# Illuminating the Dark Ages: Luminous Quasars in the Epoch of Reionisation

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**MPIA Heidelberg**

Workshop “The Reionization History of the Universe”

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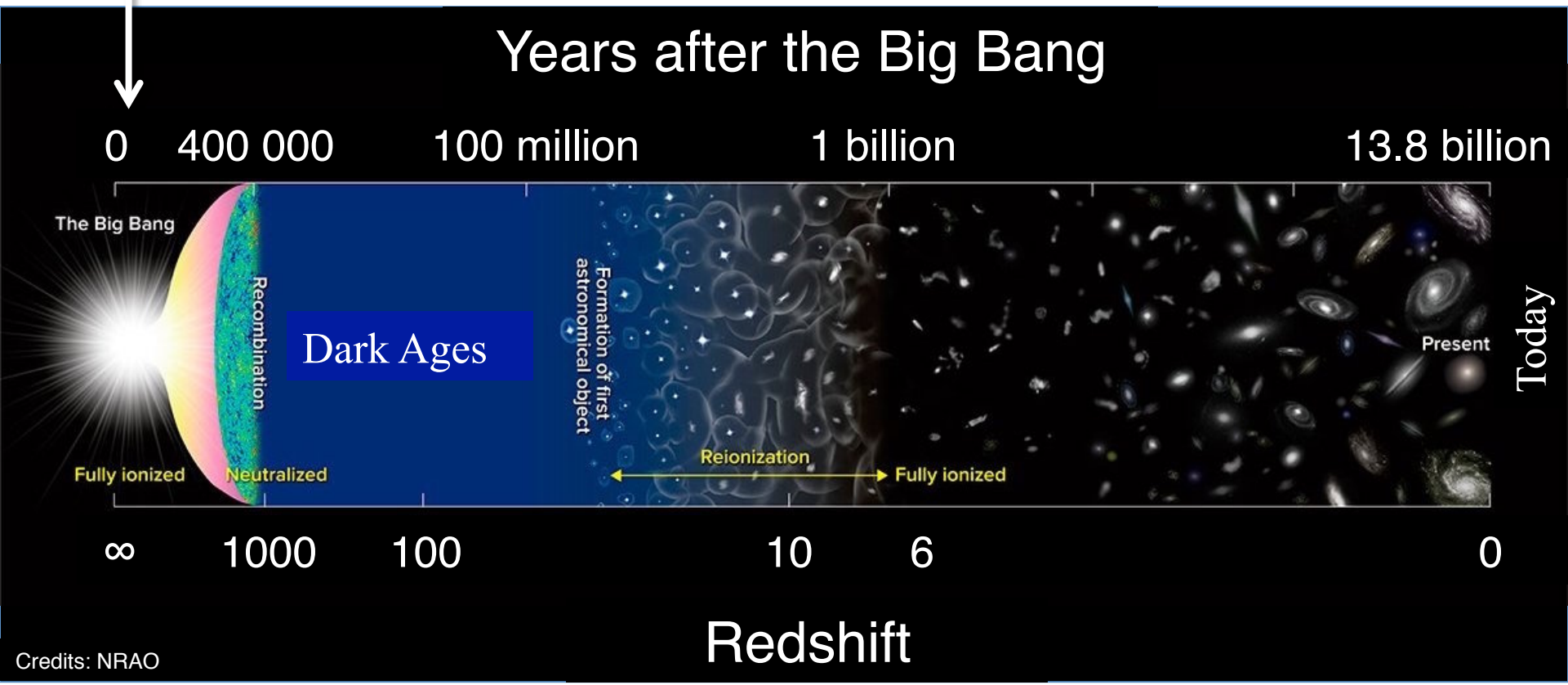
# History of the Universe

Big Bang

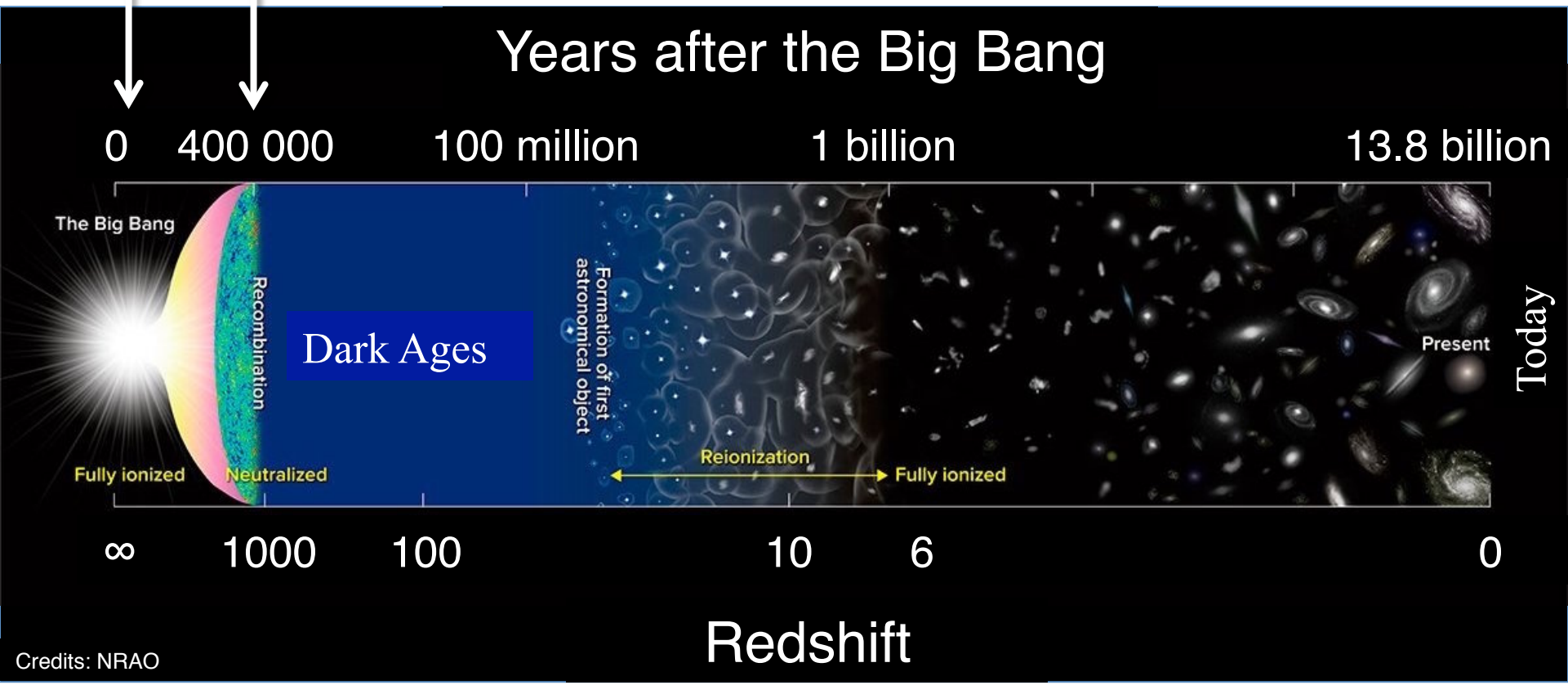



Credits: NRAO

# History of the Universe

Recombination

Big Bang

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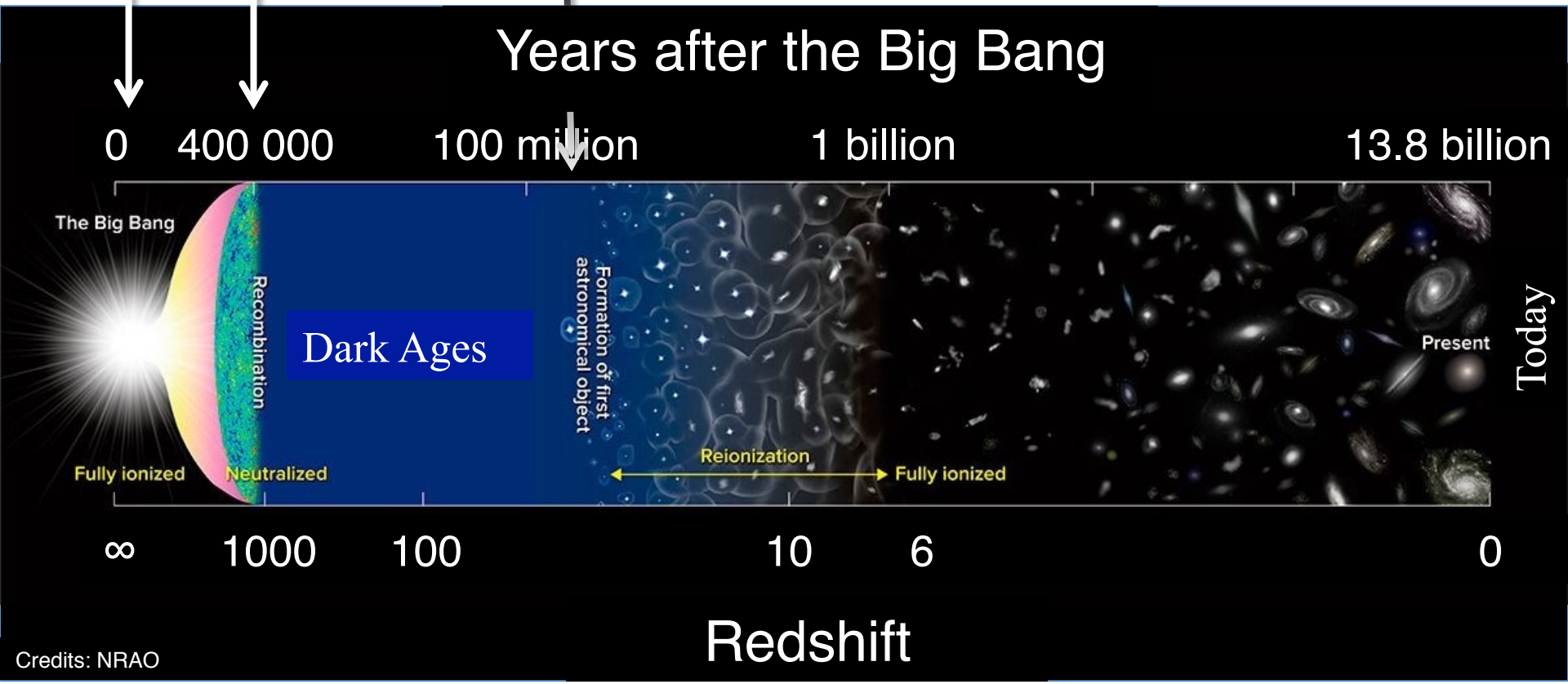
# History of the Universe

Recombination

Big Bang

Formation of first luminous sources



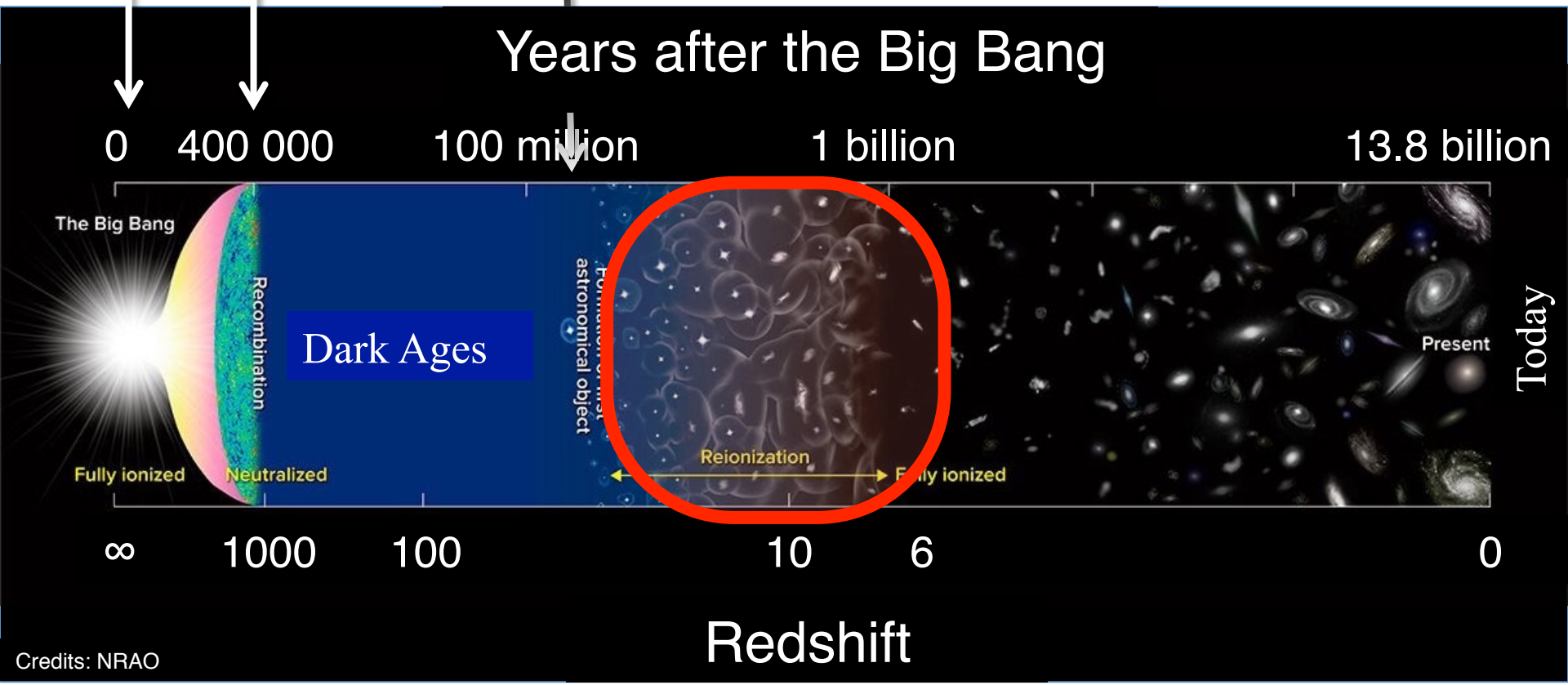

Credits: NRAO

# The Epoch of Reionisation (EoR)

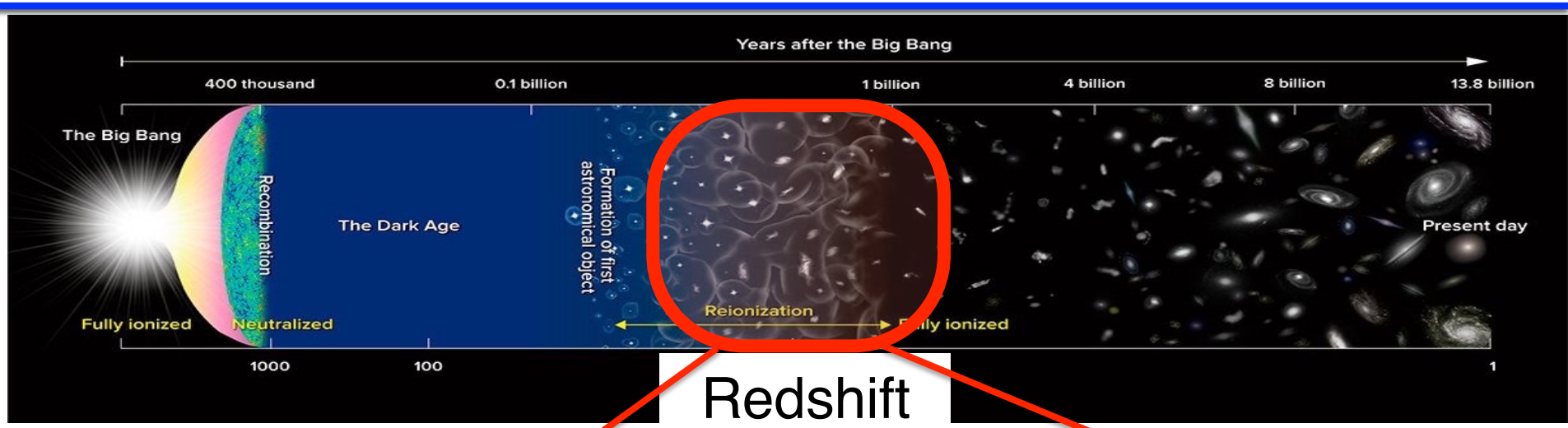
Recombination

Big Bang

Formation of first luminous sources



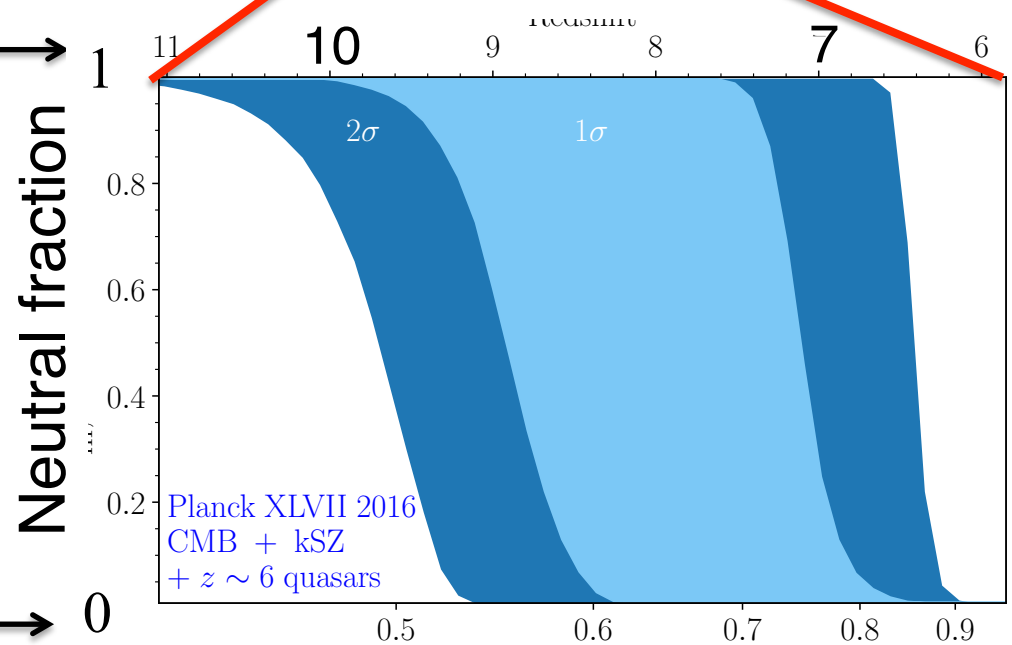
# Constraints on reionisation from CMB




Redshift

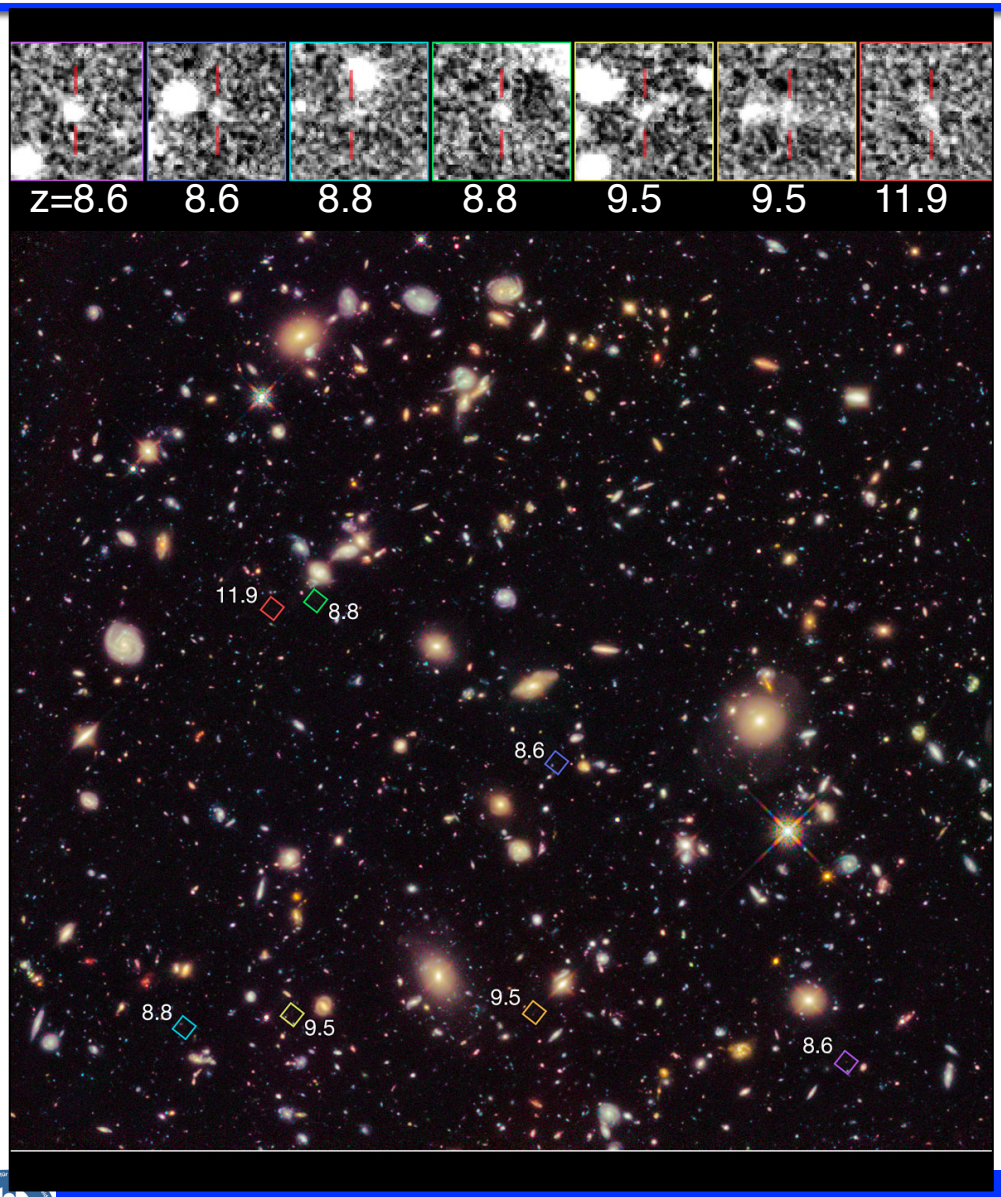
Neutral →

Ionized →




Planck XLVII 2016

# The first sources: galaxies in the EoR




Example of galaxies in the Hubble Ultra Deep Field:

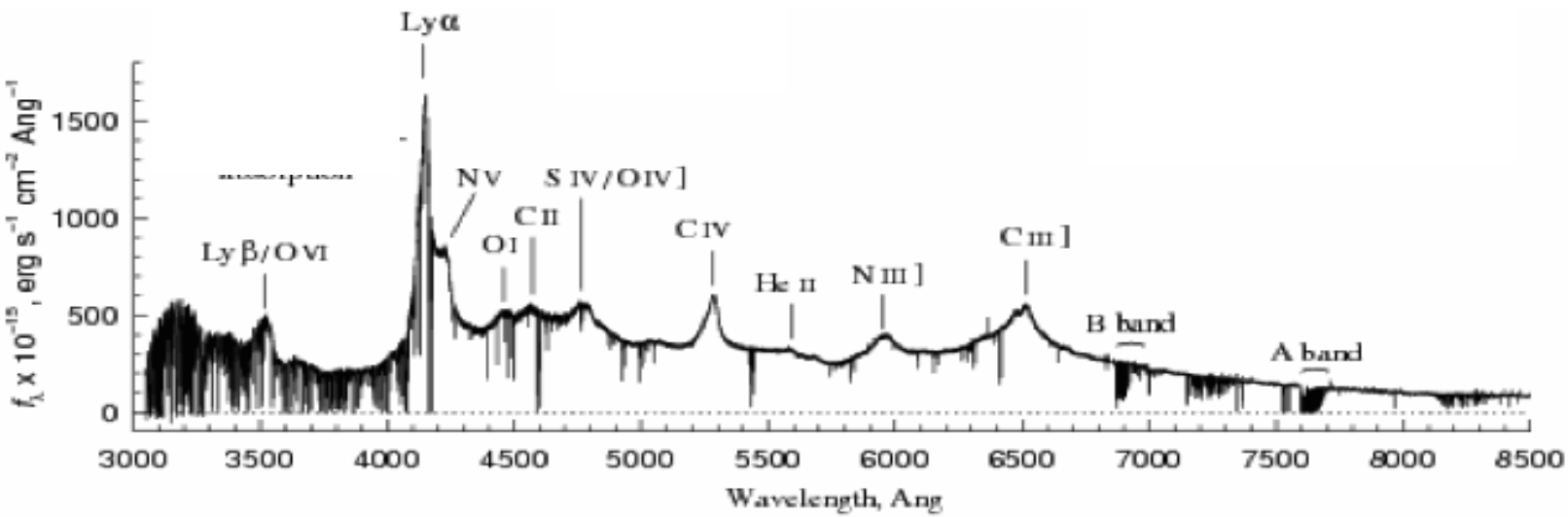
- *very* faint (mag≫26)
- difficult to confirm their distance
- nearly impossible to measure properties

**→ JWST (launch 2019)**

Bouwens+ 2016

# High luminosity objects: quasars

- powered by accreting black holes
- brightest sources in universe
- UV/optical spectrum:
  - power-law cont. by accretion disk + broad emission lines
- line width+continuum ≈ black hole mass



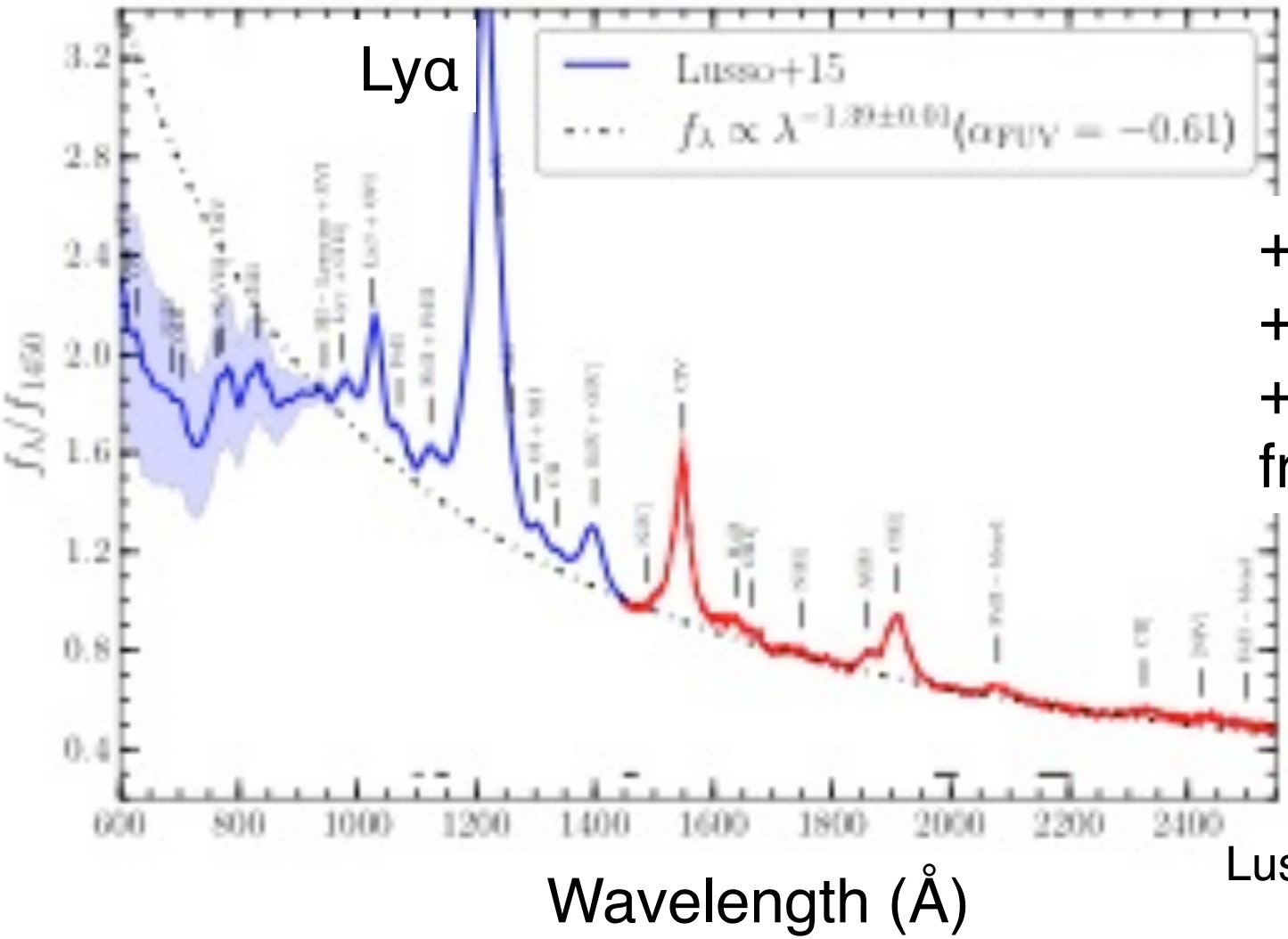
# Quasars: beacons in the early Universe

- Luminous quasar are found up to $z > 7$:
  → $>10^9$ $M_\odot$ black holes exist within first Gyr

- Hosted by starburst galaxies (SFR > 100 $M_\odot$ /yr)
  → Study the formation of massive galaxies

- Excellent probes of the Epoch of Reionisation

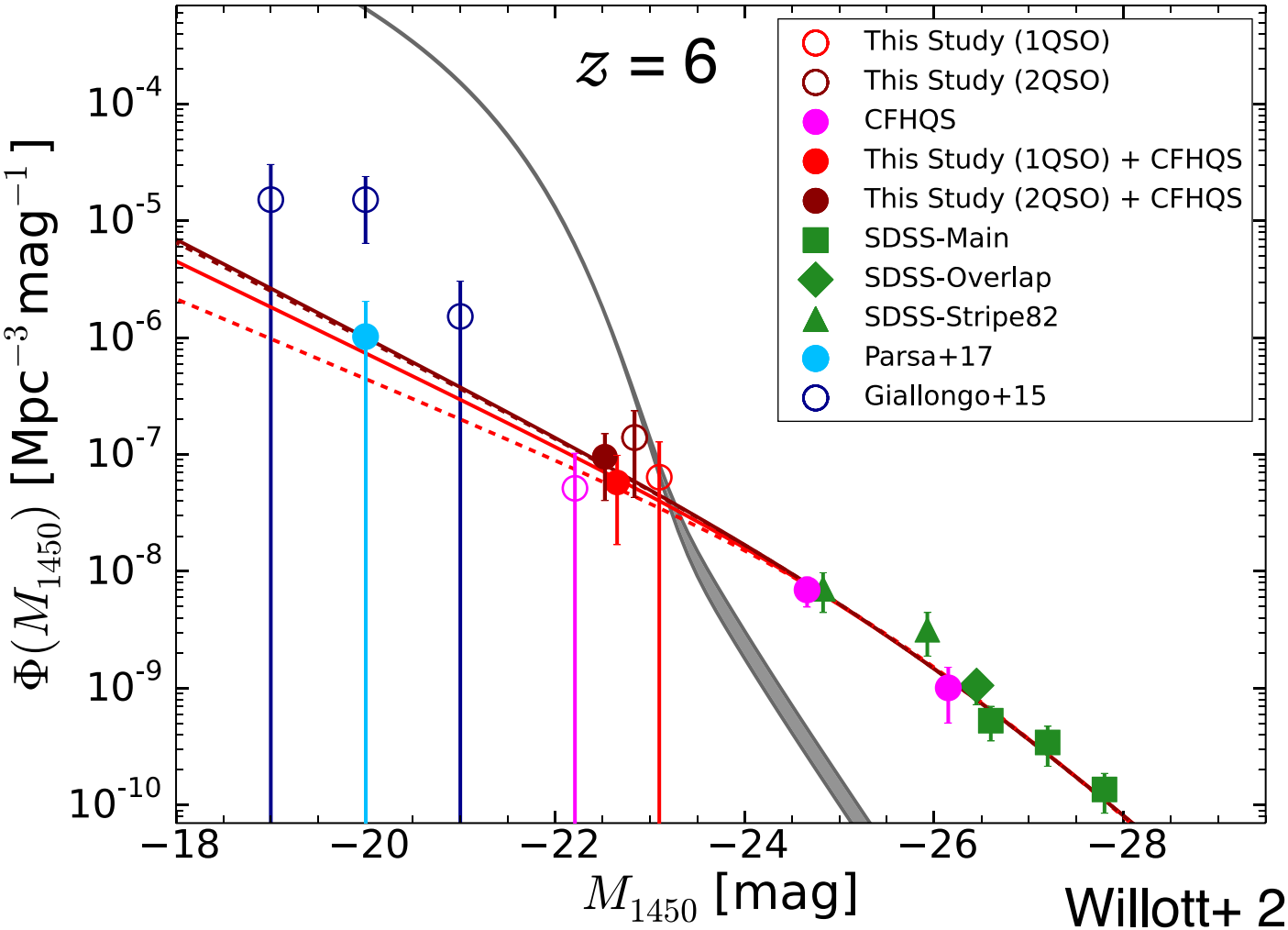
# Quasars: sources of UV photons




+ luminous
+ very blue
+ high escape fraction

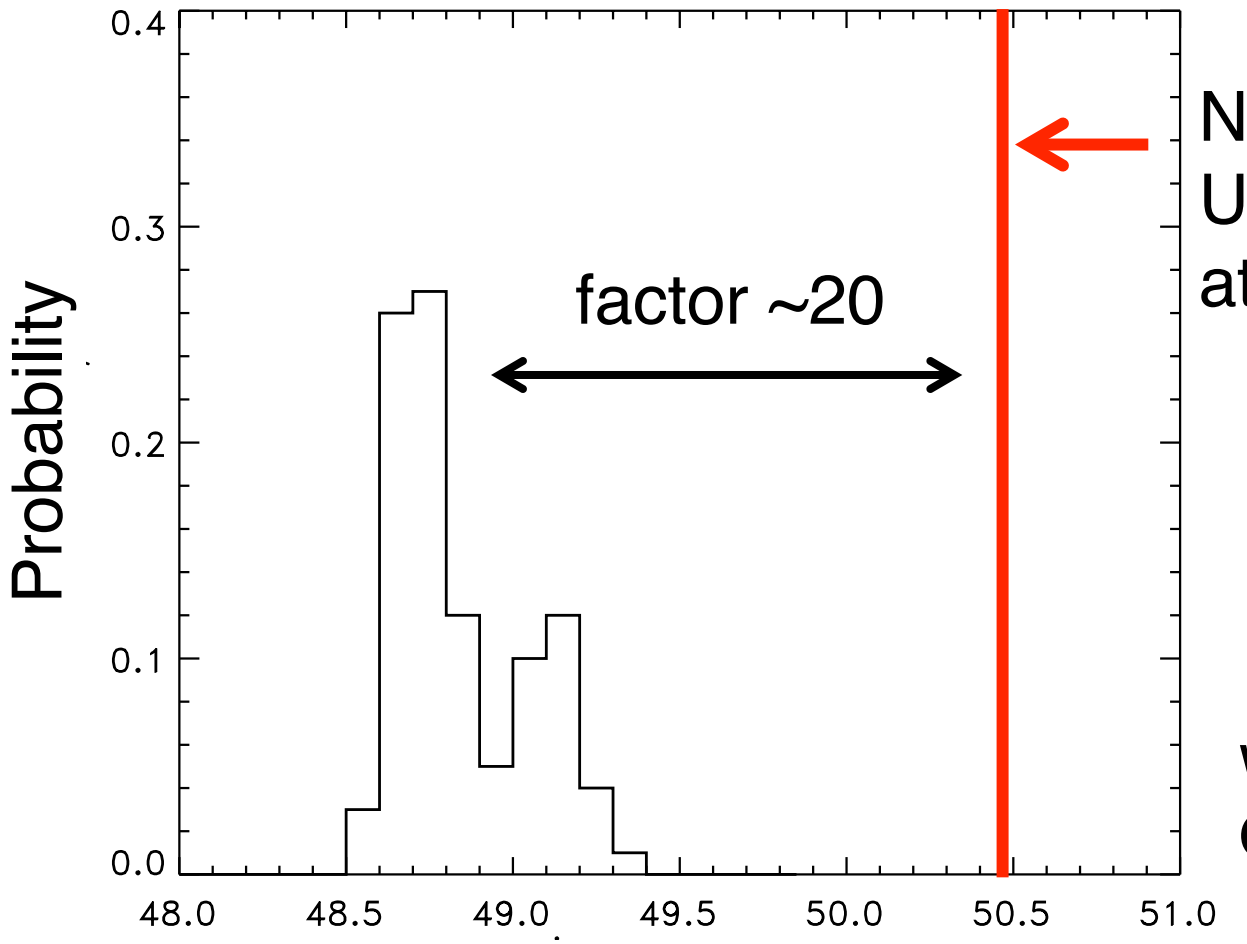
Lusso+ 2015

# High-$z$ quasar luminosity function




Willott+ 2010
Onoue+ 2017

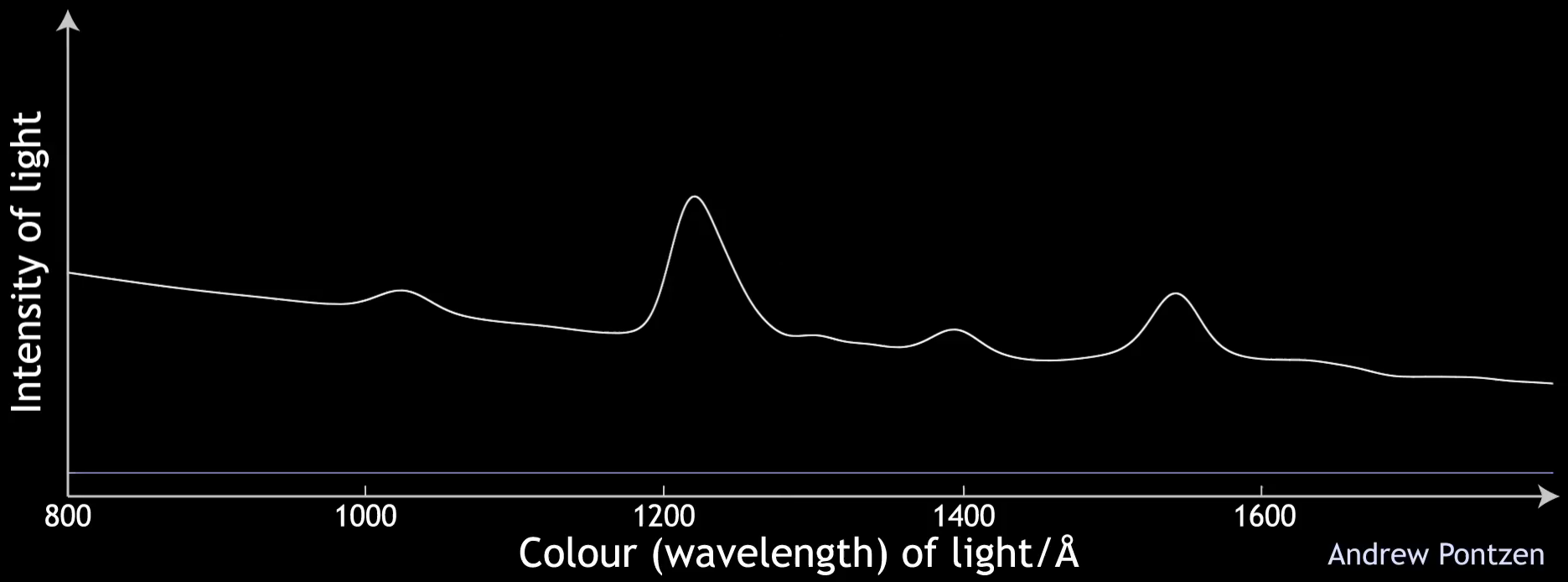
# Ionising photon production of quasars




Needed to keep Universe reionised at $z \sim 6$

Willott+ 2010
Onoue+ 2017

# Probes of the Intergalactic Medium (IGM)



# Quasars: probes of the EoR

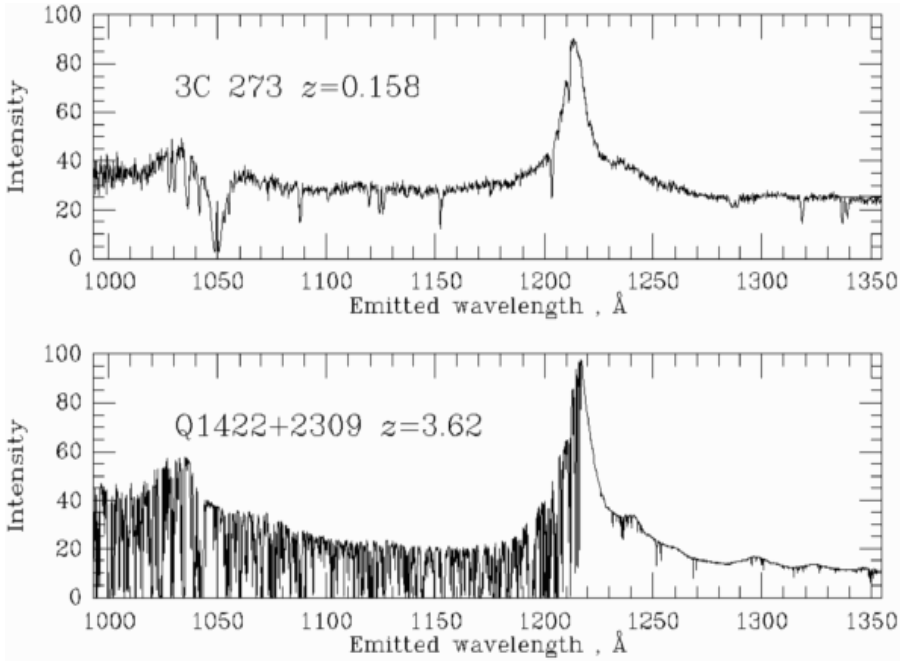
- Use quasars to “X-ray” the early Universe
- Investigate redshift evolution of

→ absorption in the Lyα forest

→ ionised region around quasars (near zone)

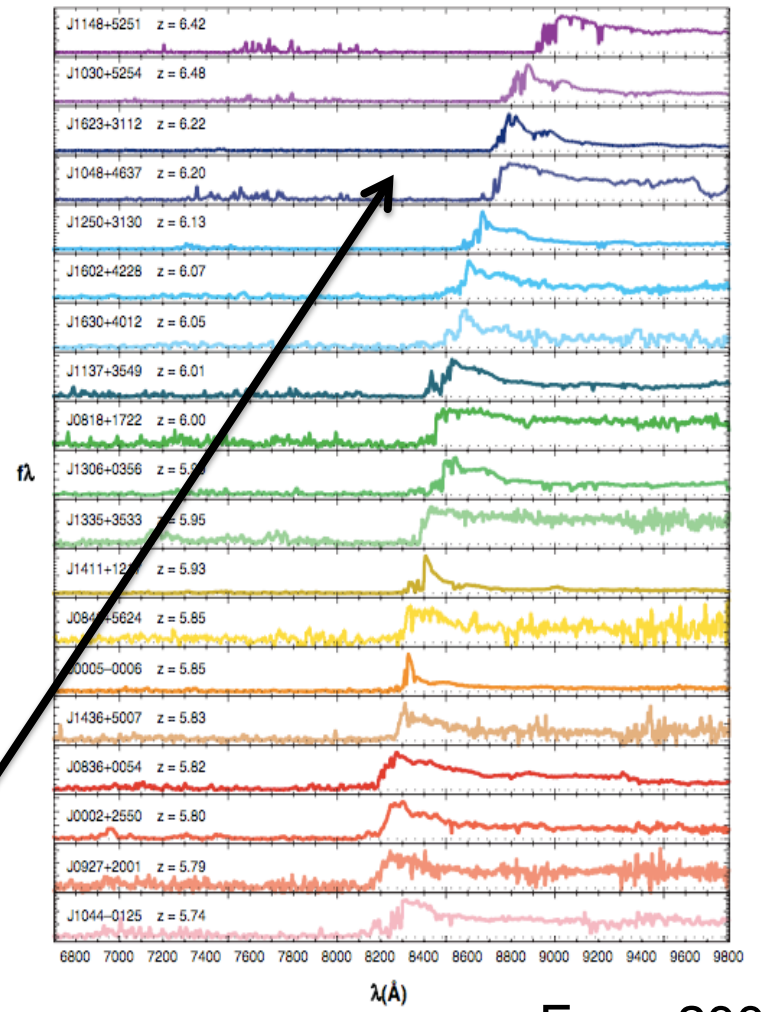
→ damping wing

# Quasar absorption due to Lyα forest



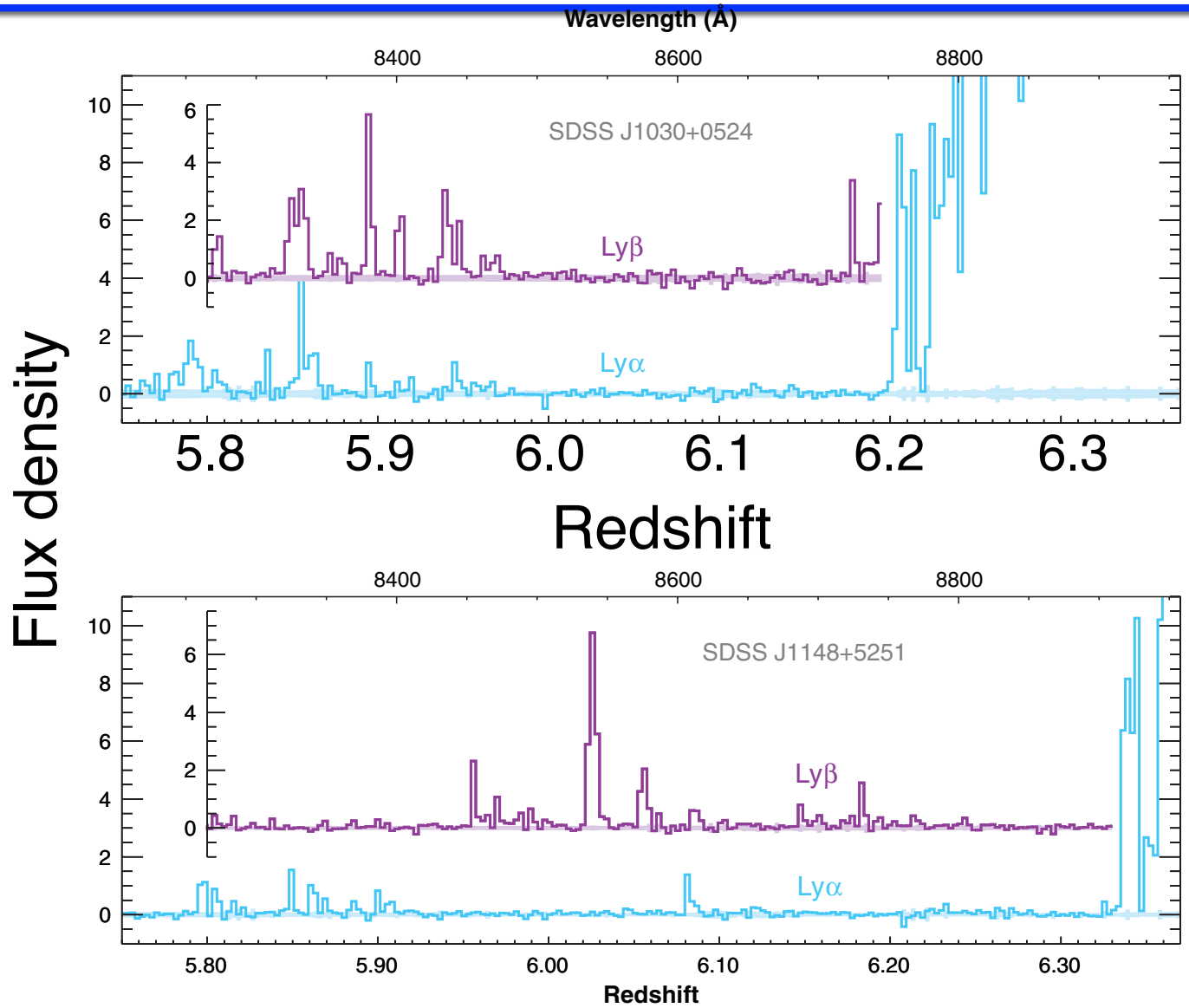

Credits: B. Keel, N. Wright

Strong absorption at $z > 6$



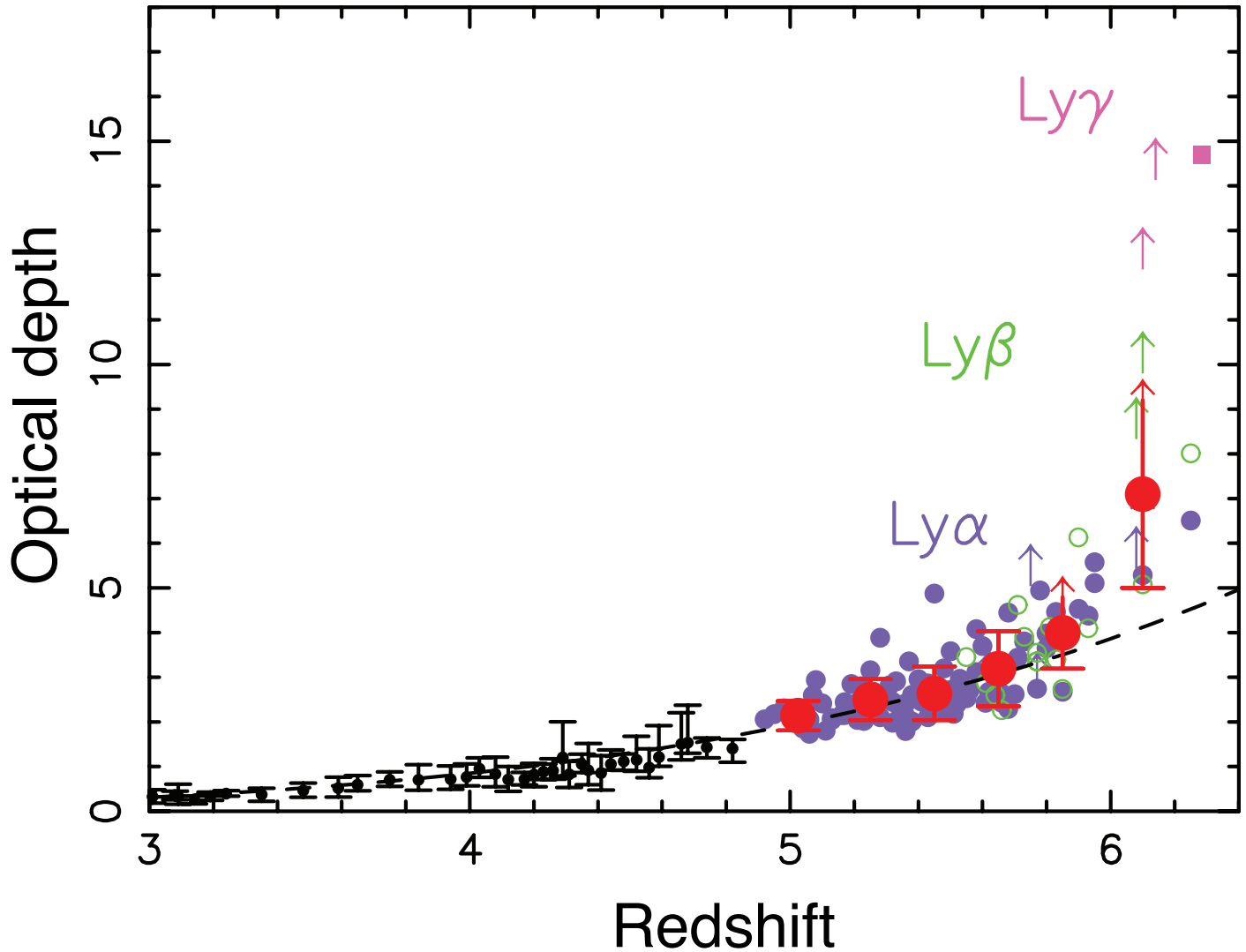

Fan+ 2006

# Probing the neutral IGM




e.g. White+ 03

# Evolution of the optical depth



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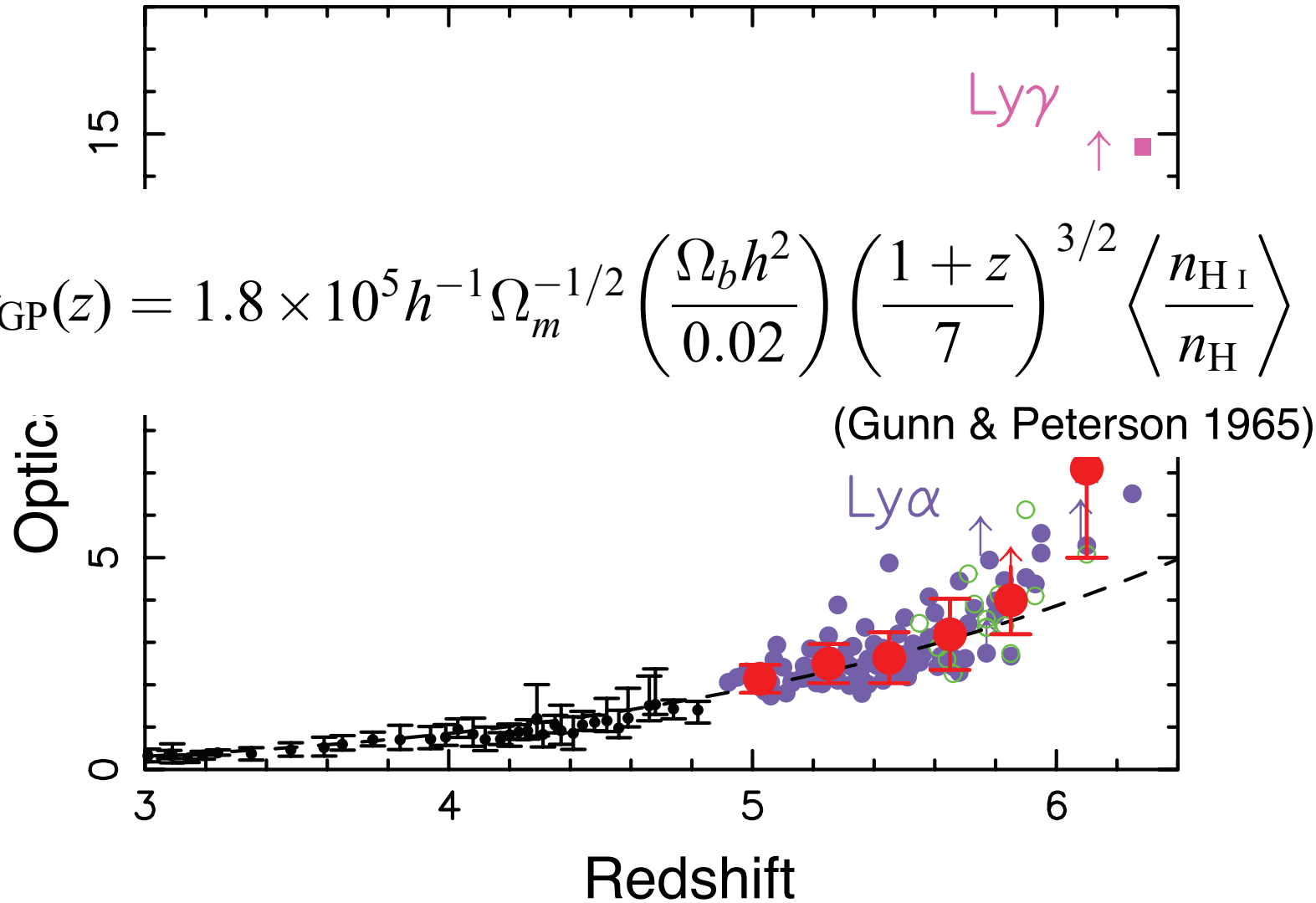
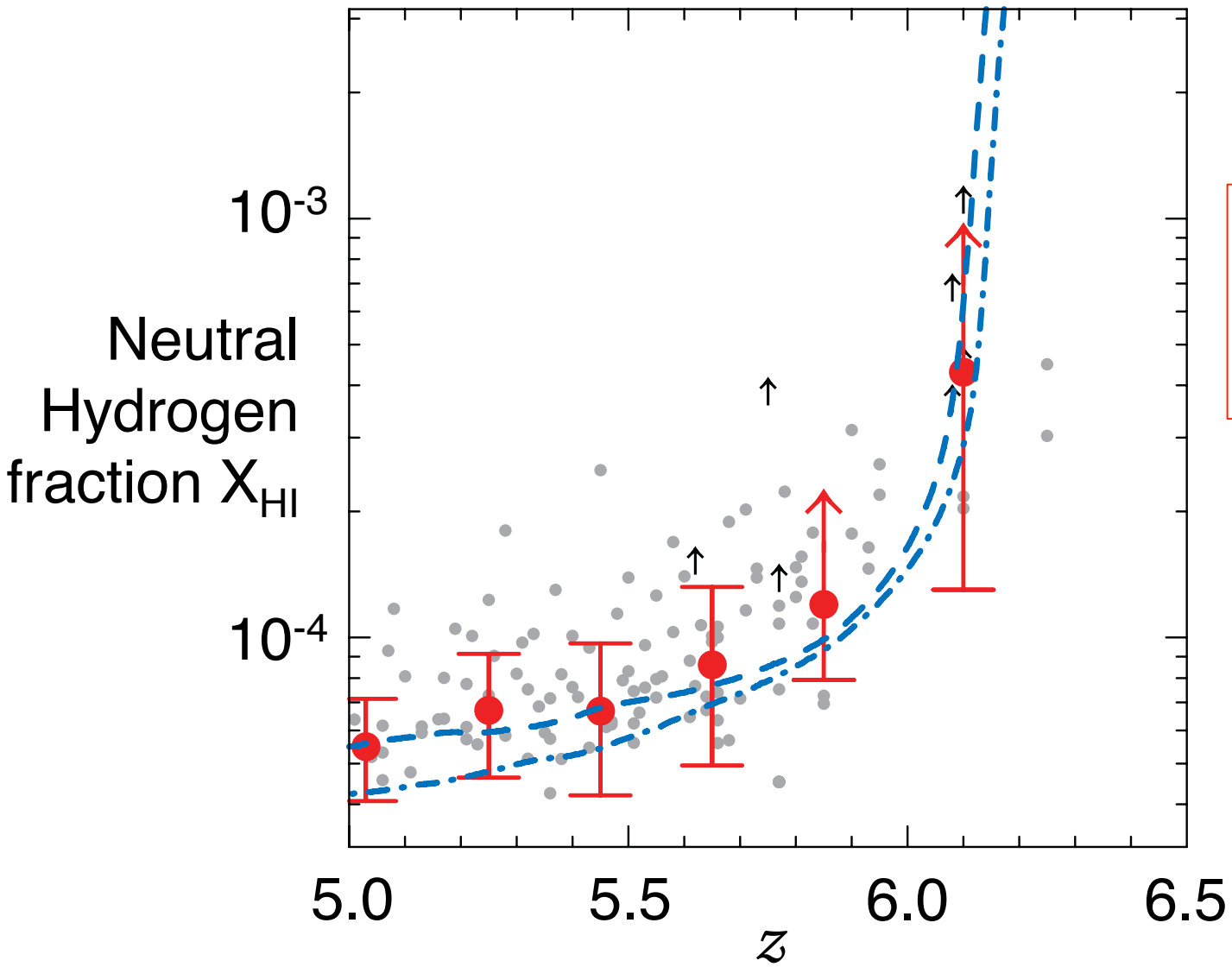



$$\tau_{\rm GP}(z) = 1.8 \times 10^5 h^{-1} \Omega_m^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left\langle \frac{n_{\rm H\,I}}{n_{\rm H}} \right\rangle$$

(Gunn & Peterson 1965)

# $X_{HI}$ from Lyα forest

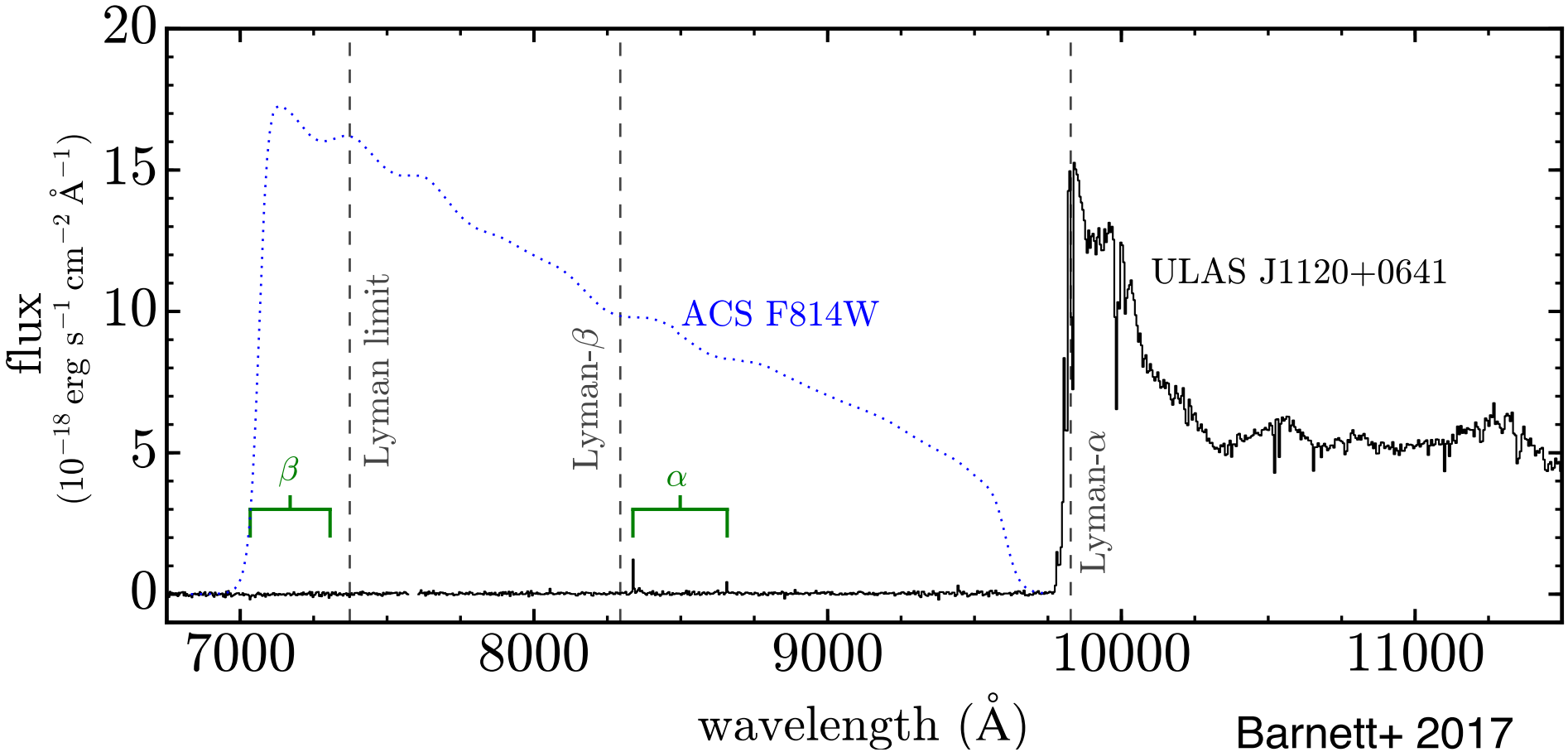



Absorption saturates at $X_{HI} \sim 10^{-4}$

e.g. Fan+ 2006

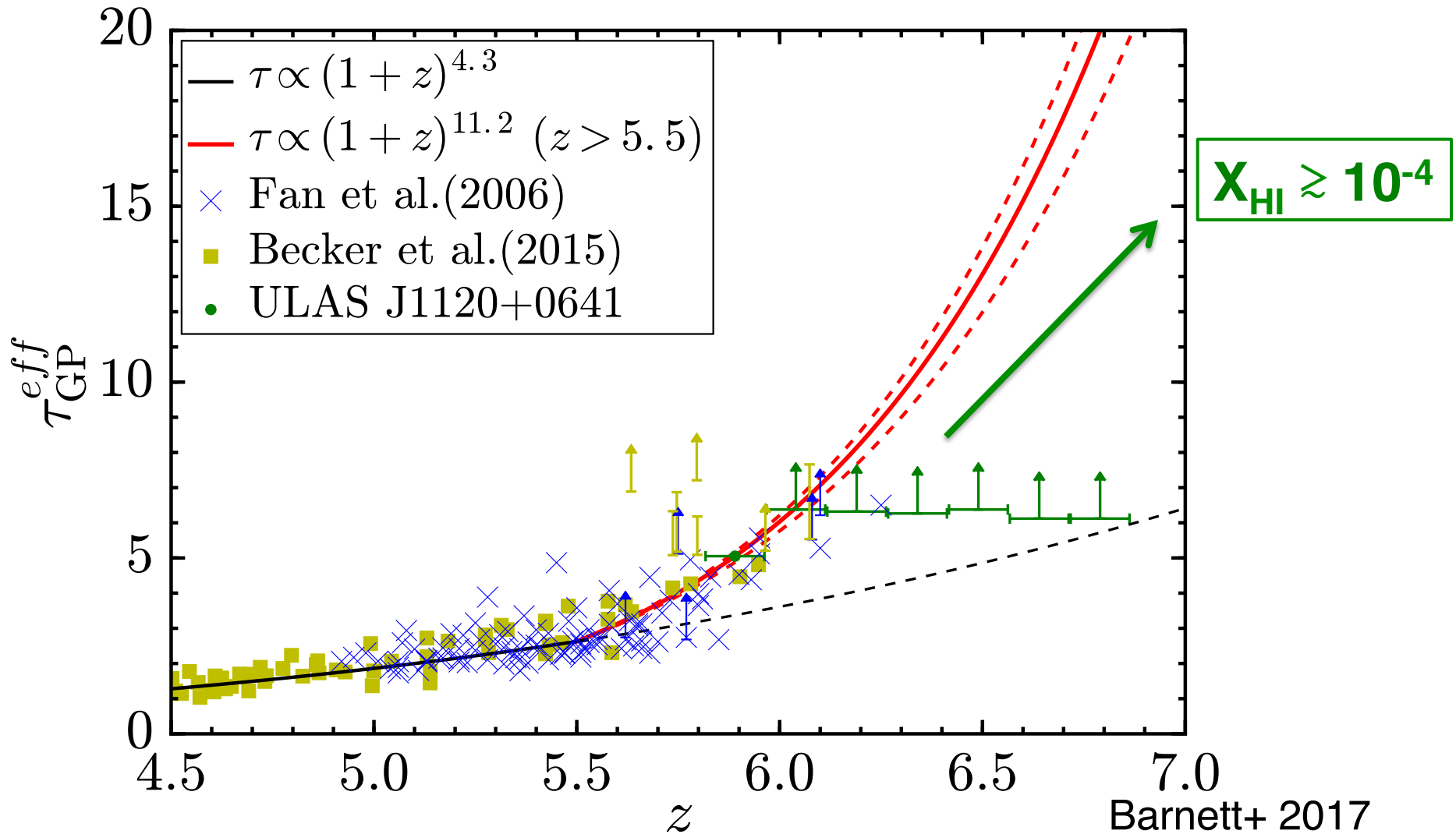
# Lyα absorption saturates

30 hour spectrum with the VLT of a quasar at $z$=7.1




Barnett+ 2017

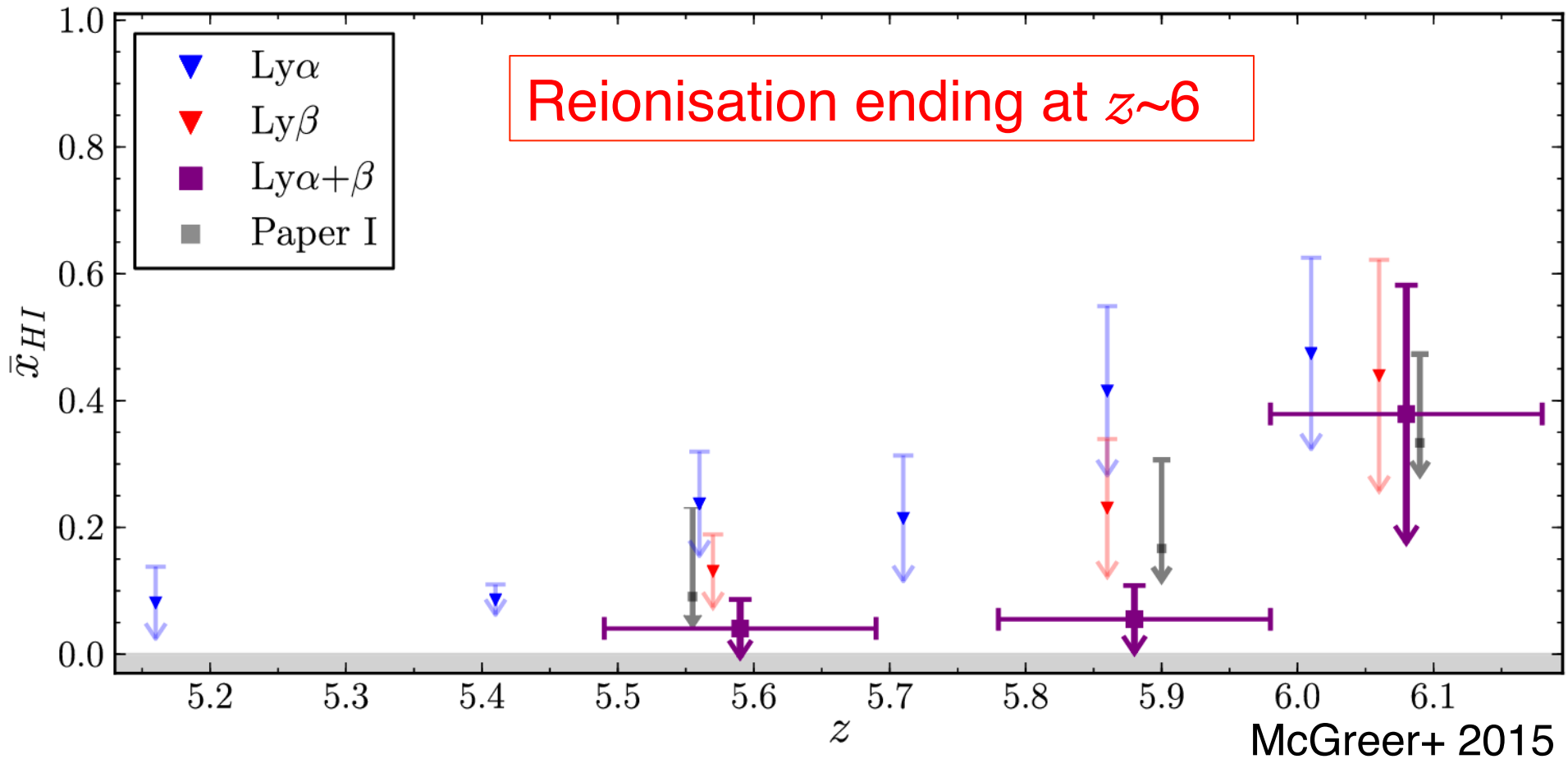
# Weak constraints on $X_{HI}$ from Lyα forest




Barnett+ 2017

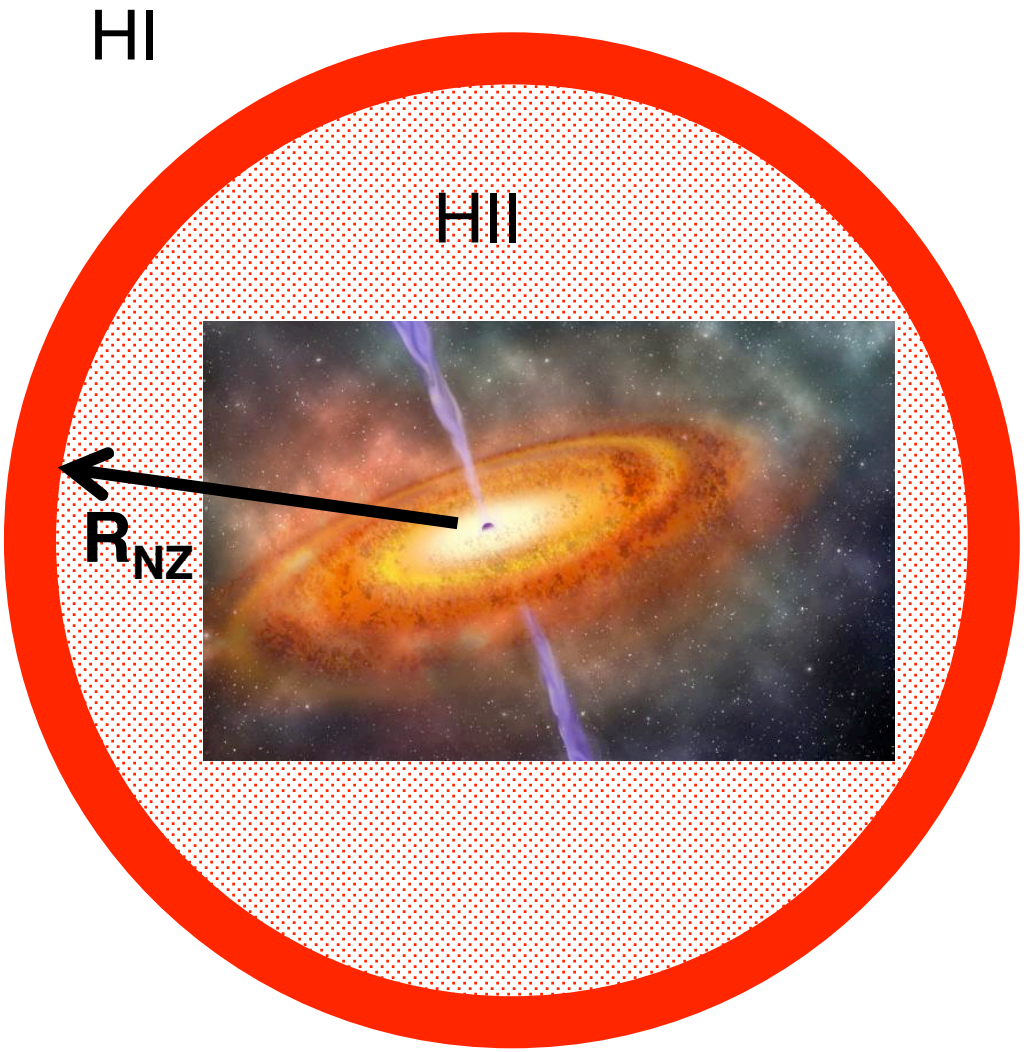
# Dark pixel statistics

Count fraction of "zero flux" pixels → upper limit on $X_{HI}$
+ Not dependent on model or quasar spectrum




McGreer+ 2015

# Quasar ionisation regions



# Quasar ionisation regions

Quasar near zone:

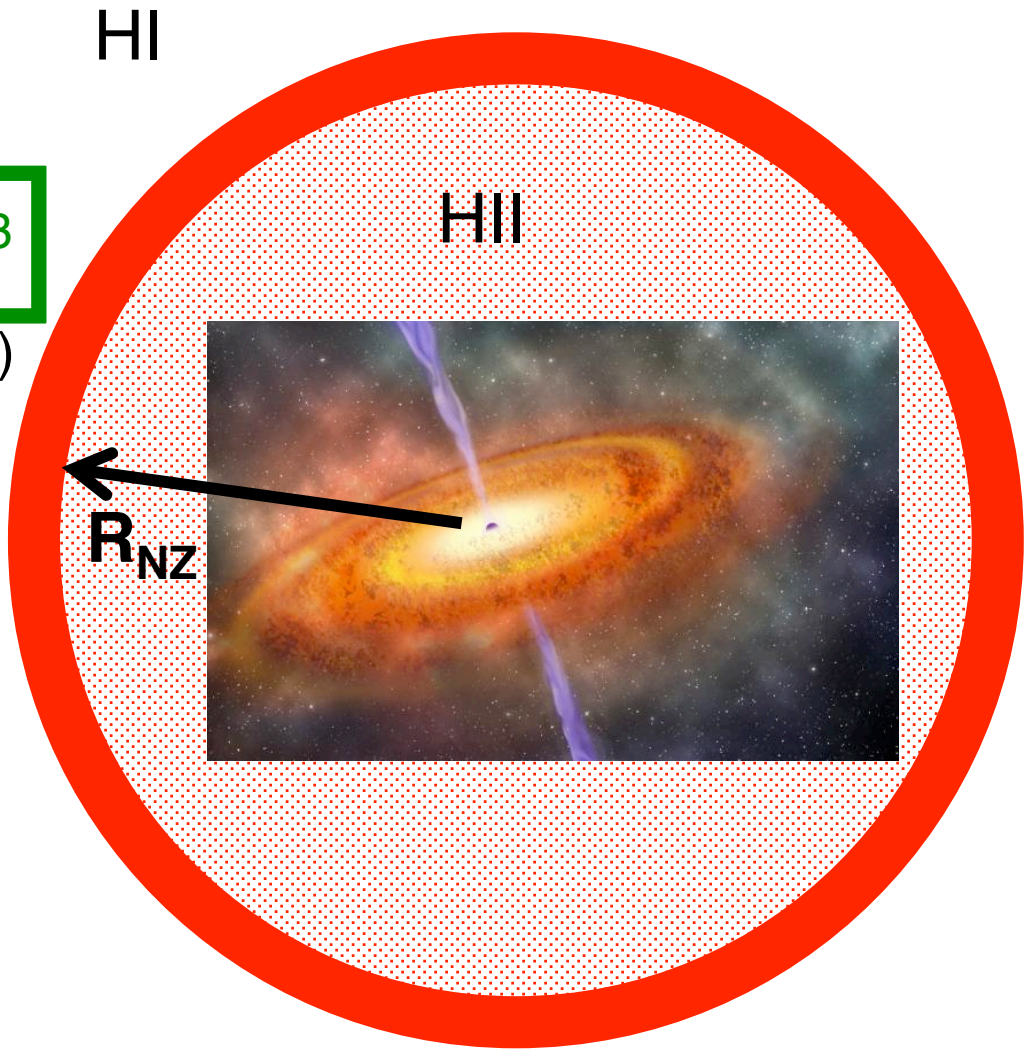
$$R_{NZ} \sim X_{HI}^{-1/3} (t_Q \times L)^{1/3}$$

(e.g. Fan+ 2006)

$X_{HI}$ neutral H fraction

$t_Q$ quasar age

$L$ quasar luminosity



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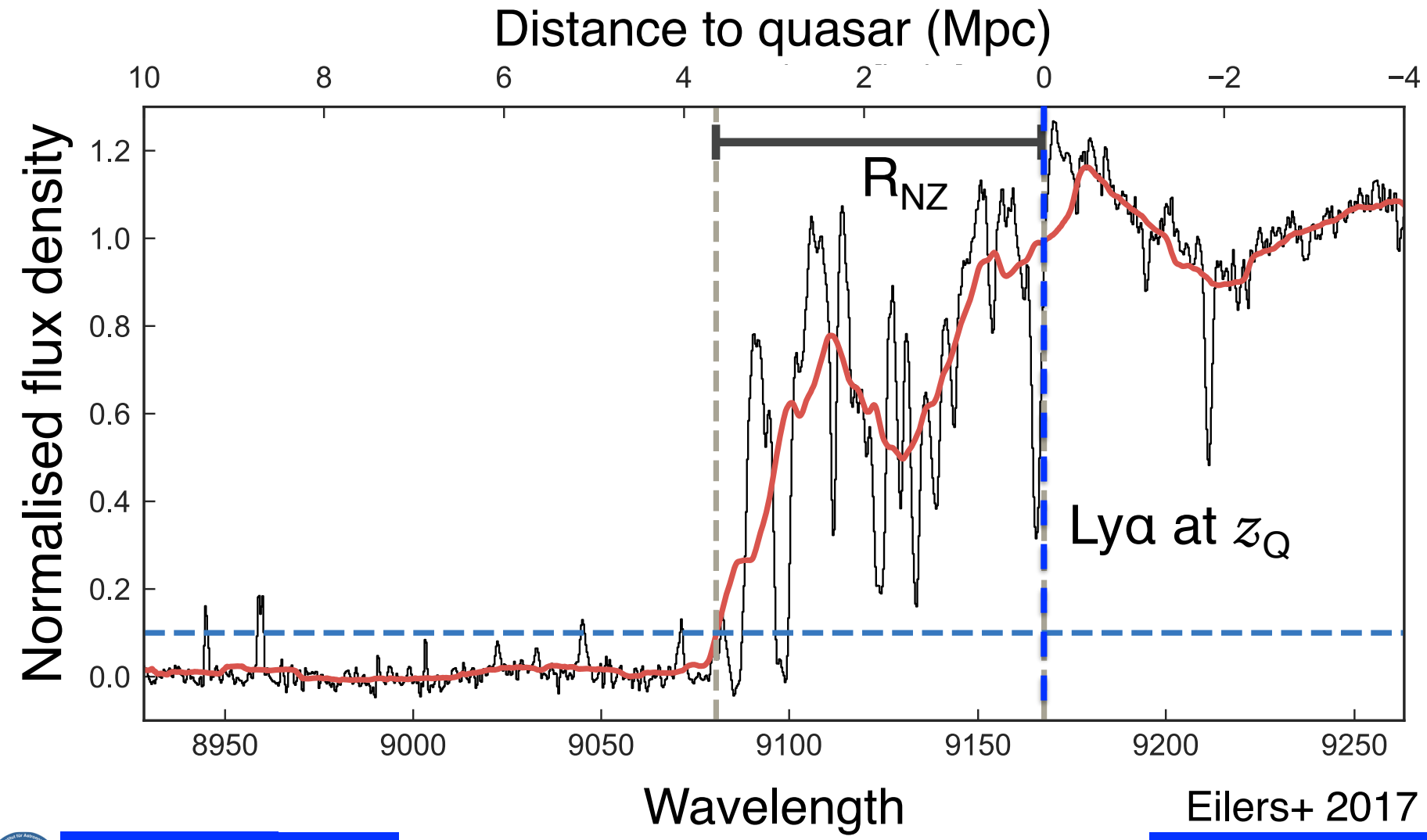


Eilers+ 2017

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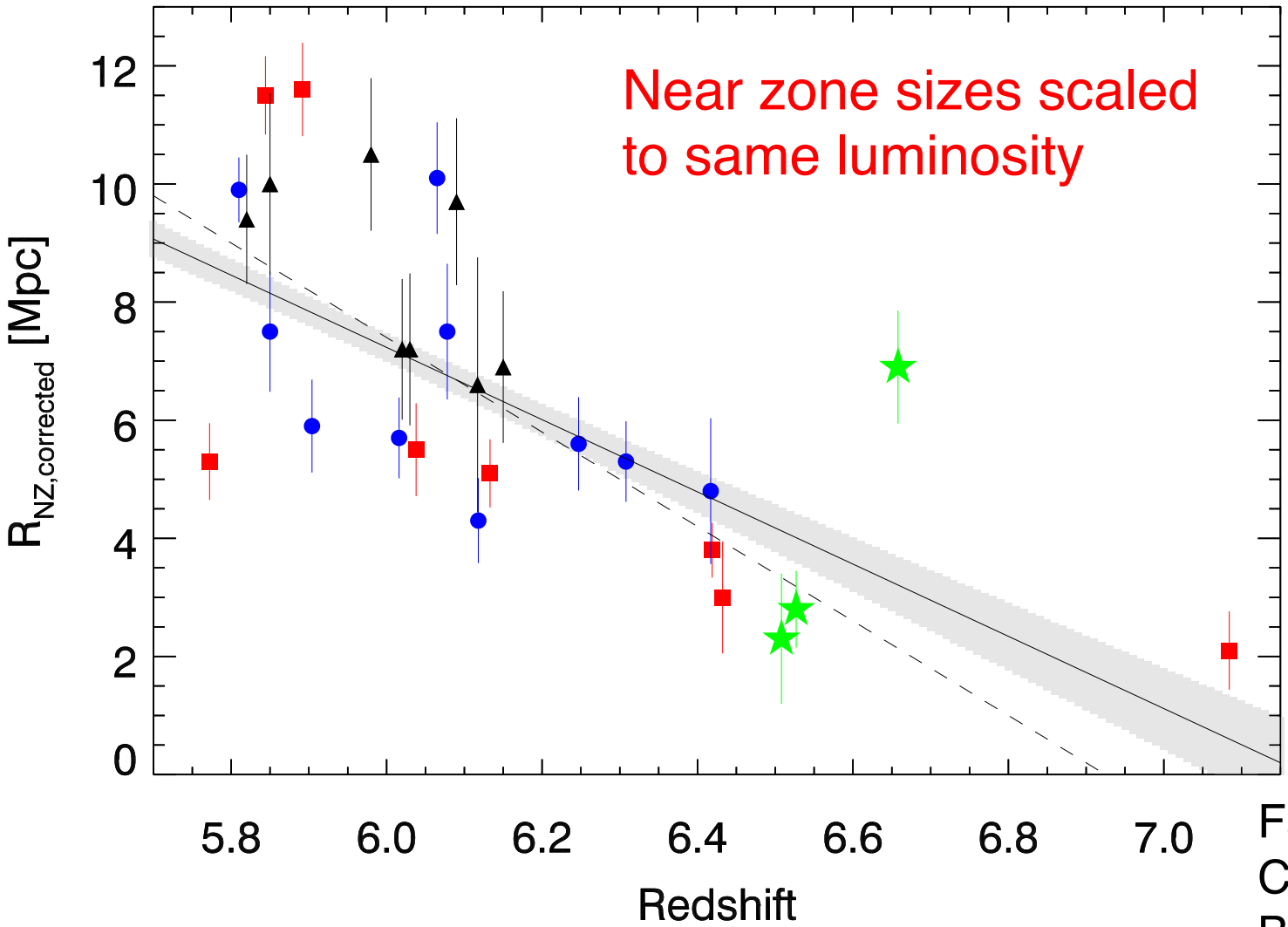


Fan+ 2006
Carilli+ 2010
BV+ 2015

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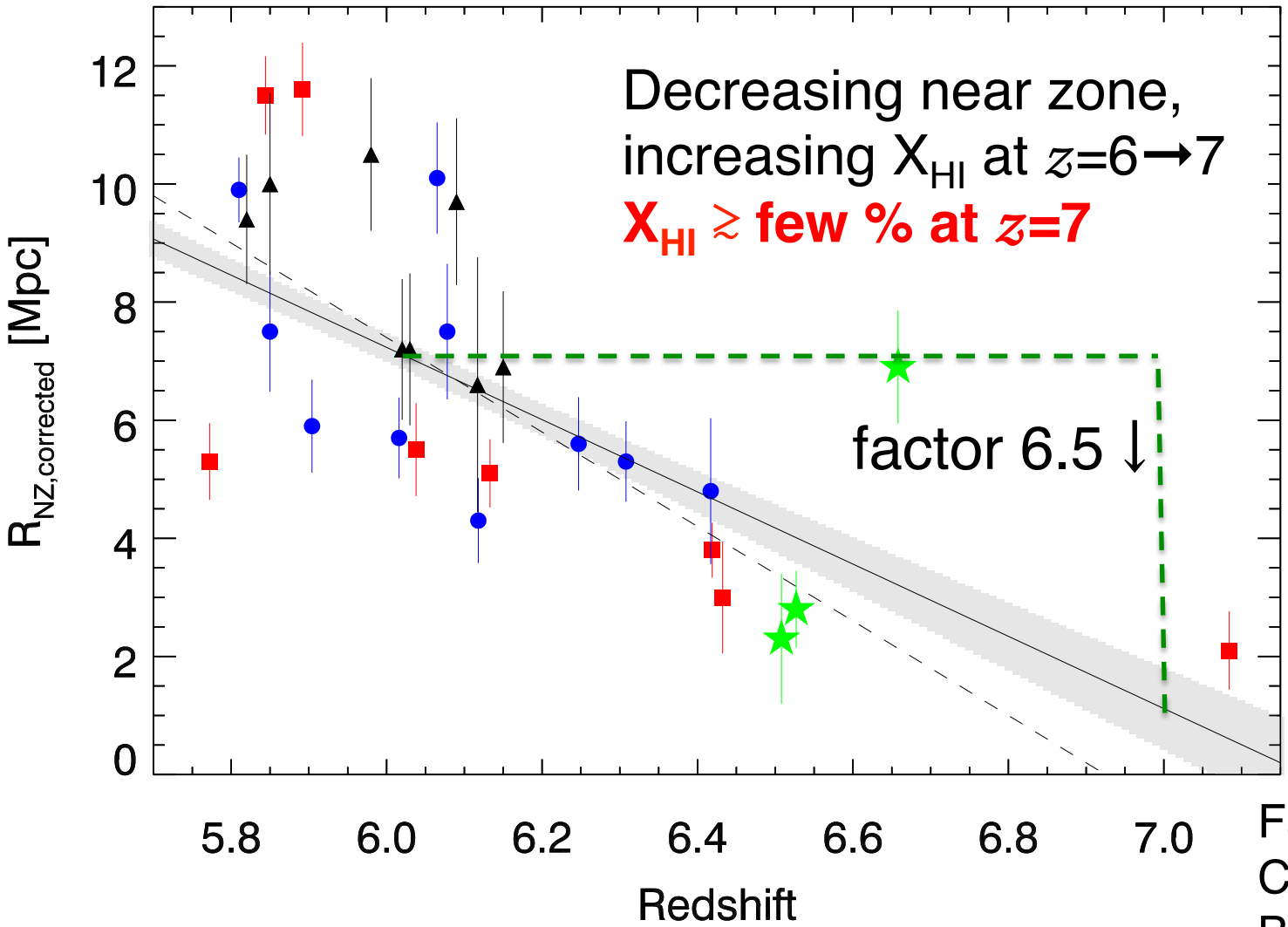
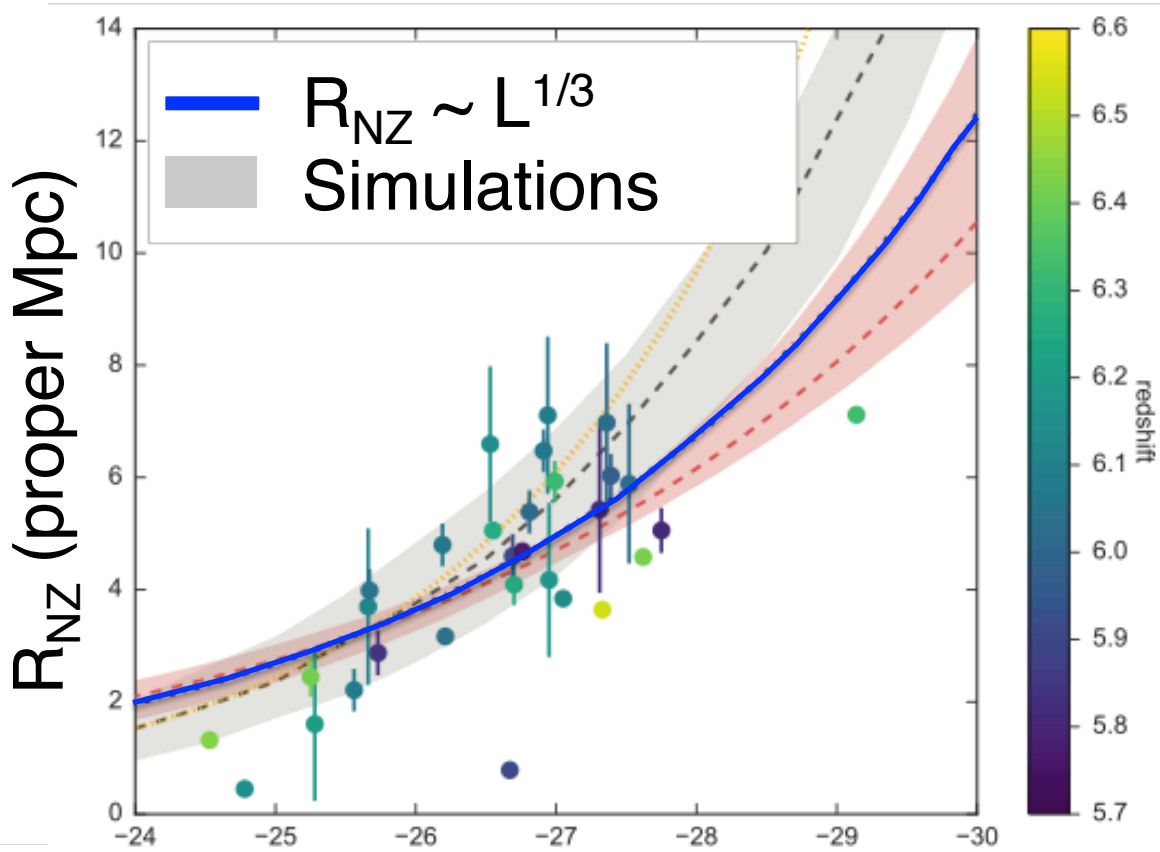



Fan+ 2006
Carilli+ 2010
BV+ 2015

# However: near zone ≠ ionisation front

- New simulations show: $R_{NZ} \sim L^{1/2.35}$



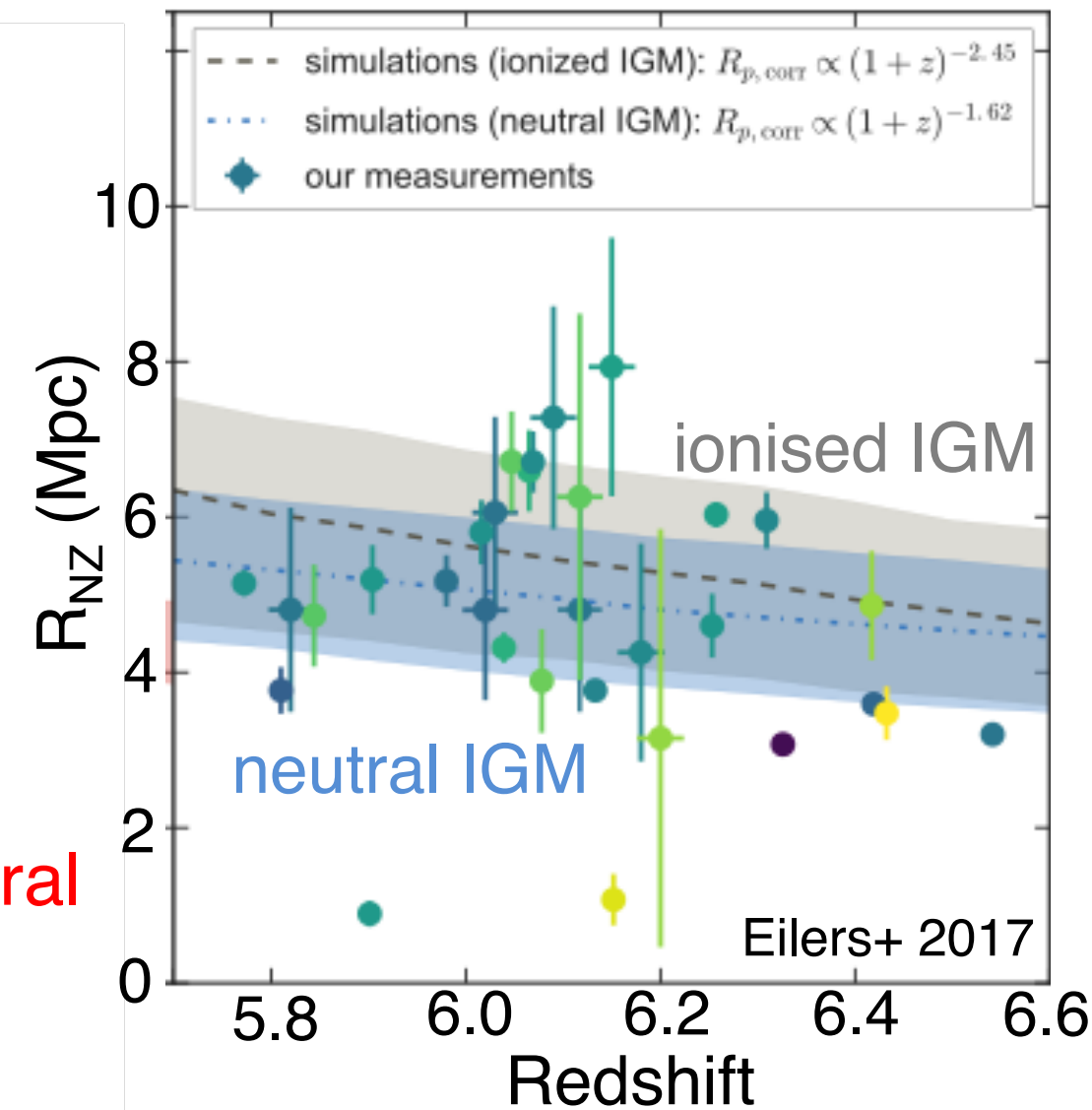

Eilers+ 2017
see also Bolton & Haehnelt 2007

# Shallower trend with redshift

Recent publications:

- New observations
- Higher S/N
- Homogeneous analysis
- Better systemic redshifts

+ simulations show same trend for neutral and ionised IGM



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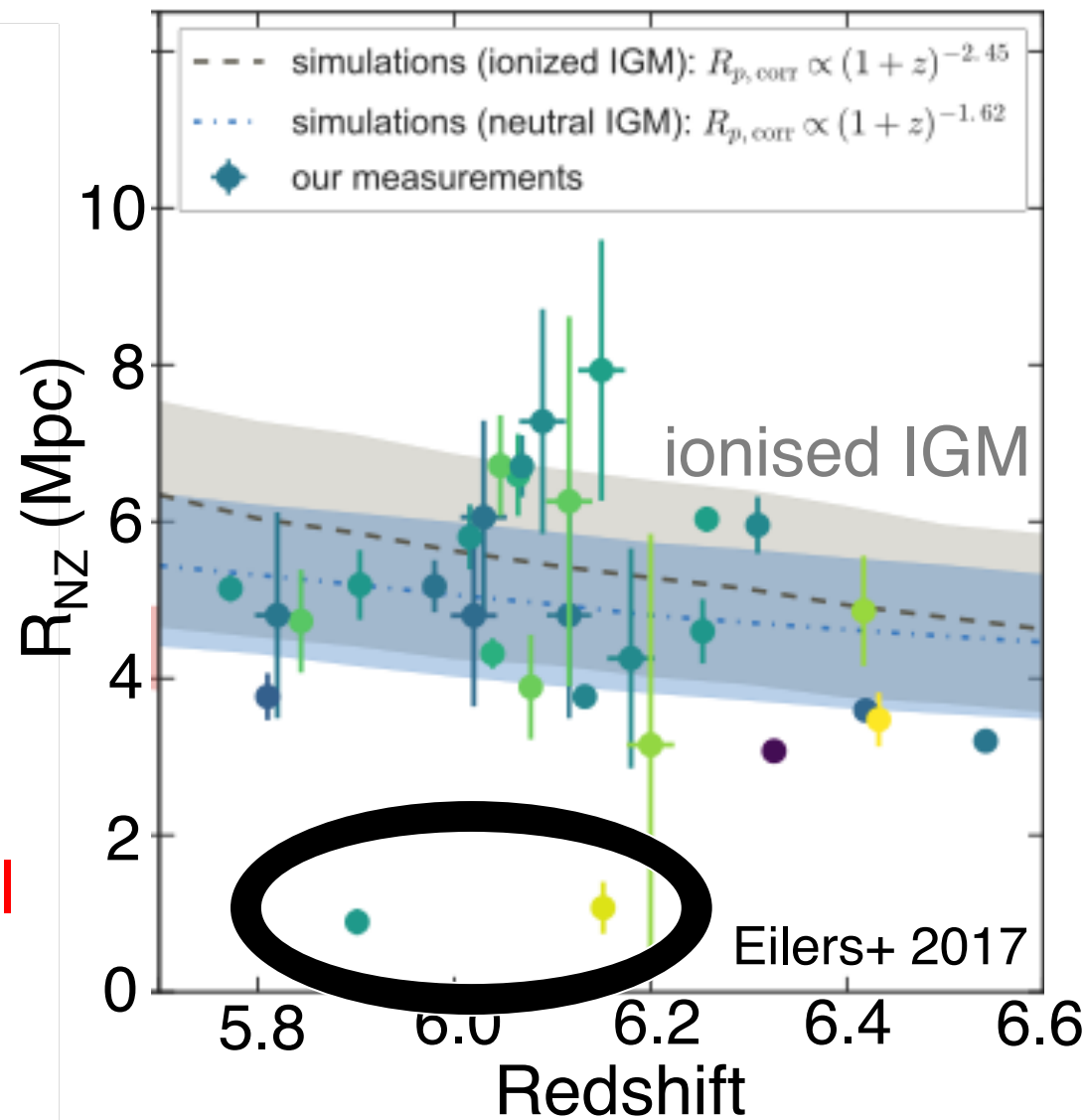


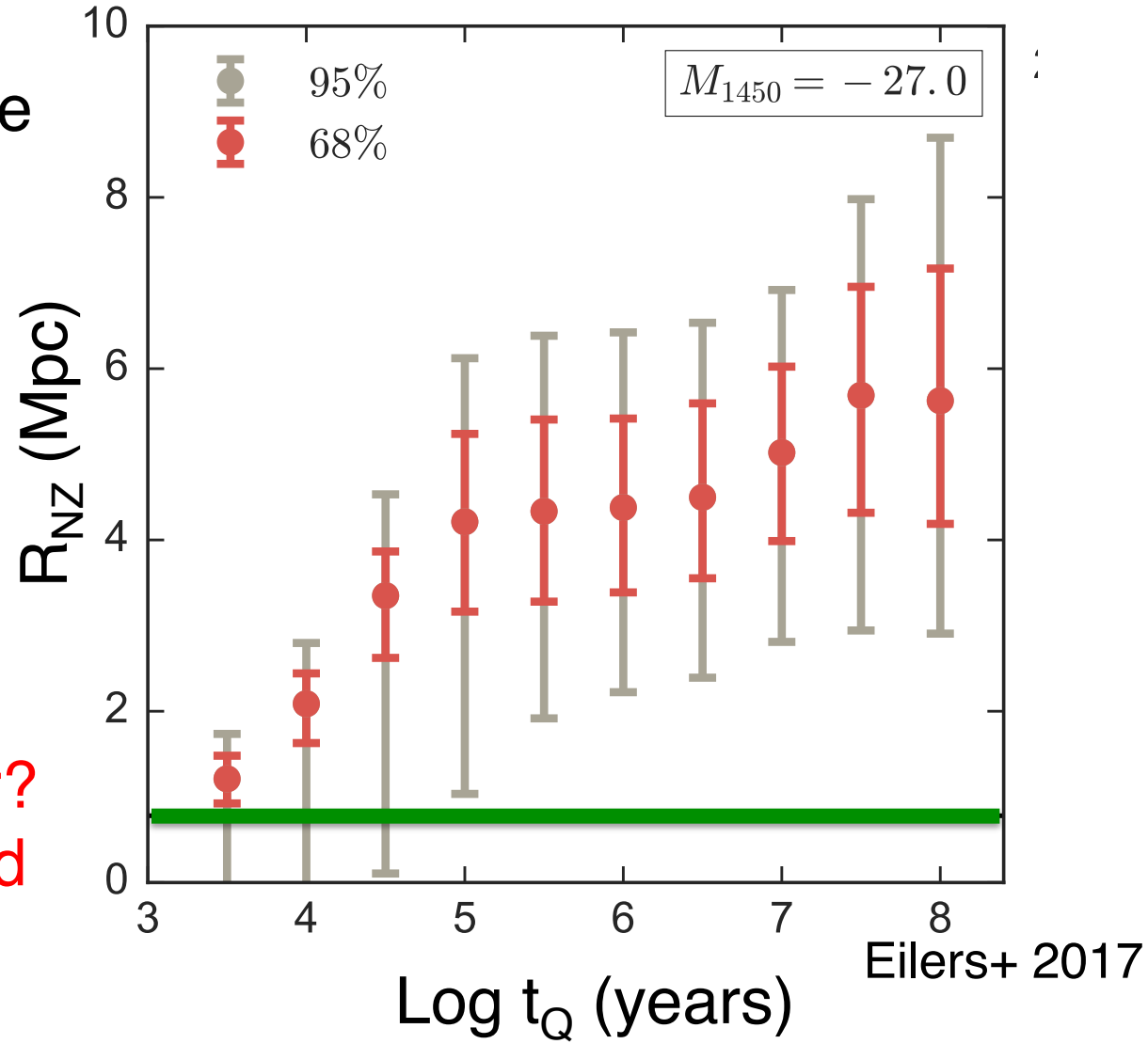
# Near zone size as function of age

~10% of quasars have a very small $R_{NZ}$

No evidence for proximate DLAs

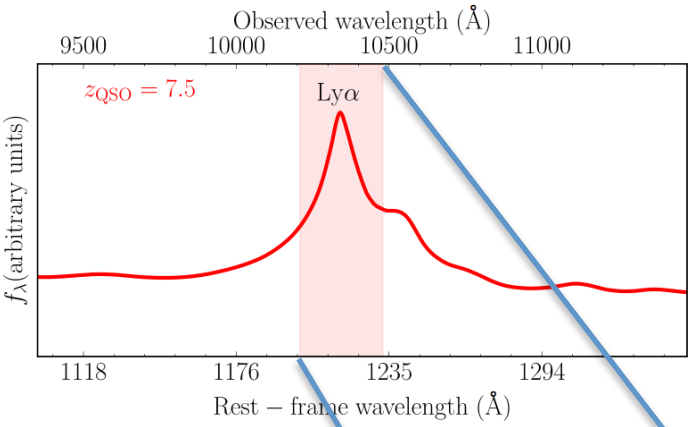
→ Short quasar lifetime of $t_Q < 10^5$ yr

Quasar lifetime 1 Myr? Inconsistent with rapid growth of black holes




Eilers+ 2017

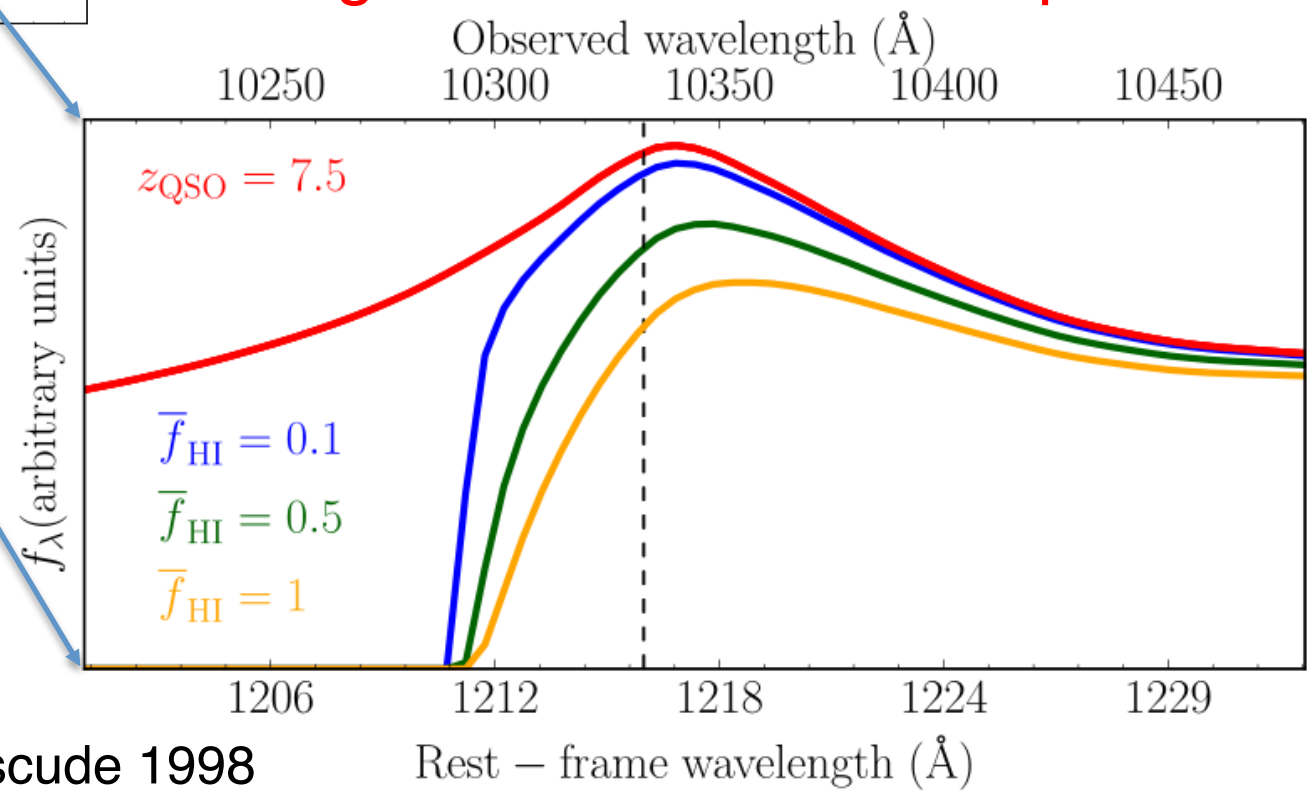
# IGM damping wing




Damping wing of the IGM:

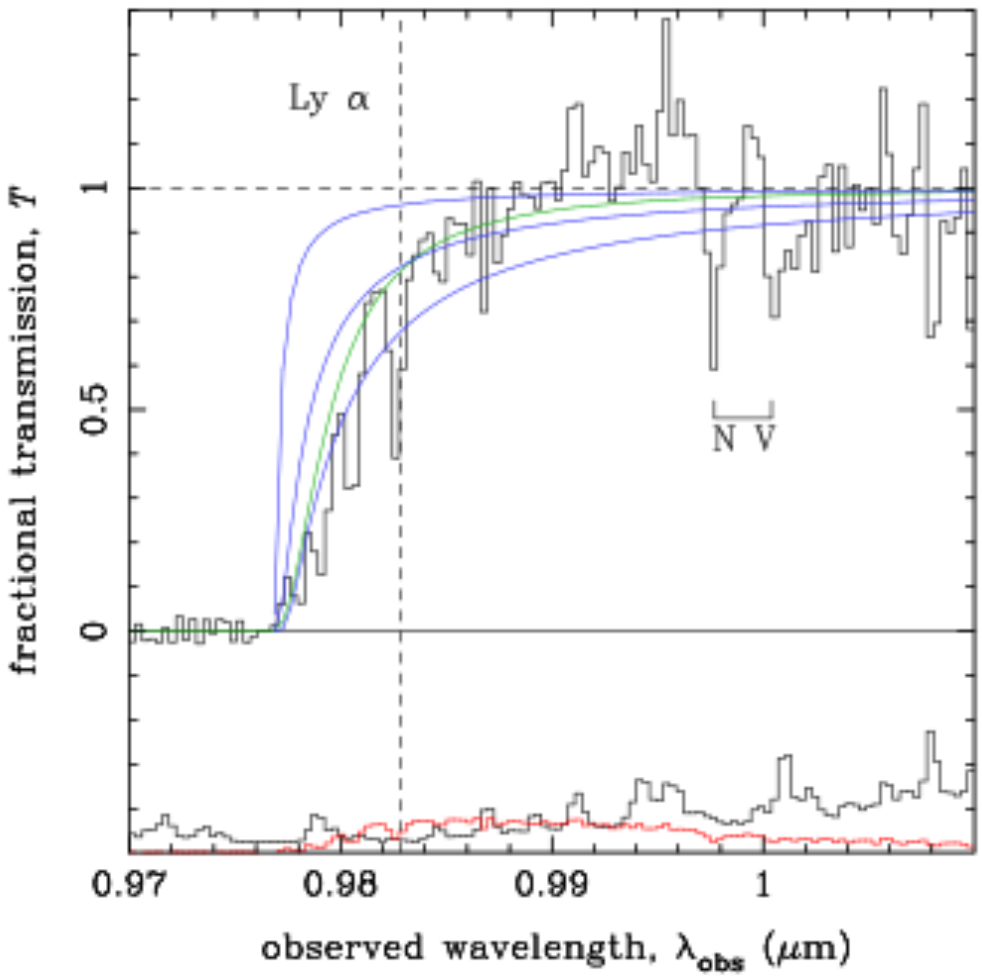
→ sensitive to neutral fractions >0.1

challenge: unknown intrinsic spectrum




see, e.g., Miralda-Escude 1998

# Tentative detection of damping wing




J1120+0641 at $z$=7.1 shows a damping wing signature (Mortlock+ 11):

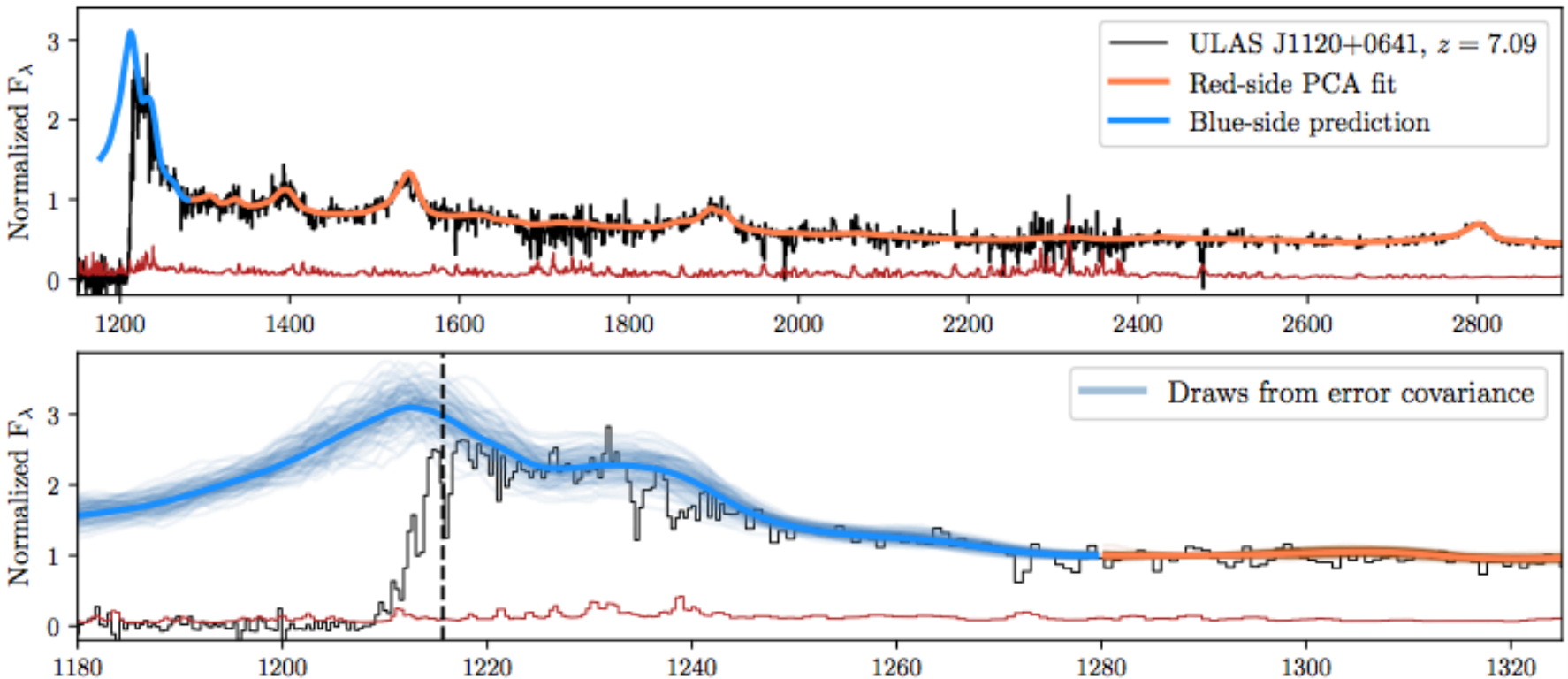
$X_{HI}$ = 0.4 +/- 0.2

However, claim disputed

Bosman & Becker 2015: *"no need for damping wing"*

Mortlock+ 2011; see also Bolton+ 2011; Greig+ 2016

# Principle Component Analysis



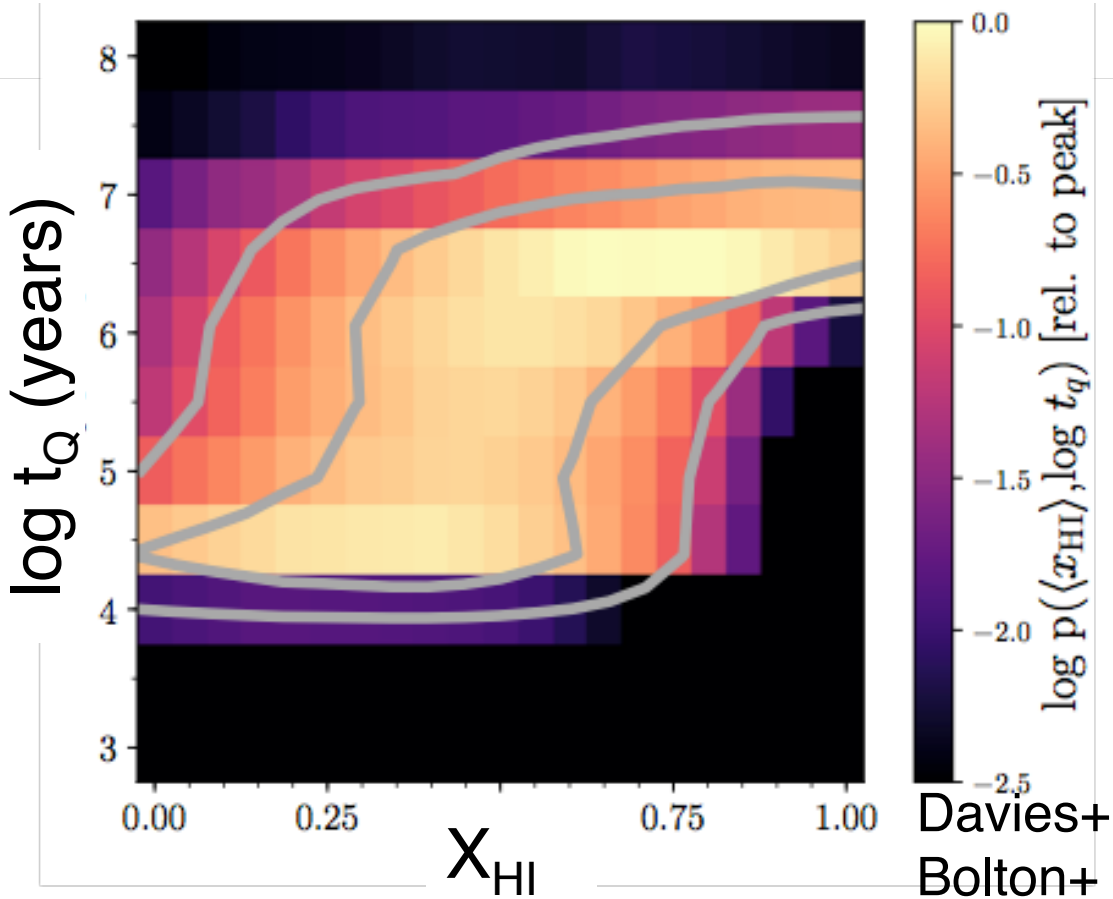

Davies+ 2018

Wavelength

- Model red side of spectrum to predict blue side
- Use $z \approx 2$ quasars as training set

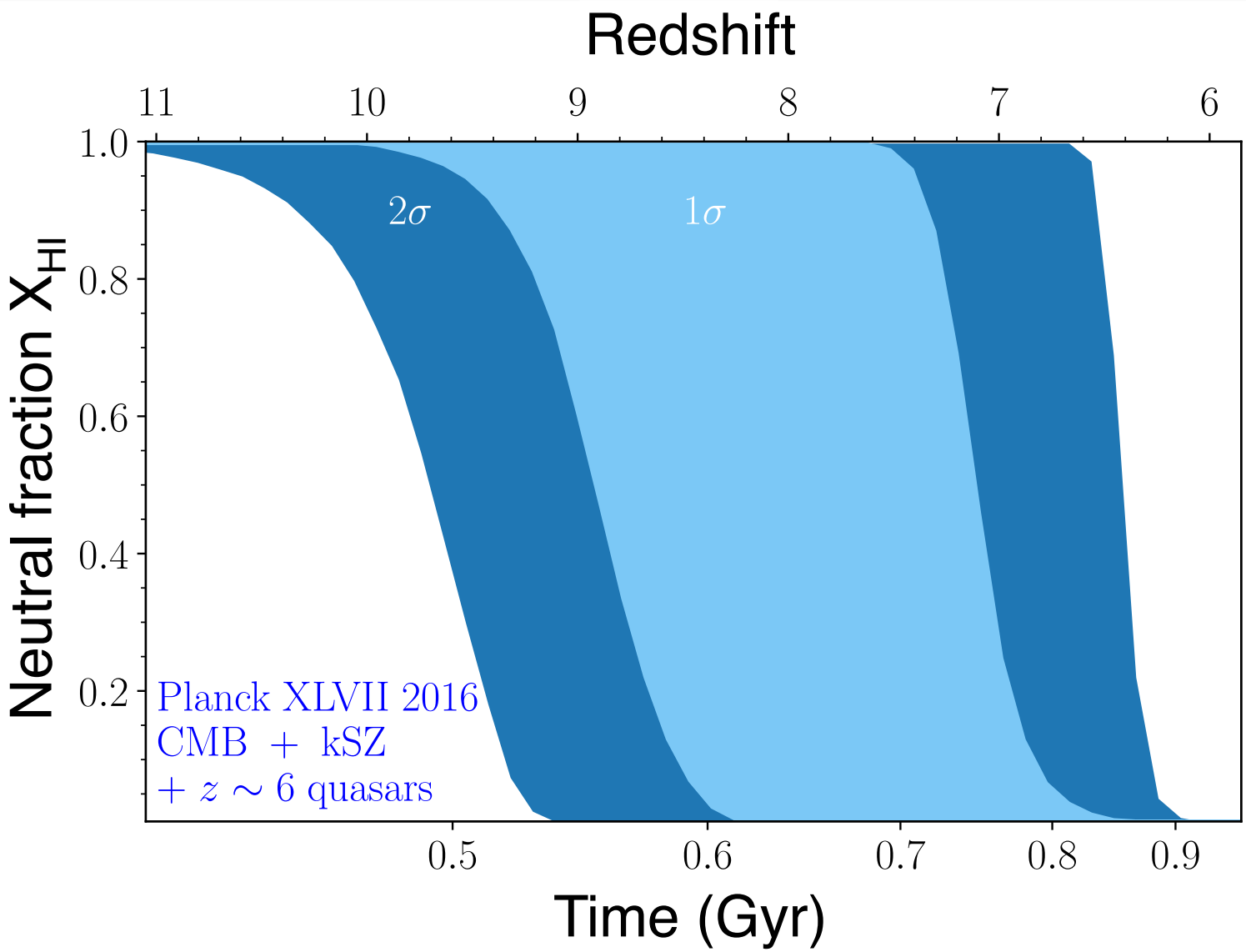
# Damping wing modeling

- Model IGM neutral fraction and quasar age simultaneously




Davies+ 2018; Bolton+ 2011

# Evolution of neutral Hydrogen fraction



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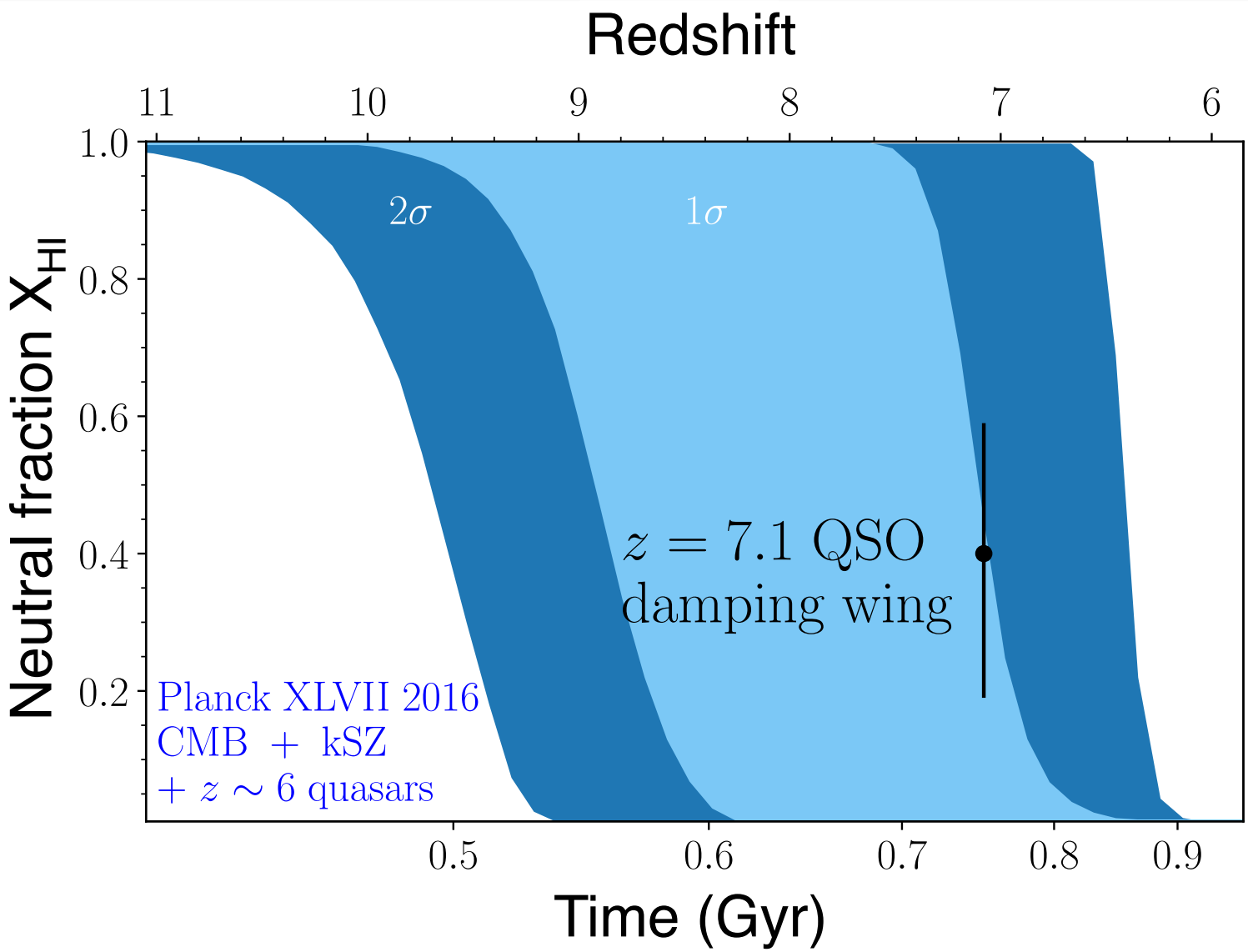

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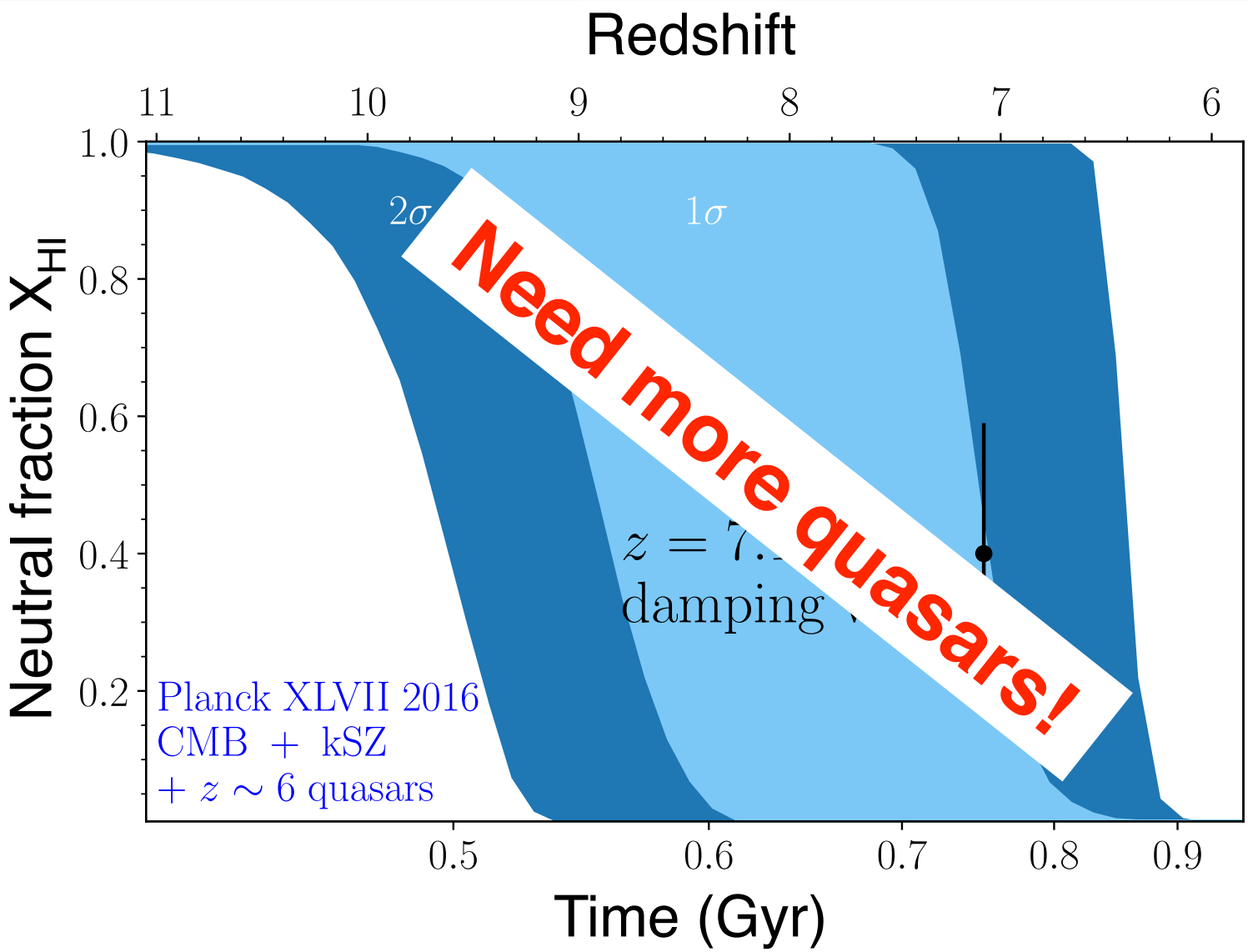
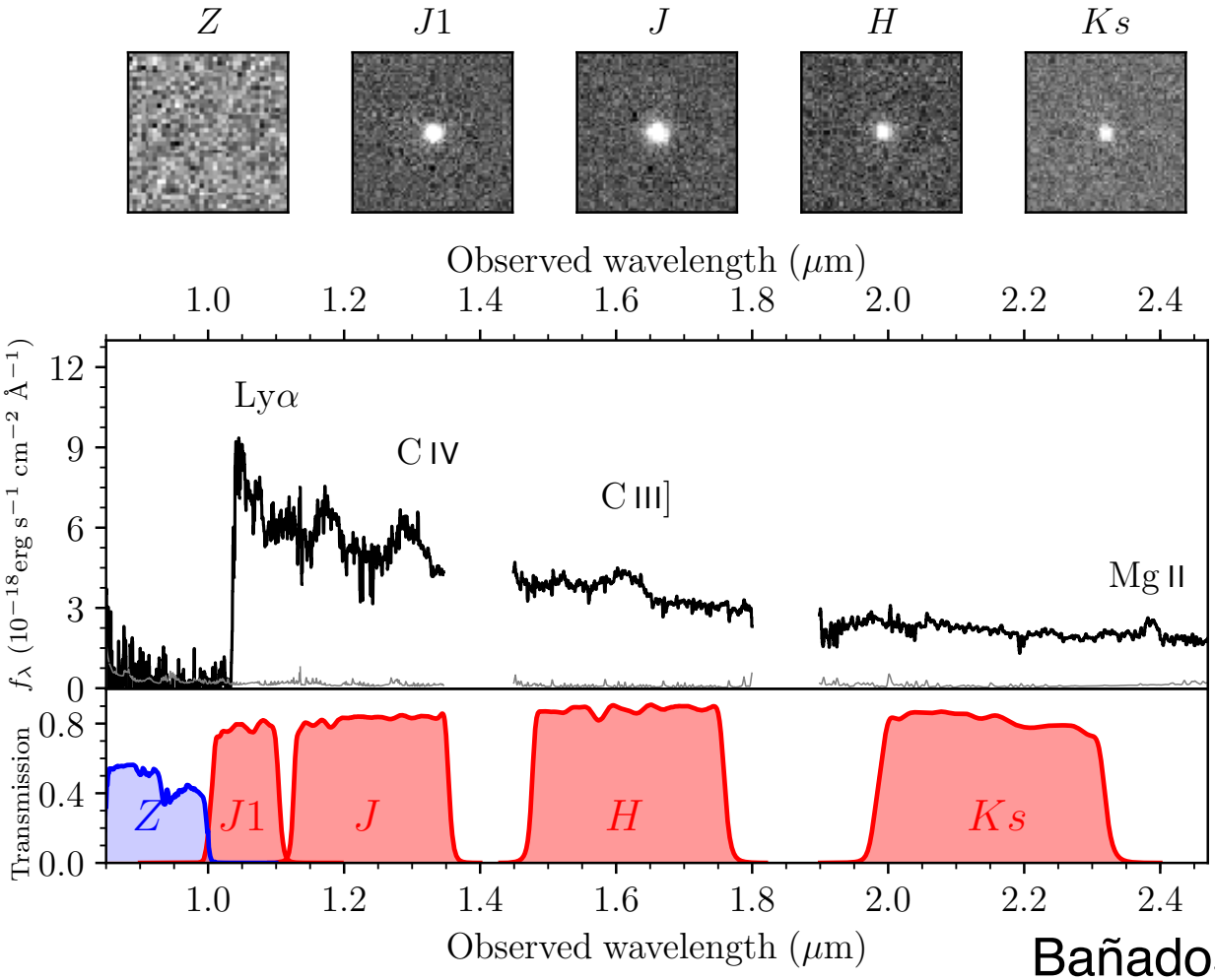


# New quasar at record redshift: $z$=7.54!

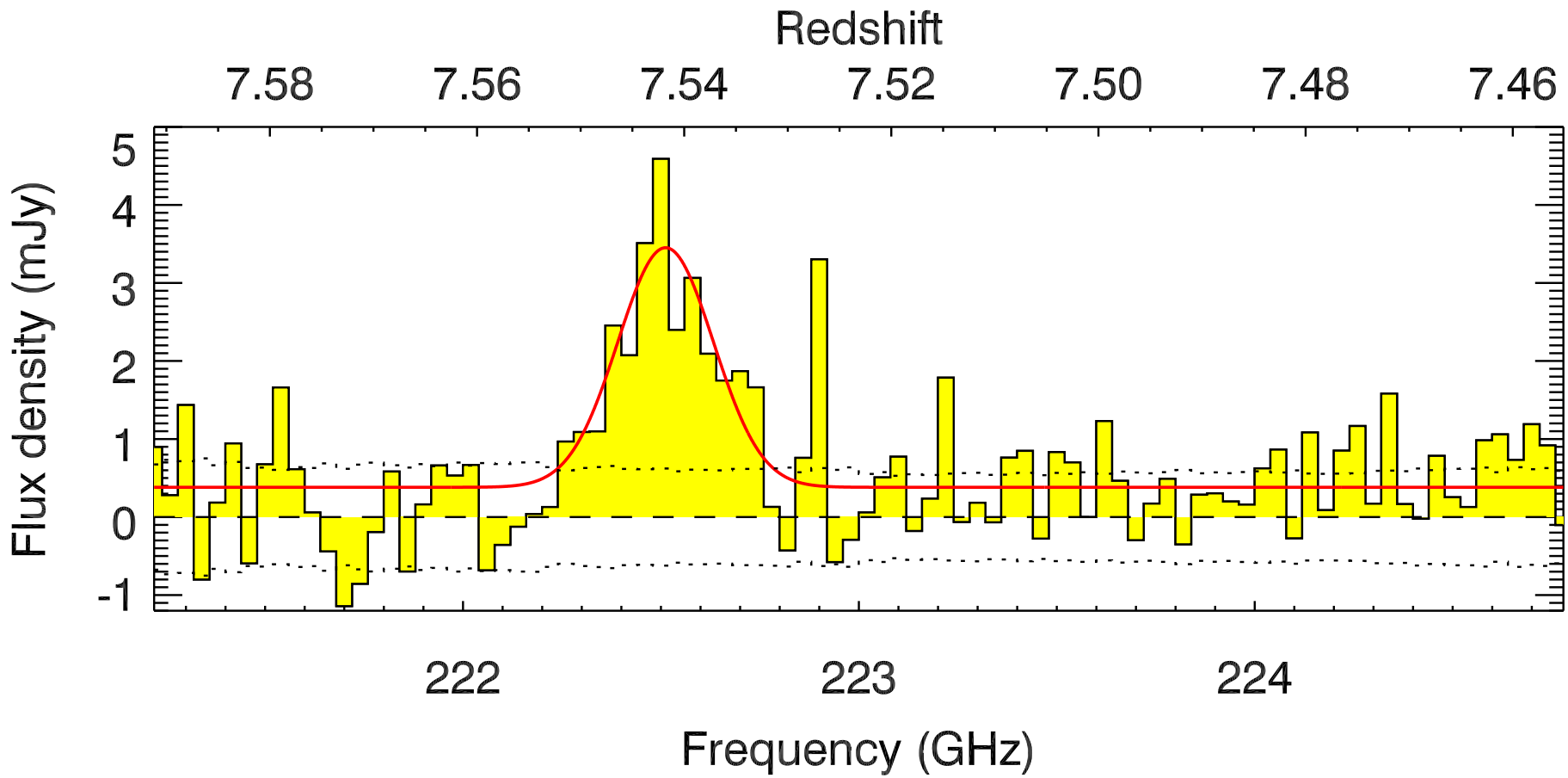
Age of universe: 690 Myr → ~10% younger than at $z$=7.1




Bañados, BV+ 2018

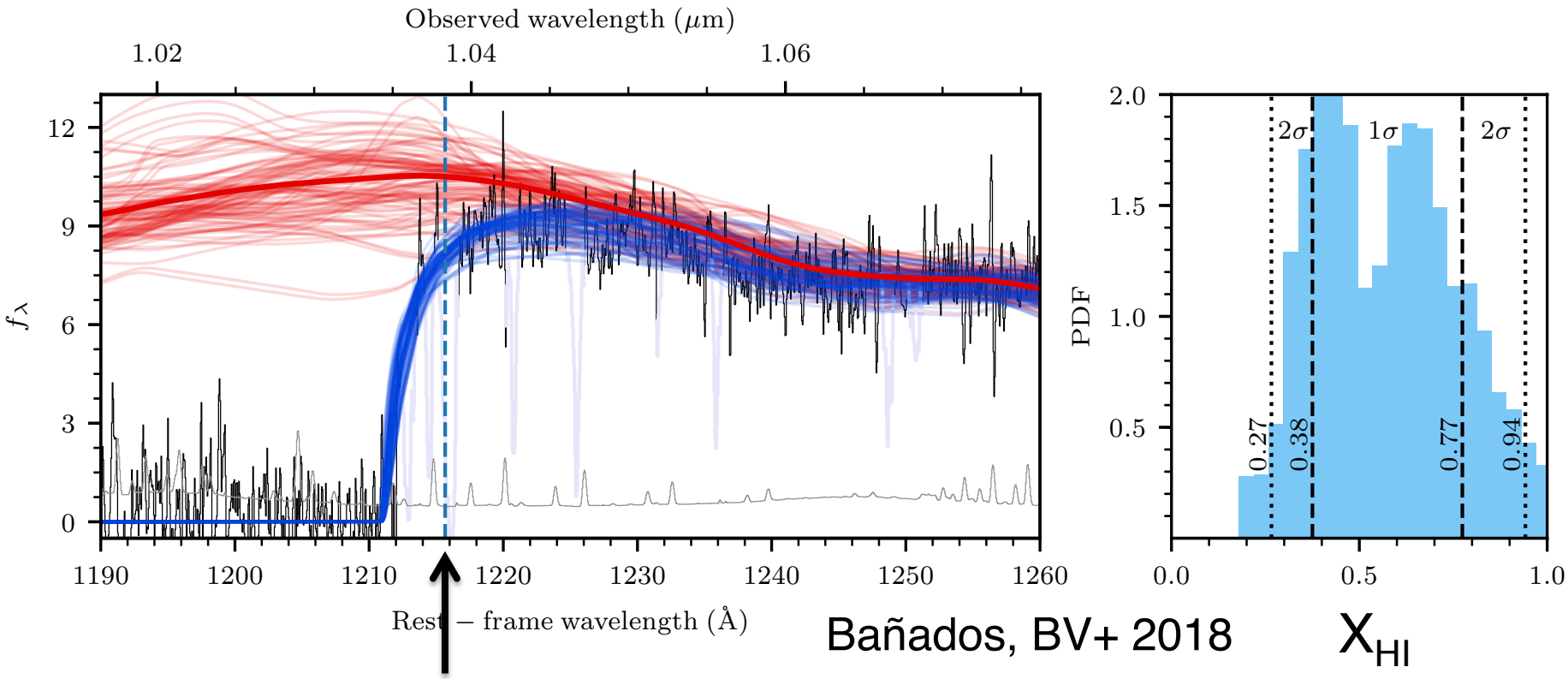
# New quasar at record redshift: $z$=7.54!

Very accurate measurement of systemic redshift




BV+ 2017

# IGM damping wing at $z$=7.5

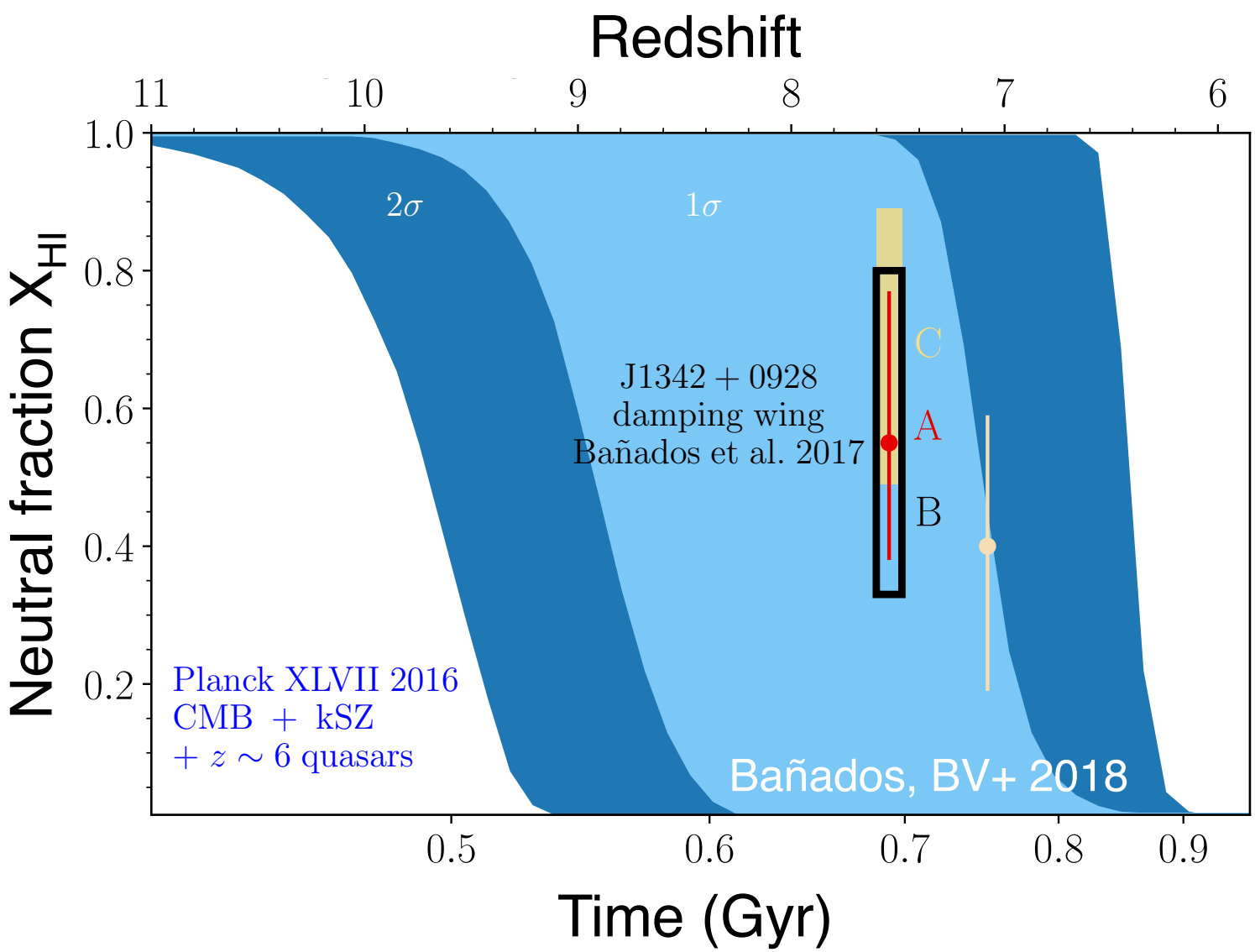



Bañados, BV+ 2018

$X_{HI}$

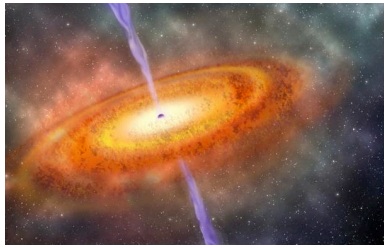
Lyα at systemic redshift

# Reionisation occurred “late”?



# Conclusions

- Luminous quasars are ideal objects to study the Epoch of Reionisation



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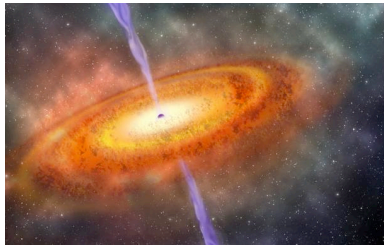
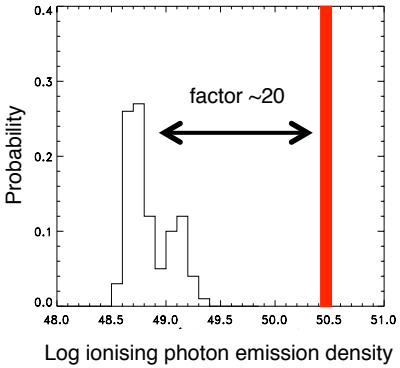
- Quasar do not contribute significantly to the ionising photon rate density





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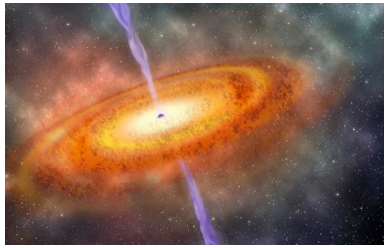

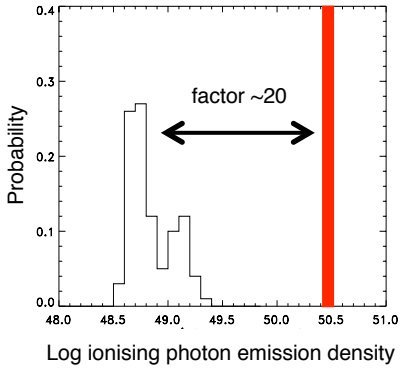


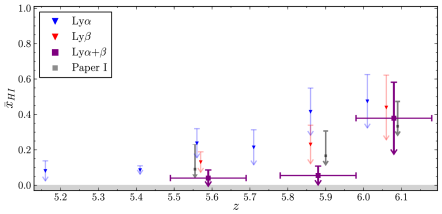

# Conclusions

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- Quasar do not contribute significantly to the ionising photon rate density
- Analysis of Lyα forest suggests reionisation ended around $z$=6
- Size of near zones insensitive to neutral fraction
- Damping wing in two most distant quasars indicate a highly neutral Universe at $z$>7