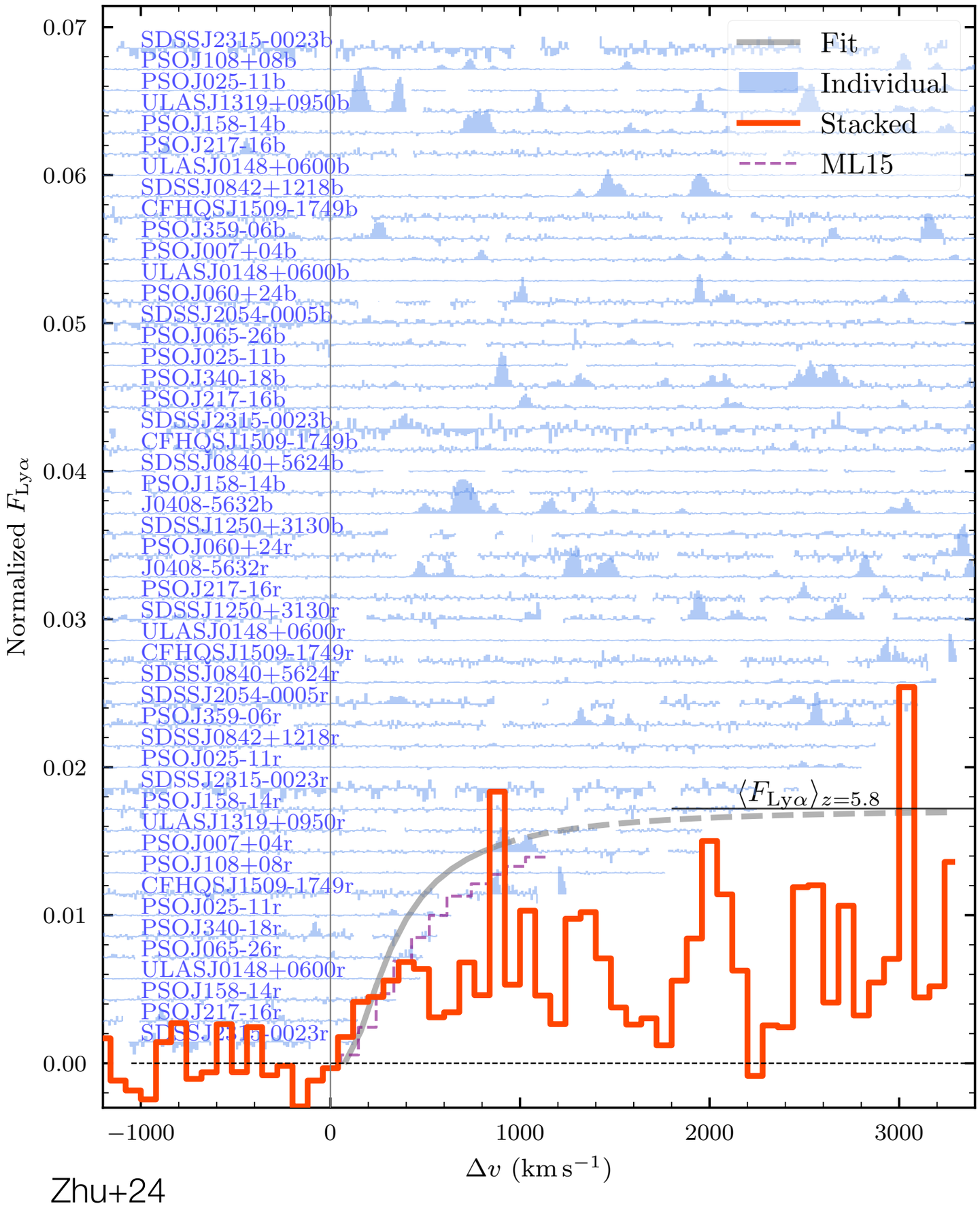


Gaikwad+23



Gaikwad+23

see also: Kulkarni+19, Nasir & D'Aloisio 20, Qin+21, Choudhury+21, Garaldi+22, Davies+24



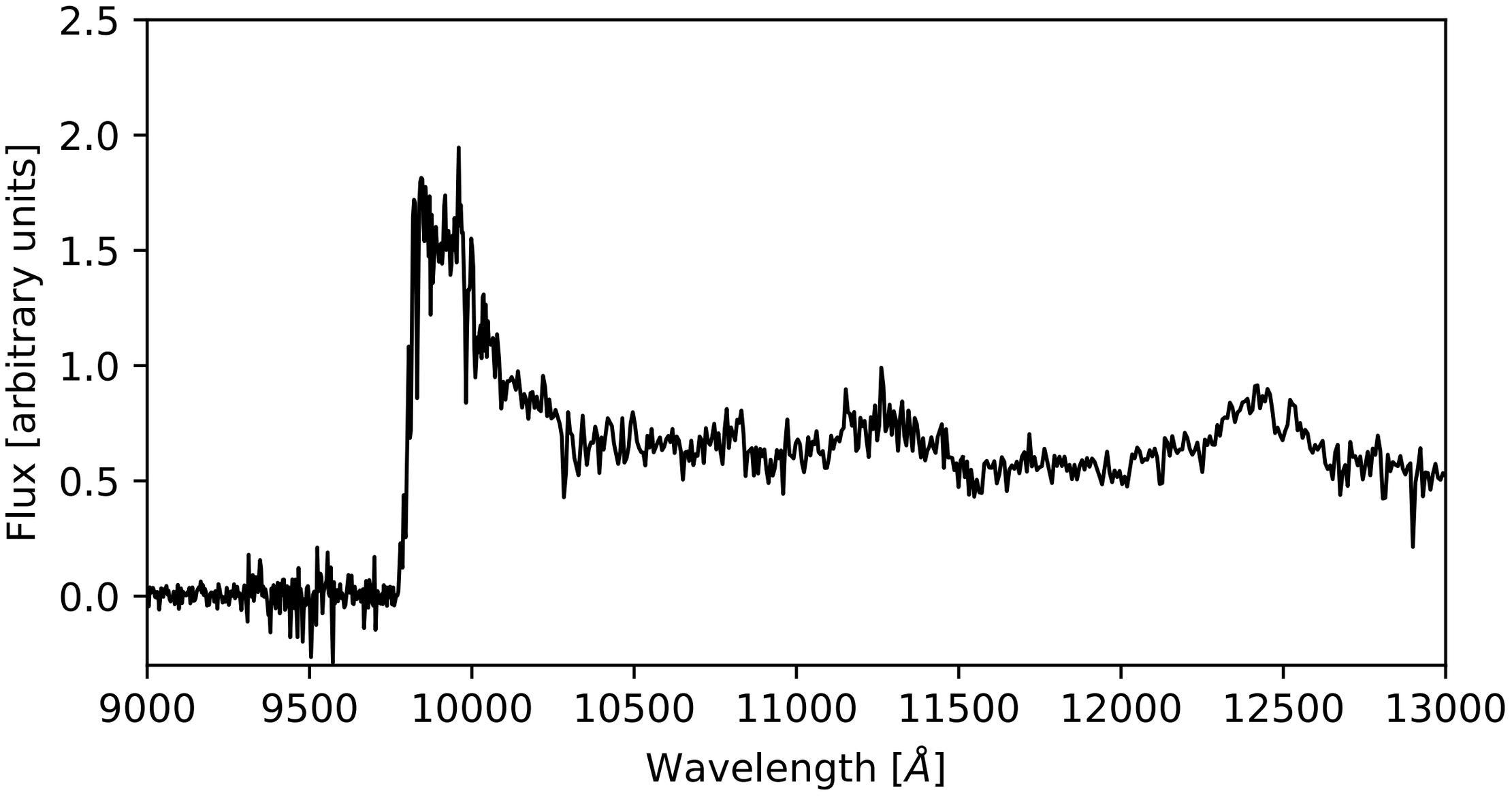
Zhu+24

Potential damping wings at the edges of Gunn-Peterson troughs:

Direct evidence for islands of neutral hydrogen?

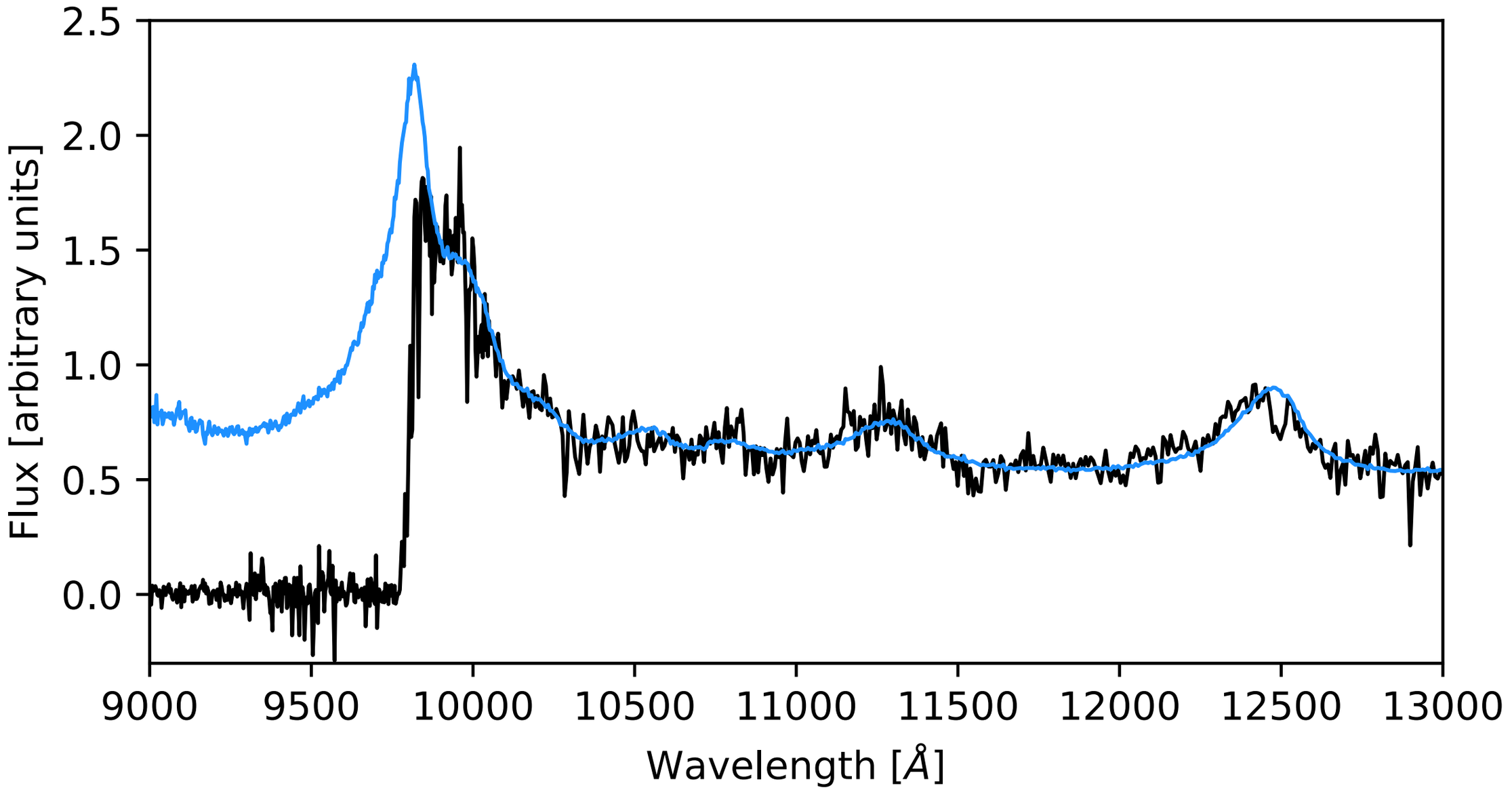
see also:
Lidz & Malloy 15,
Becker+24, Spina+24

Absorption redward of Lyman-α in the highest redshift quasars points to a significantly neutral IGM



Adapted from Mortlock+11

Absorption redward of Lyman-α in the highest redshift quasars points to a significantly neutral IGM



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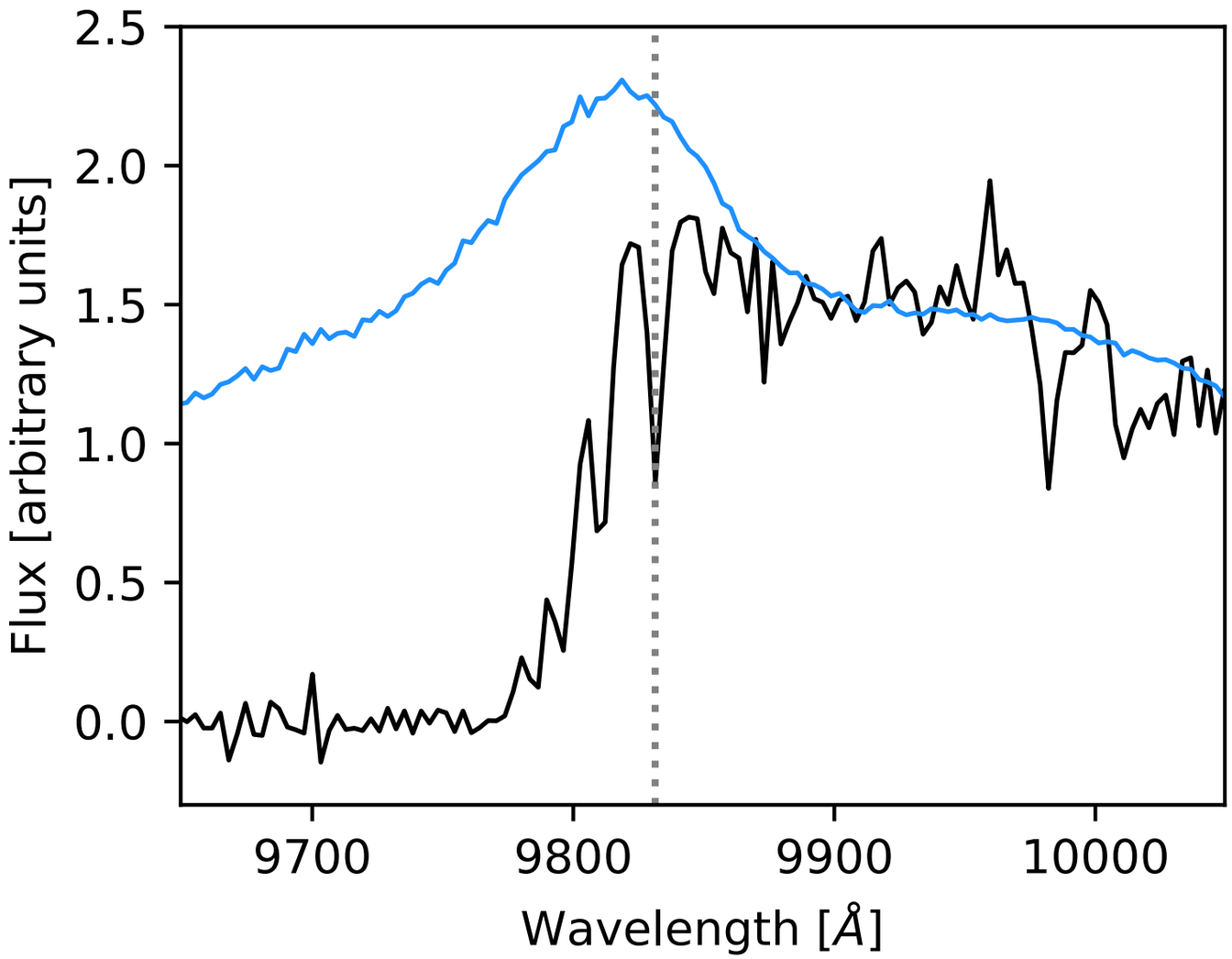
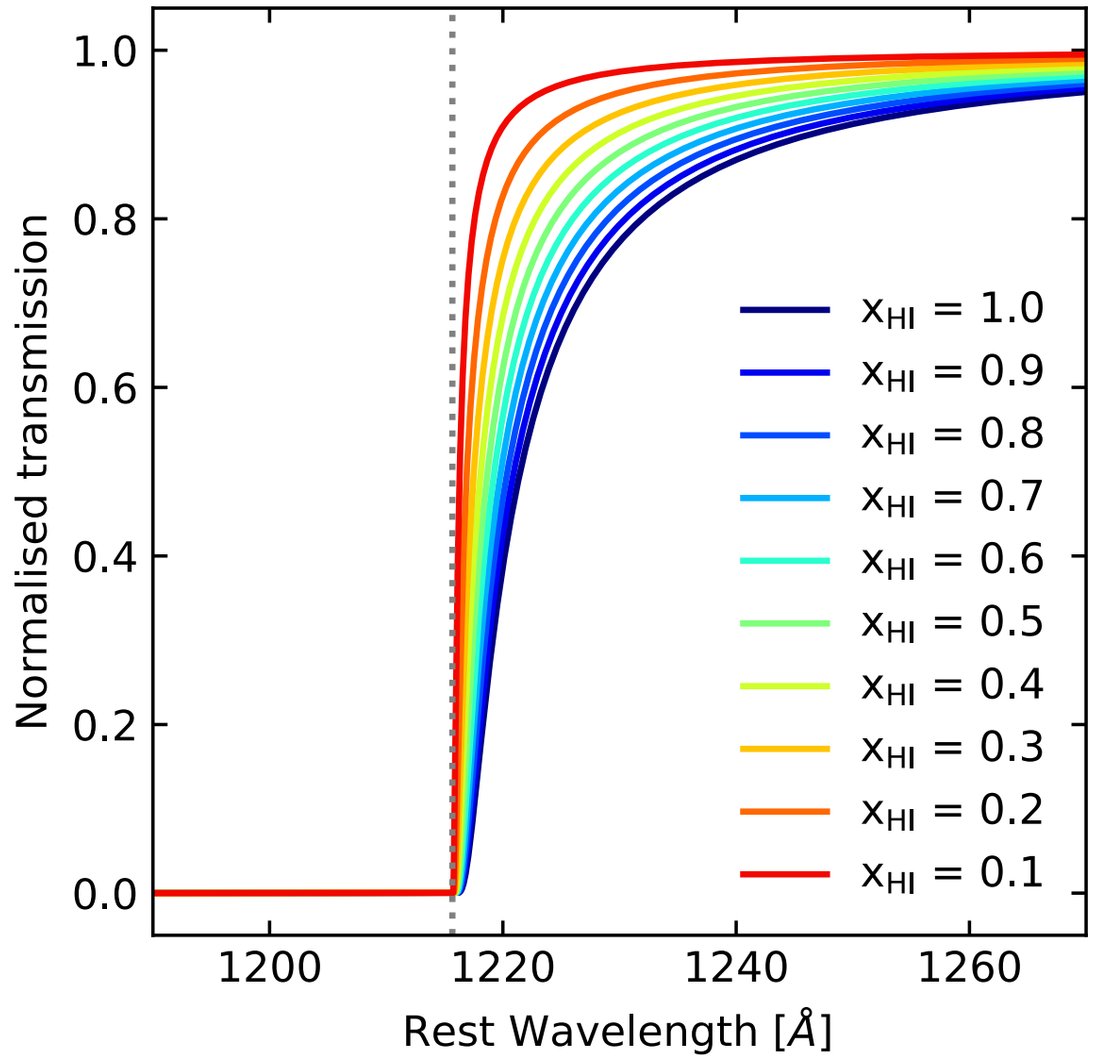
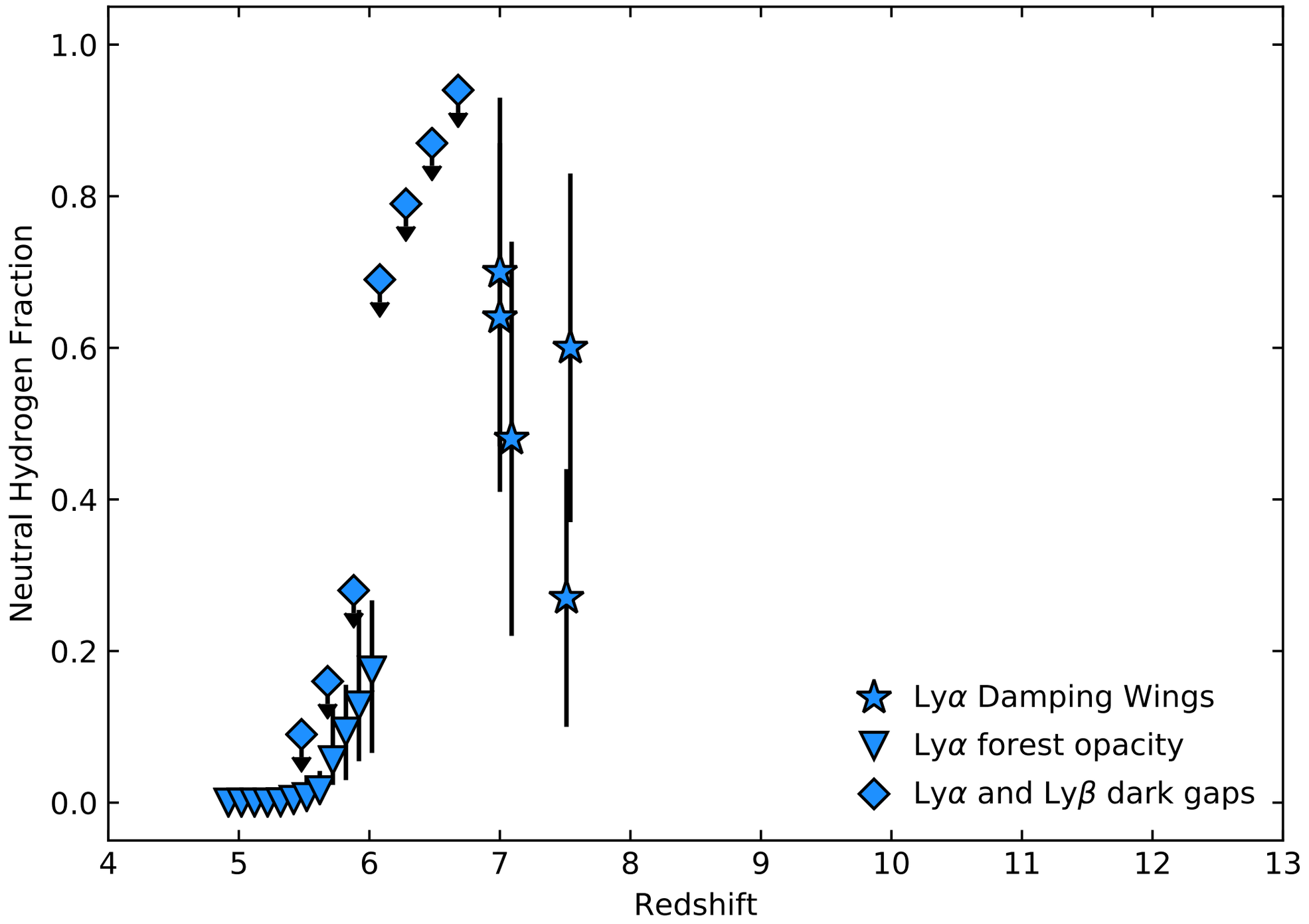




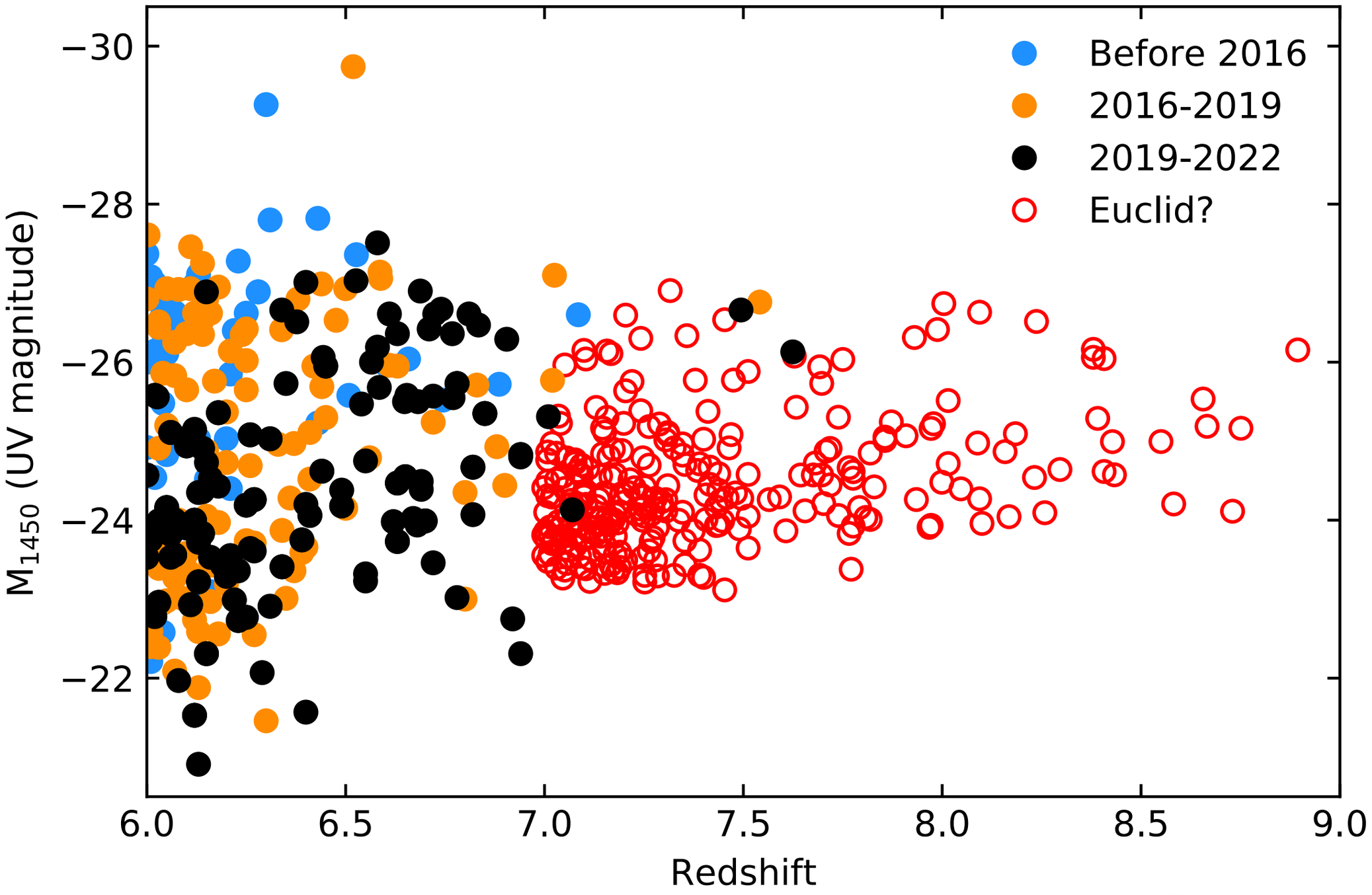
Adapted from Mortlock+11



Davies+18, Greig+22, Wang+22

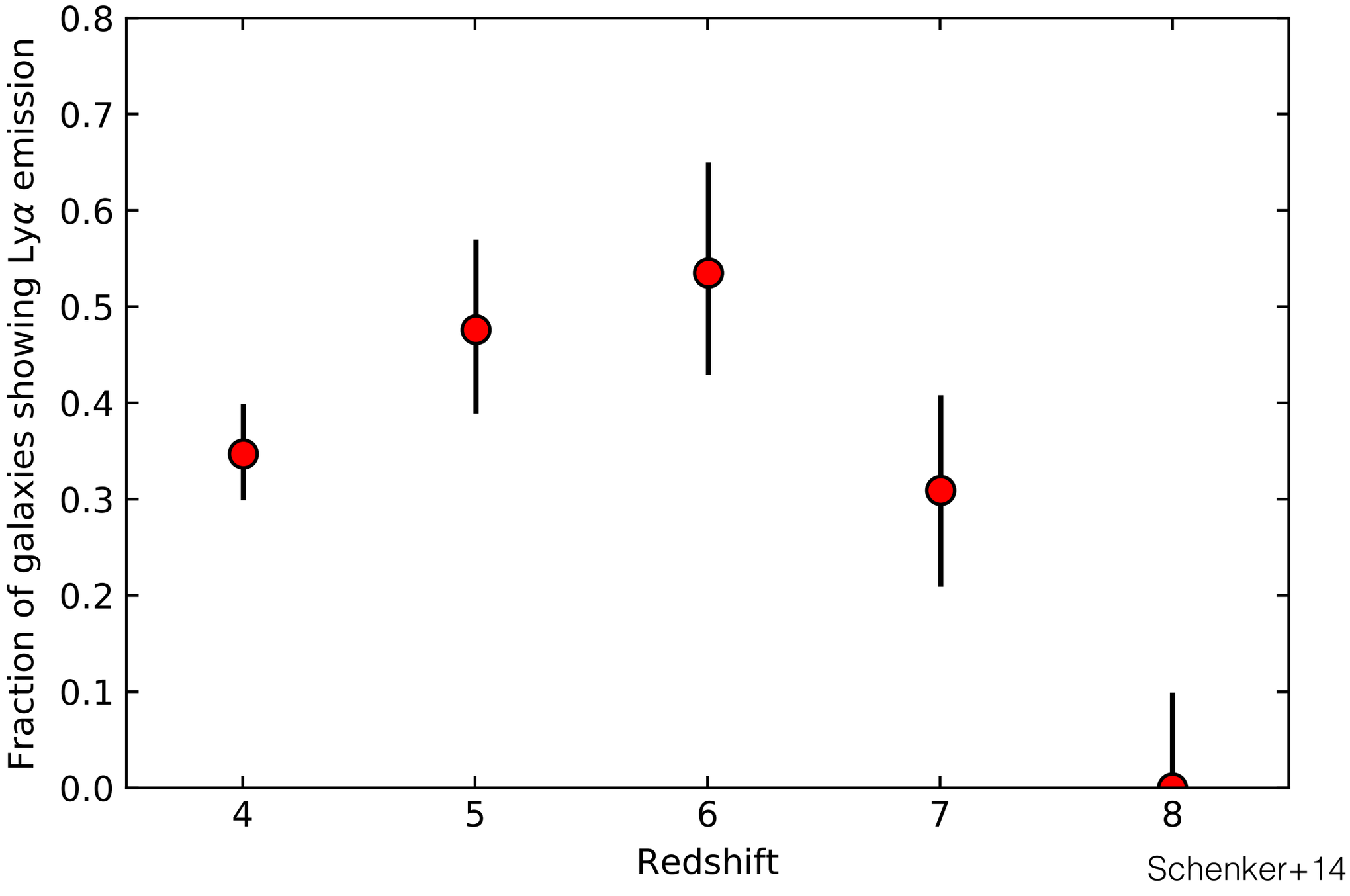
see also: Mesinger & Haiman 07, Mortlock+11, Bolton+11, Schroeder+13, Greig+17, Banados+18, Yang+20, Durovcikova+24, Greig+24

Euclid may push studies of reionization with QSOs to higher redshifts

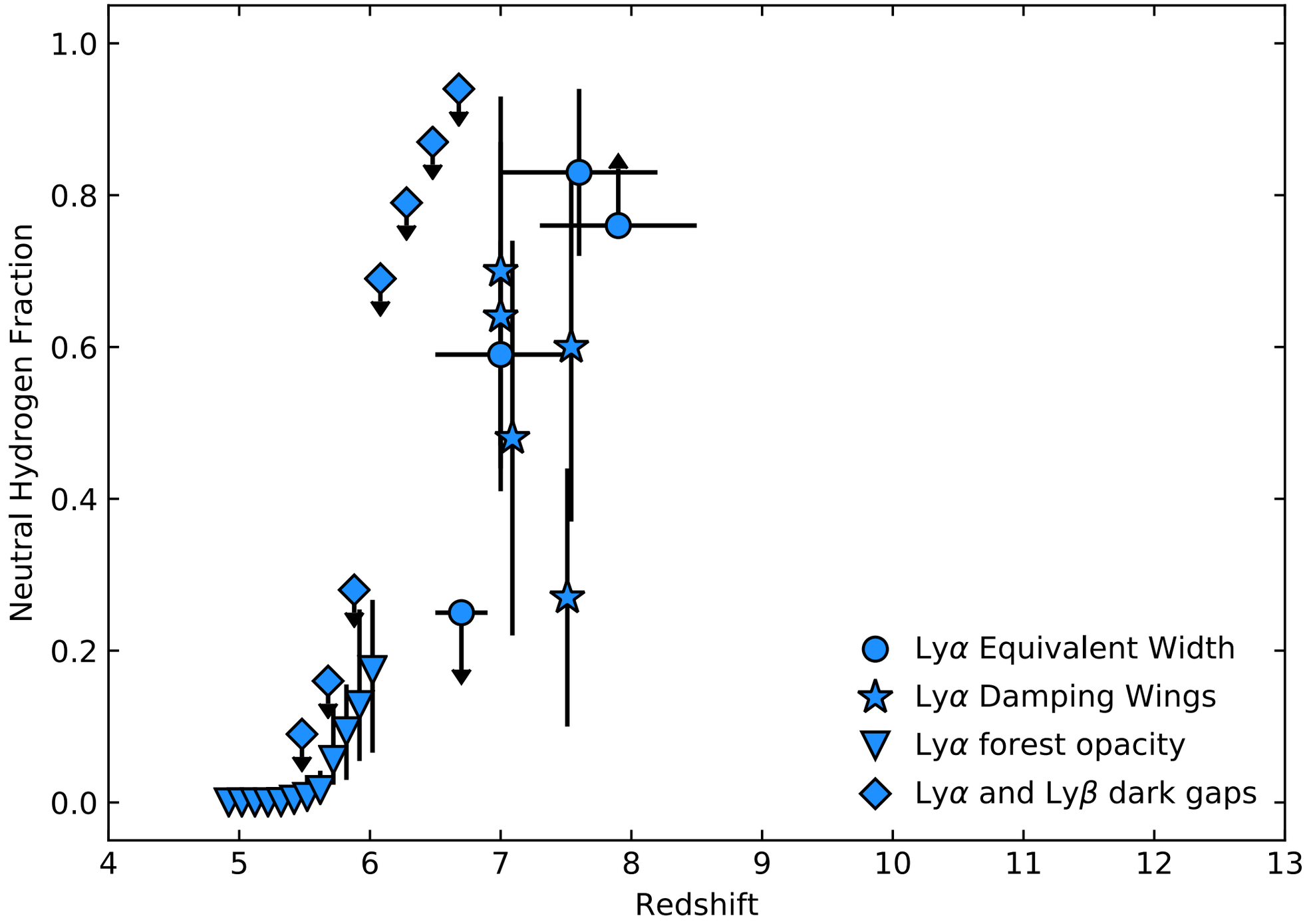


Based on Fan+23
and Barnett+19

Lyman-α emission from galaxies also constrains the progress of reionization



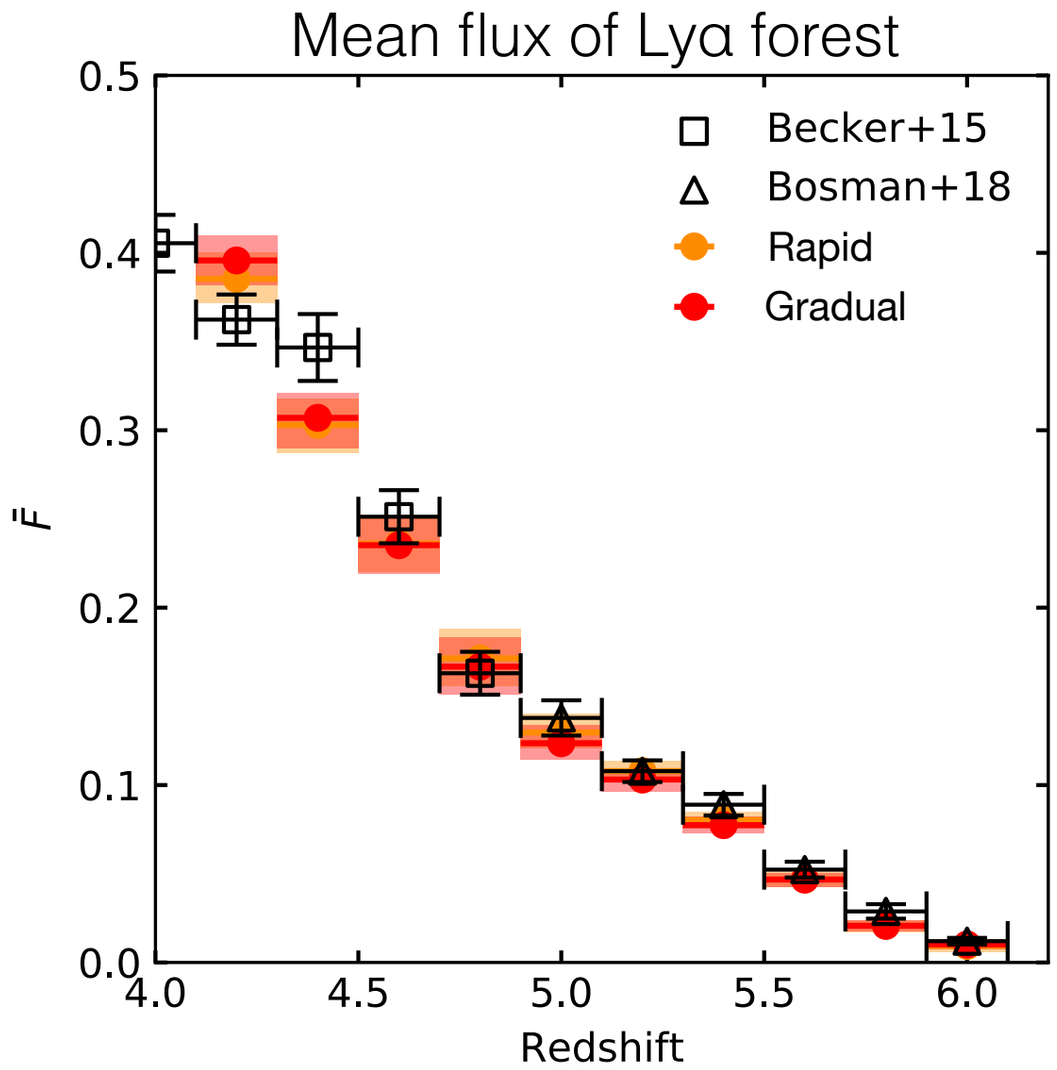
Redshift evolution of the IGM neutral fraction



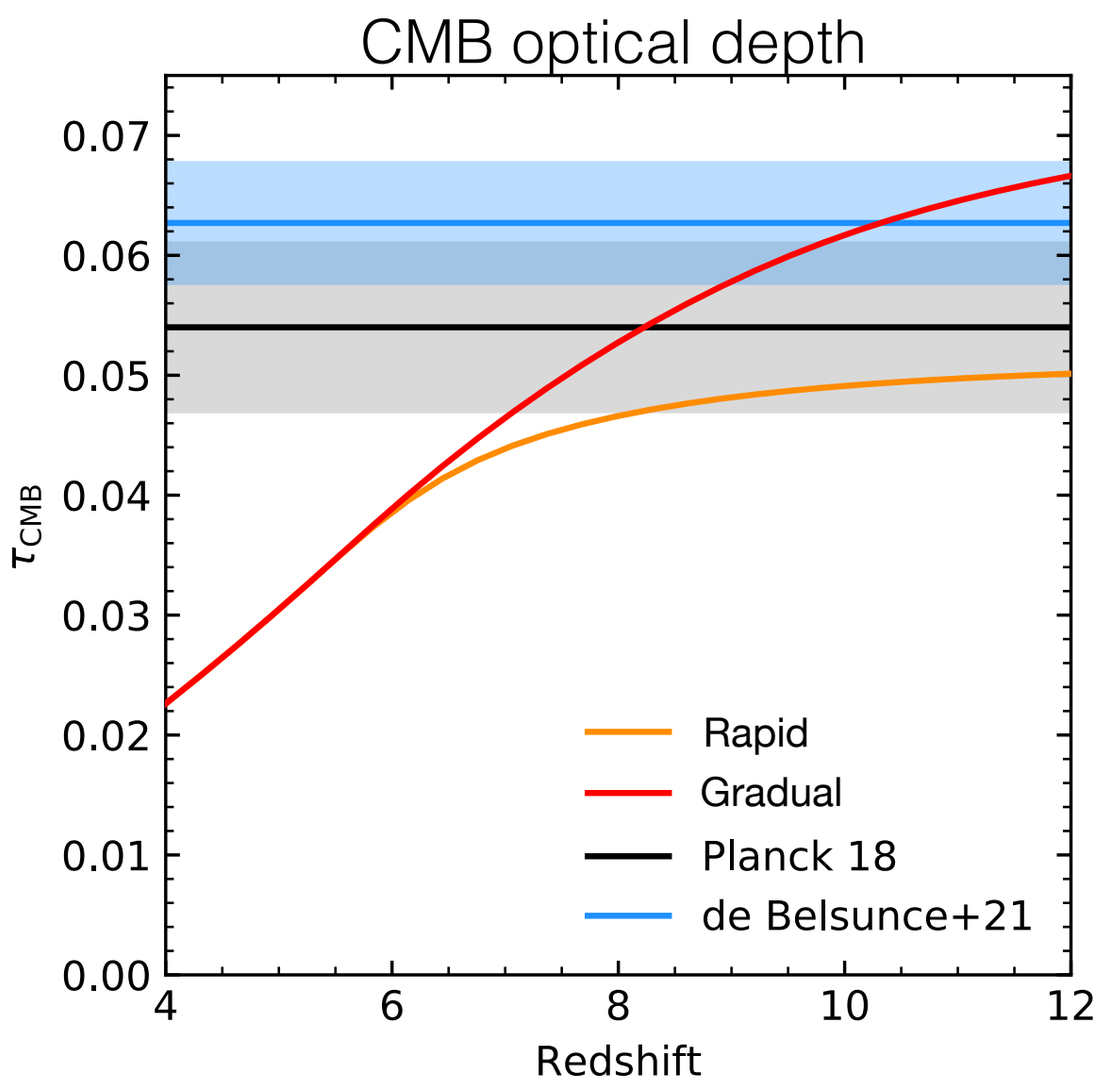
Mason+18, Mason+19, Bolan+22

see also: Stark+10, Pentericci+11,14, Konno+14,18, Ouchi+18, Sobacchi & Mesinger 15, Inoue+18, Whitler+20, Morales+21, Bruton+23, Jones+23, Nakane+23

The Lyα forest tightly constrains the end of reionization, but it cannot alone tell us whether reionization was rapid or more gradual

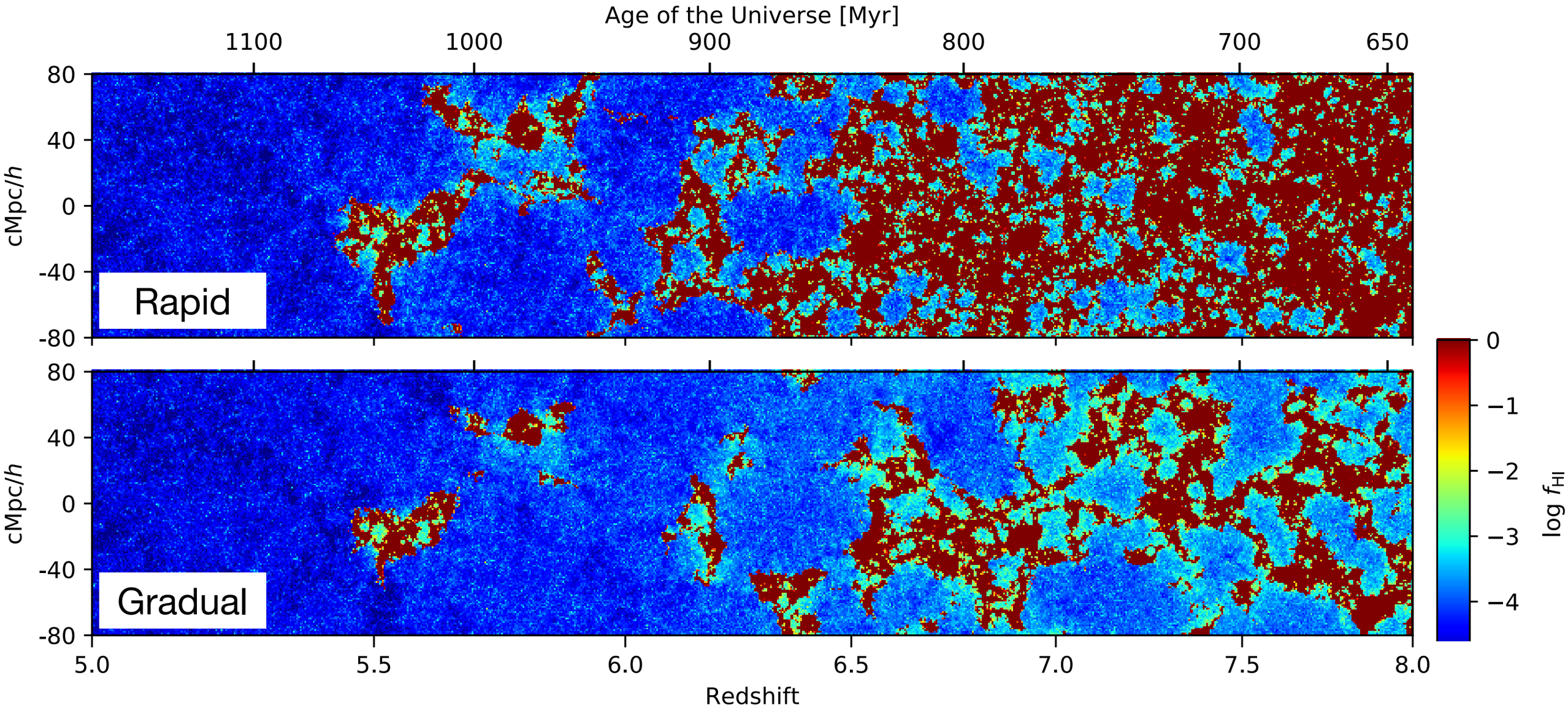


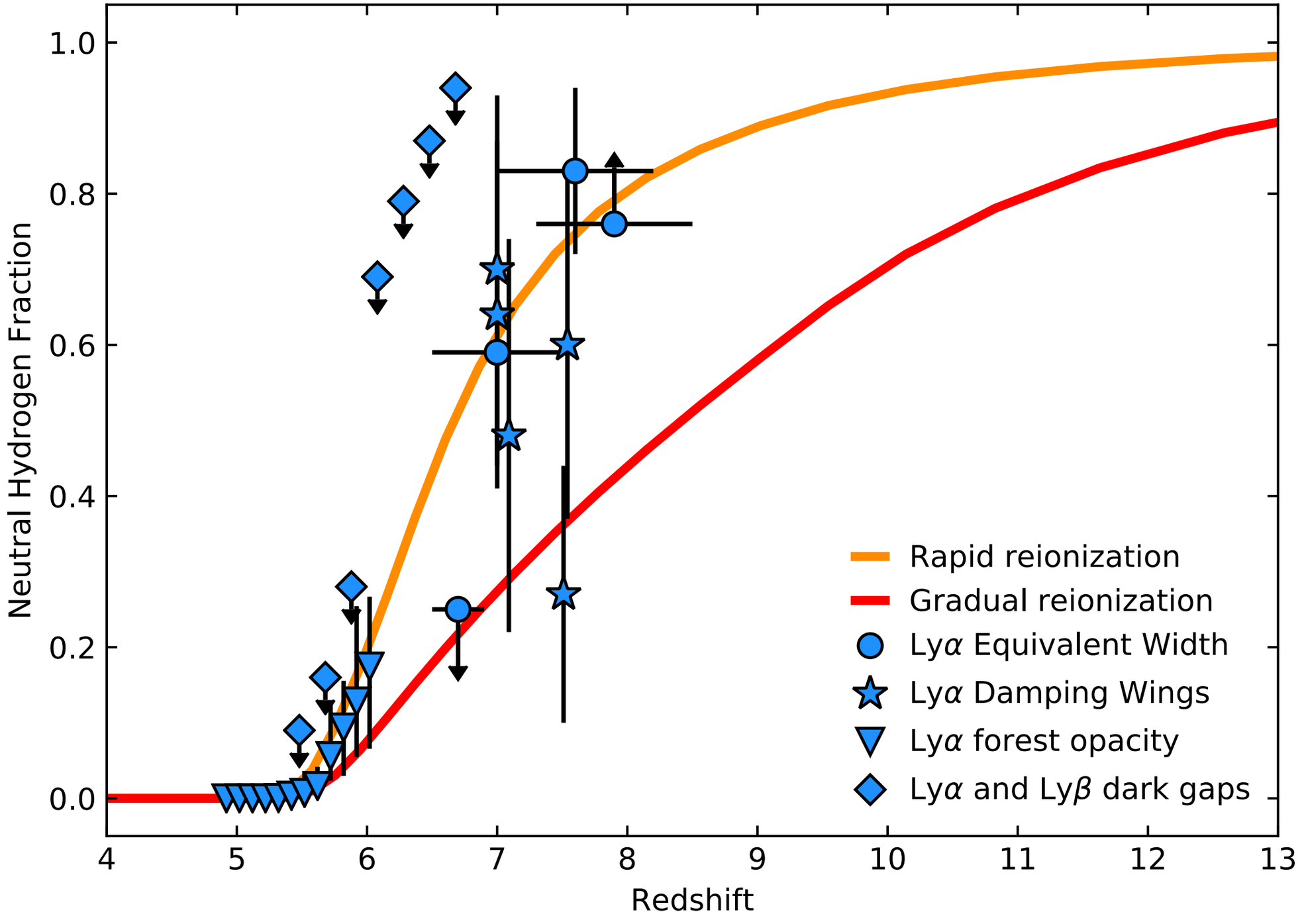
When did reionization end?



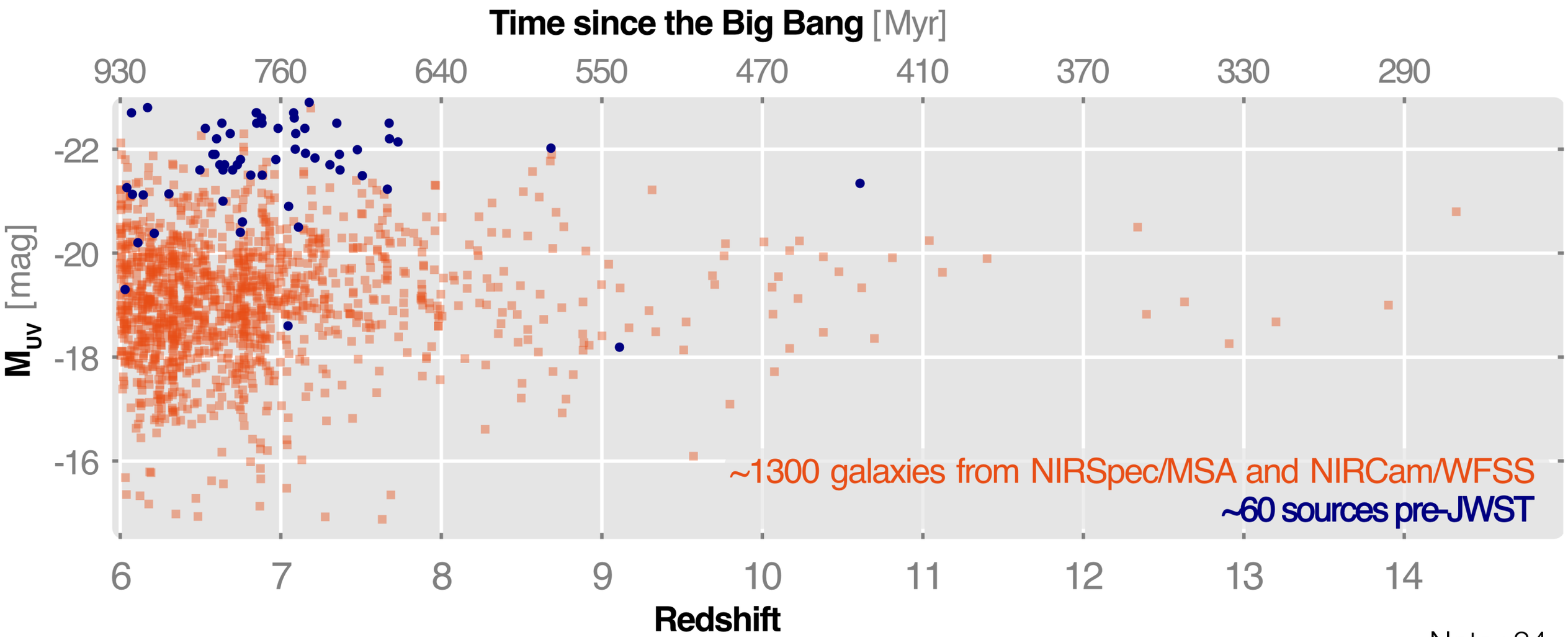
What was the mid-point of reionization?

Models look similar up to z ~ 6, but the structure of the ionized regions is very different for different midpoints of reionization



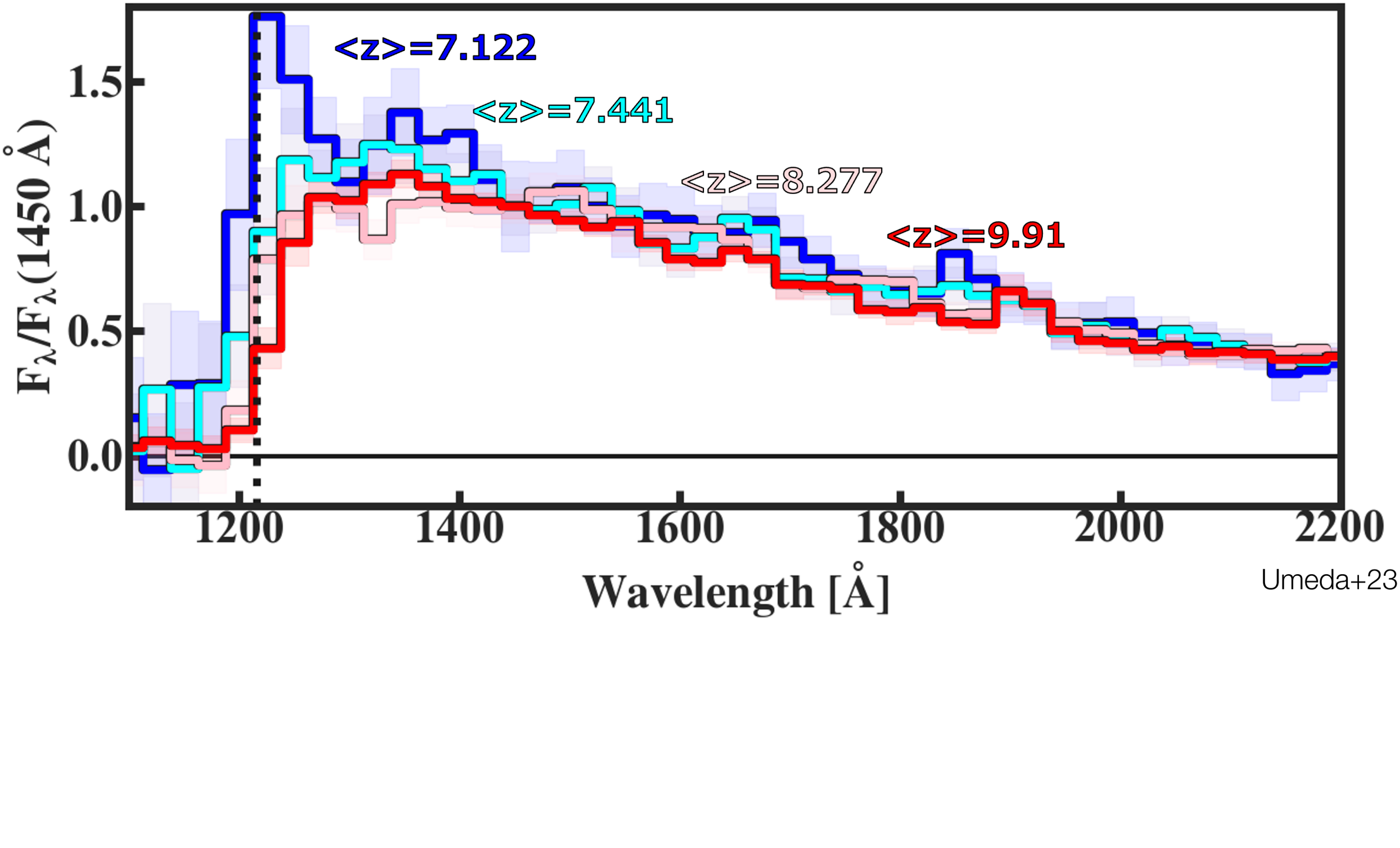

Redshift evolution of the IGM neutral fraction
Neutral Hydrogen Fraction
1.0
0.8
0.6
0.4
0.2
0.0
4
5
6
7
8
9
10
11
12
13
Redshift
Rapid reionization
Gradual reionization
Lyα Equivalent Width
Lyα Damping Wings
Lyα forest opacity
Lyα and Lyβ dark gaps

JWST is providing a new view of the first half of reionization

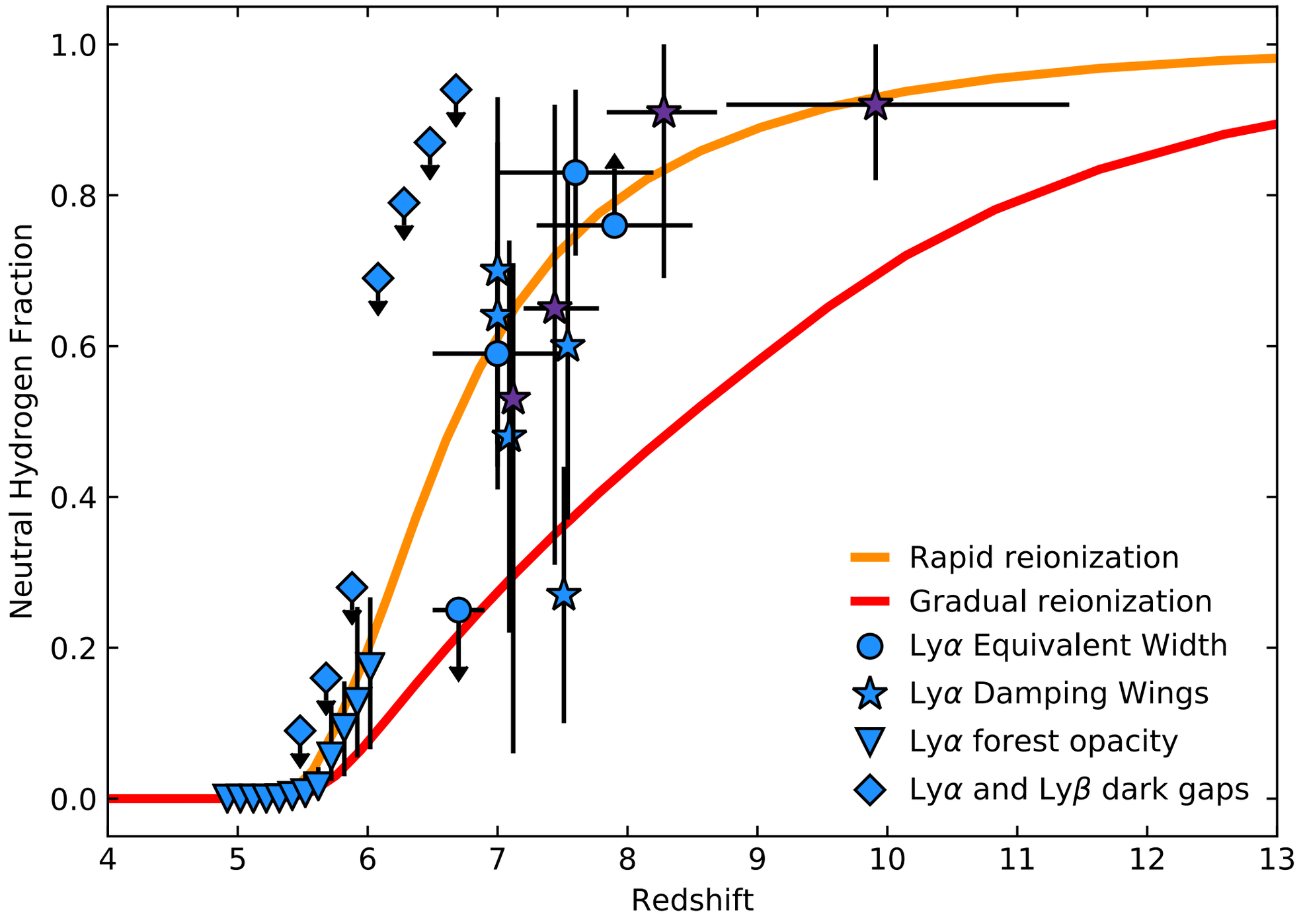


Nota+24

Damping wings are now visible in galaxies at z > 9



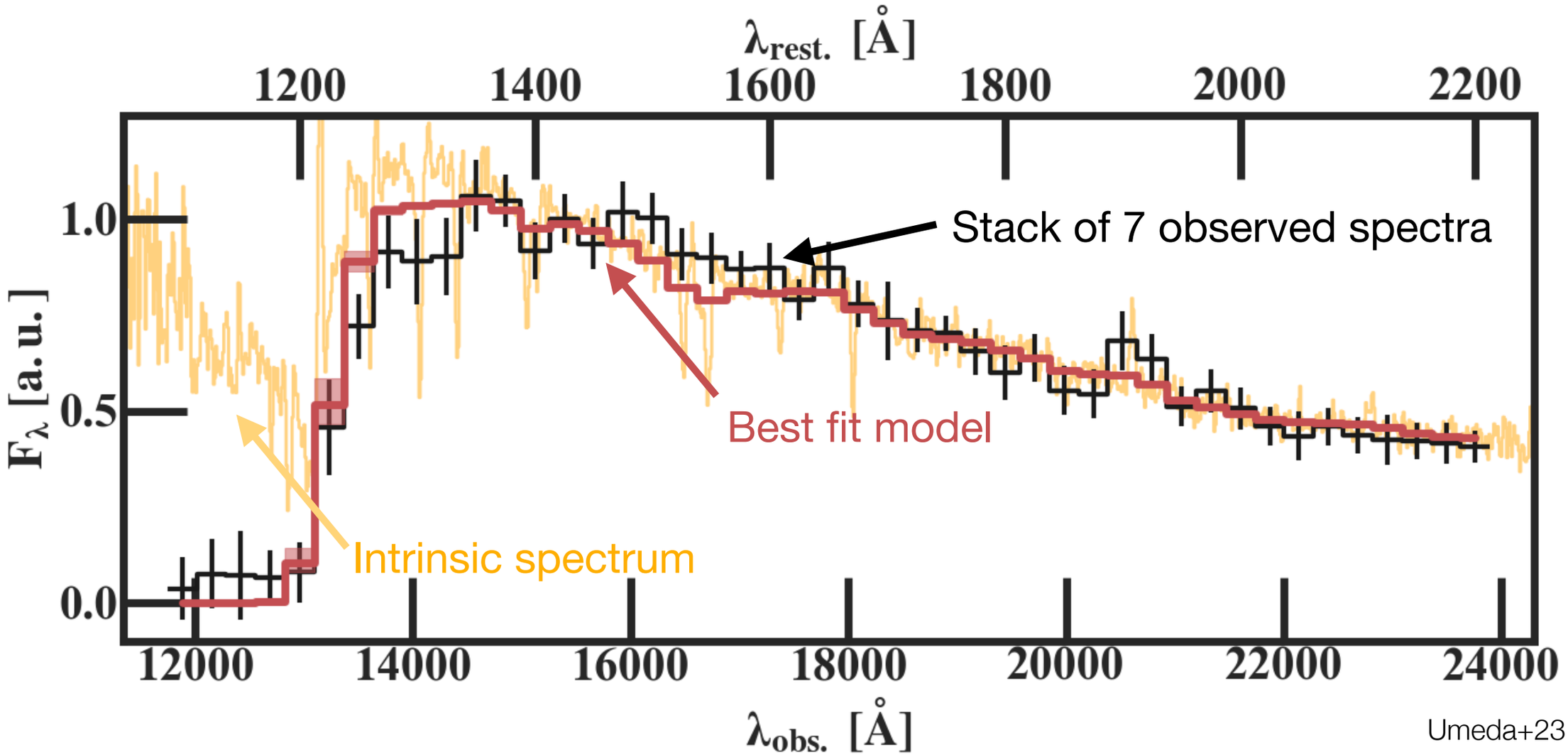
Umeda+23



Umeda+23

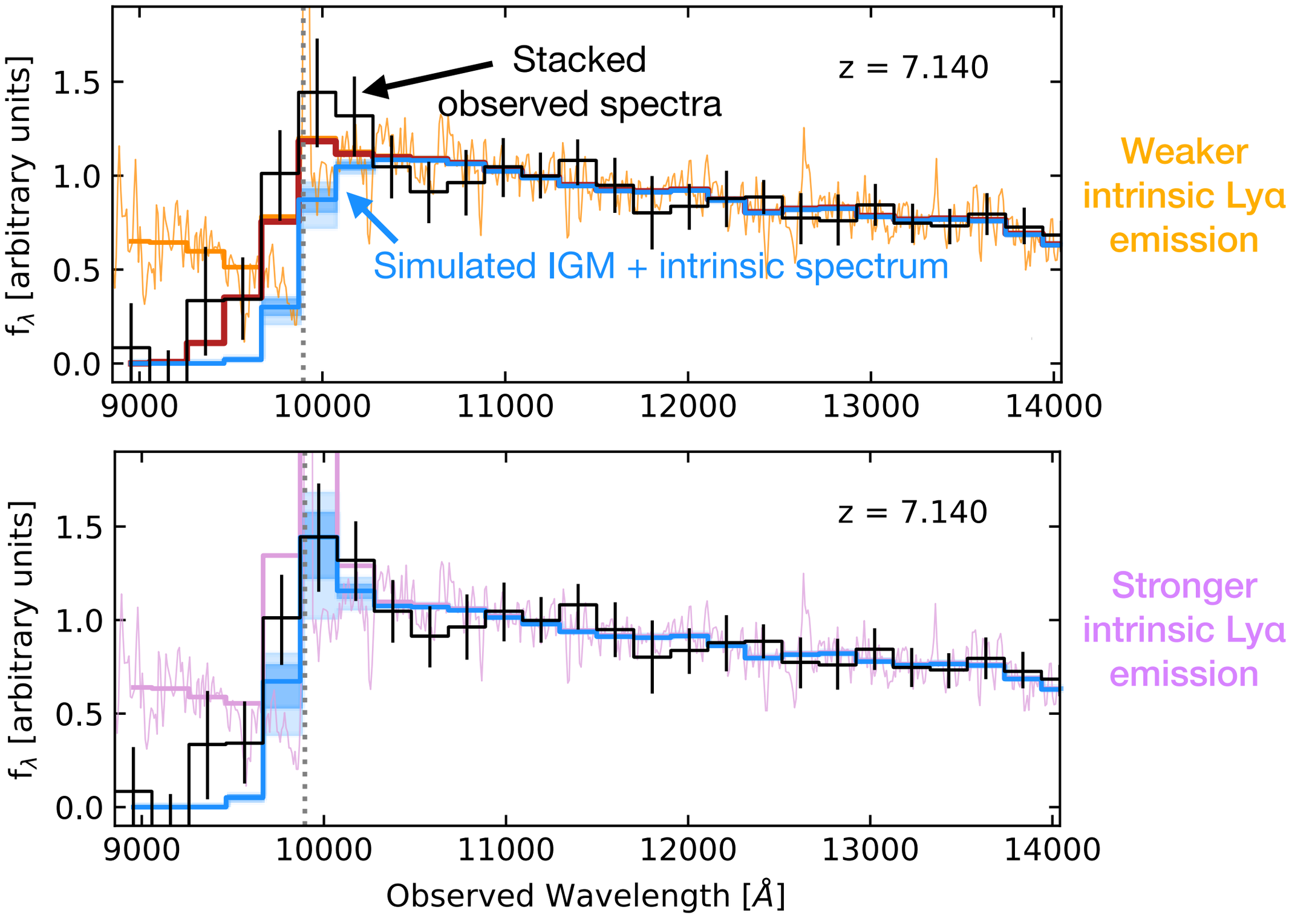
see also: Curtis-Lake+23, Hsiao+23

By applying a damping wing model to a template for the intrinsic galaxy spectrum, best fitting reionization parameters can be estimated

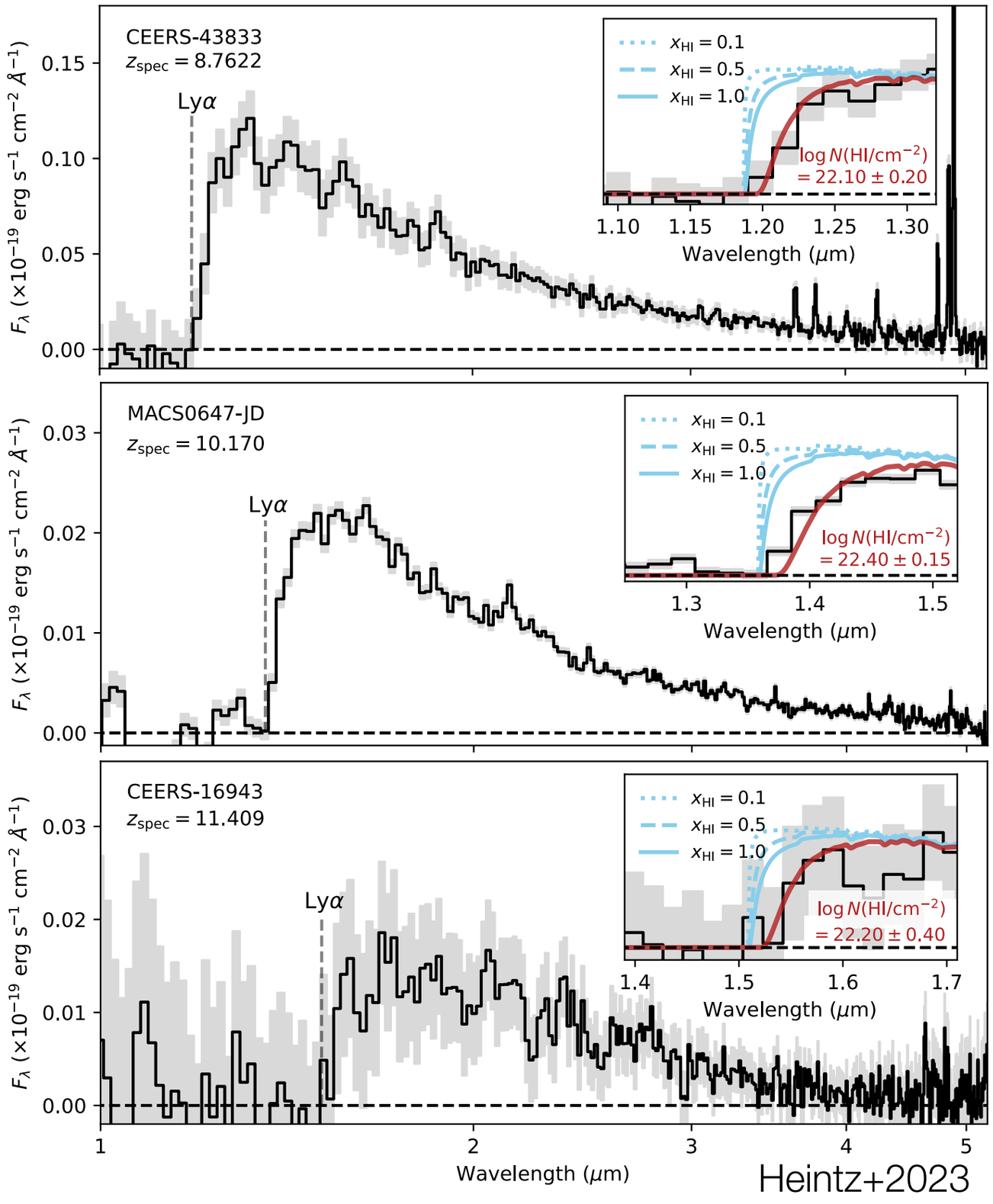


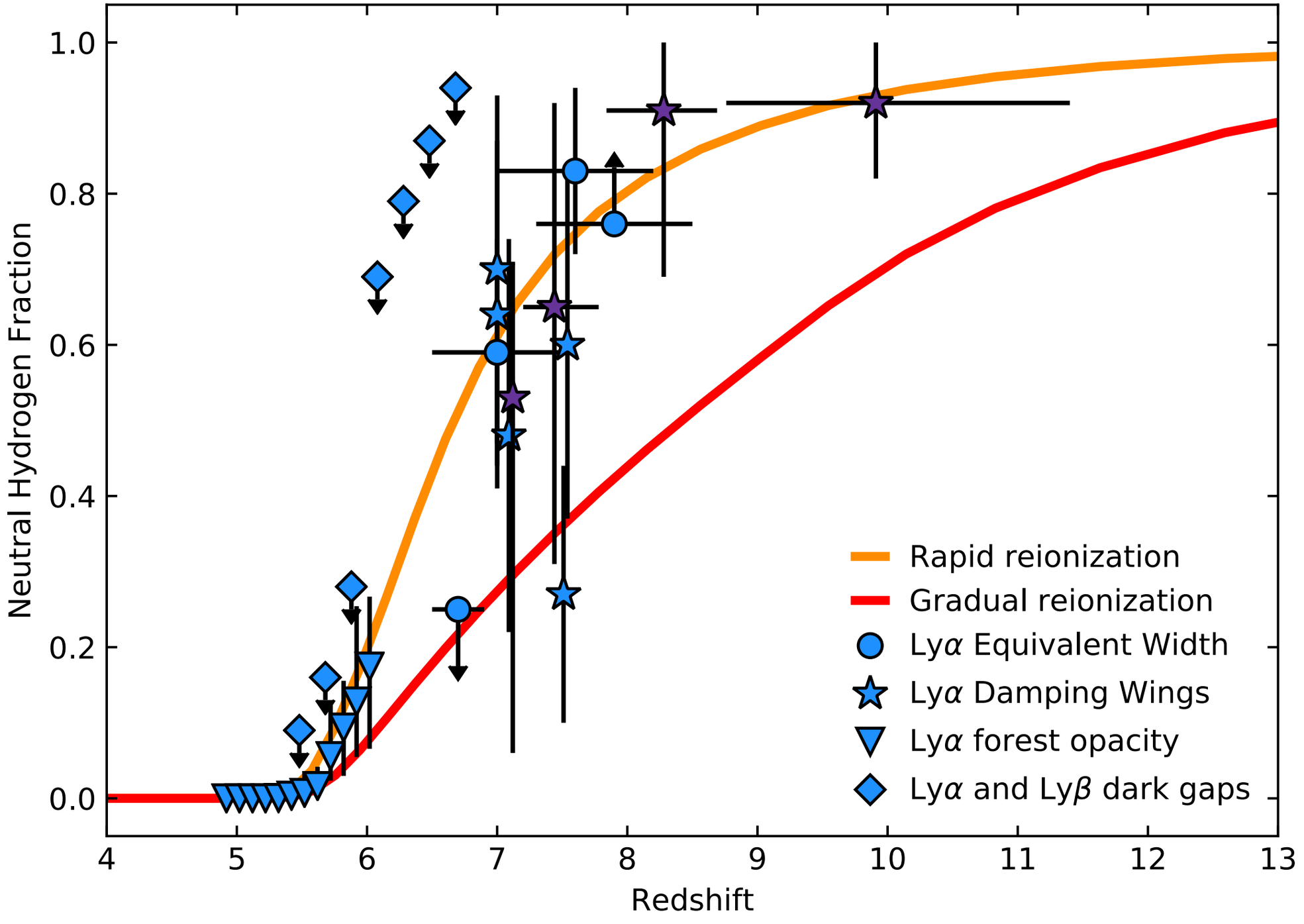
Umeda+23

Stronger intrinsic Lyα emission results in more transmission below 1216 Å, mimicking the effect of large bubble sizes



The other complication is strong HI absorption within the host galaxy, which also produces a damping wing

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