

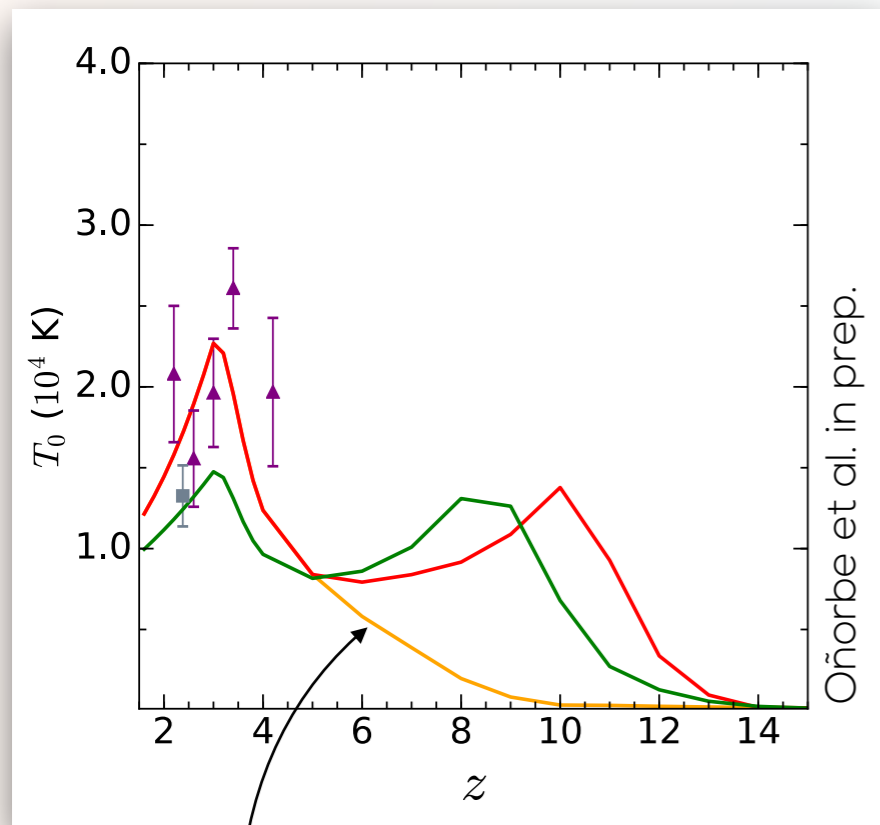
THE INTERGALACTIC MEDIUM AT HIGH REDSHIFTS AND ITS IMPLICATIONS FOR THE EPOCH OF REIONIZATION

Anna-Christina Eilers (MPIA)

with Joe Hennawi (MPIA) and Frederick Davies (MPIA)

THREE OPEN QUESTIONS

onset and **duration**
of reionization?

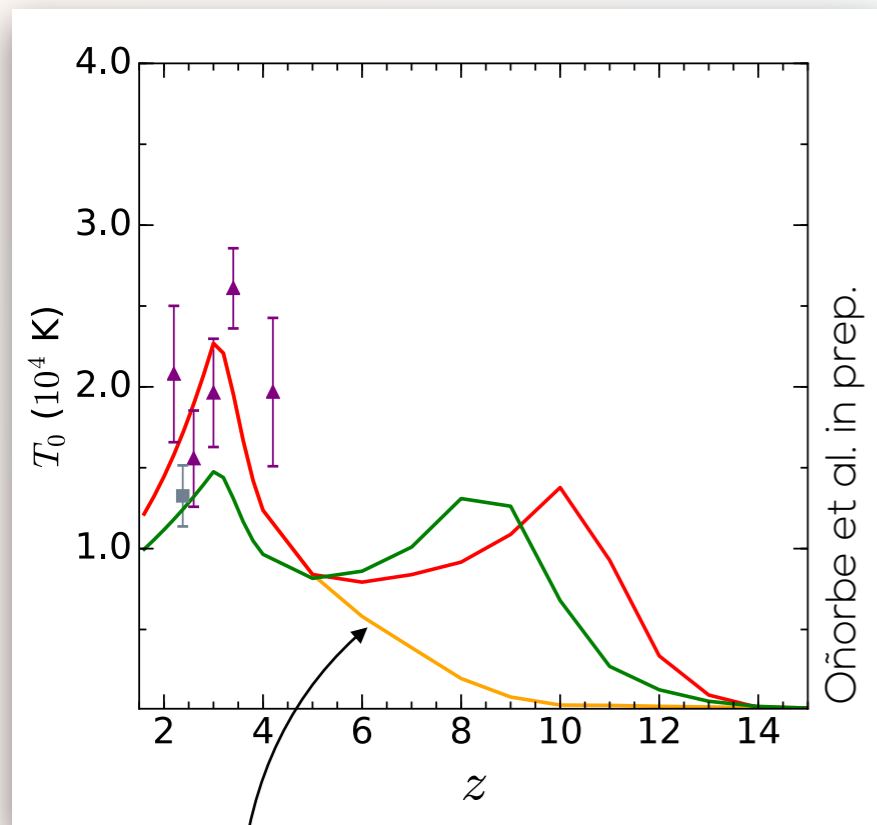


different ionization
histories

(e.g. McGreer et al. 2014, Nasir et al. 2016,
Upton Sanderbeck et al. 2015,
Planck Collaboration 2016, ...)

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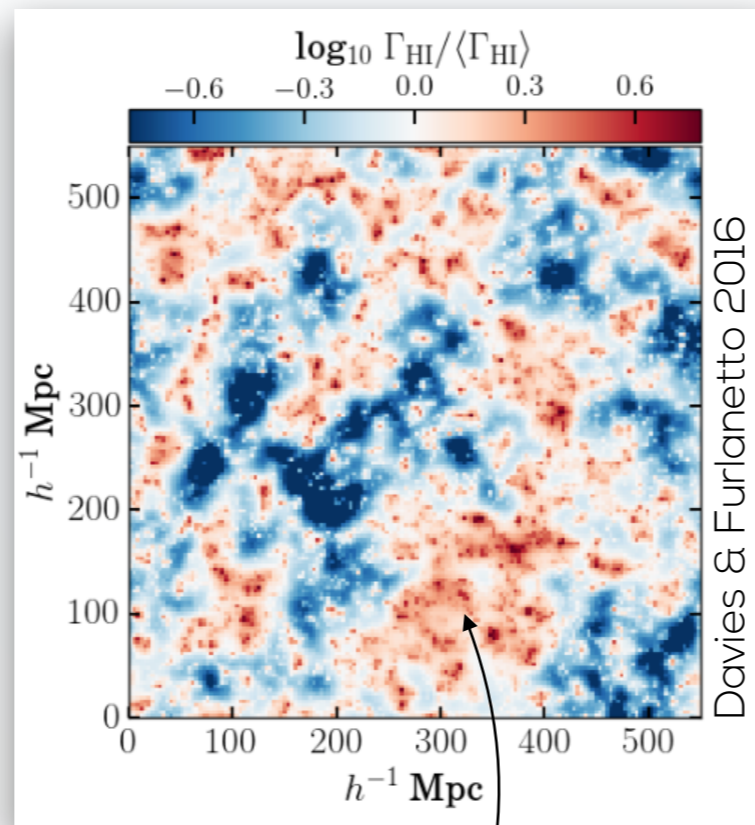
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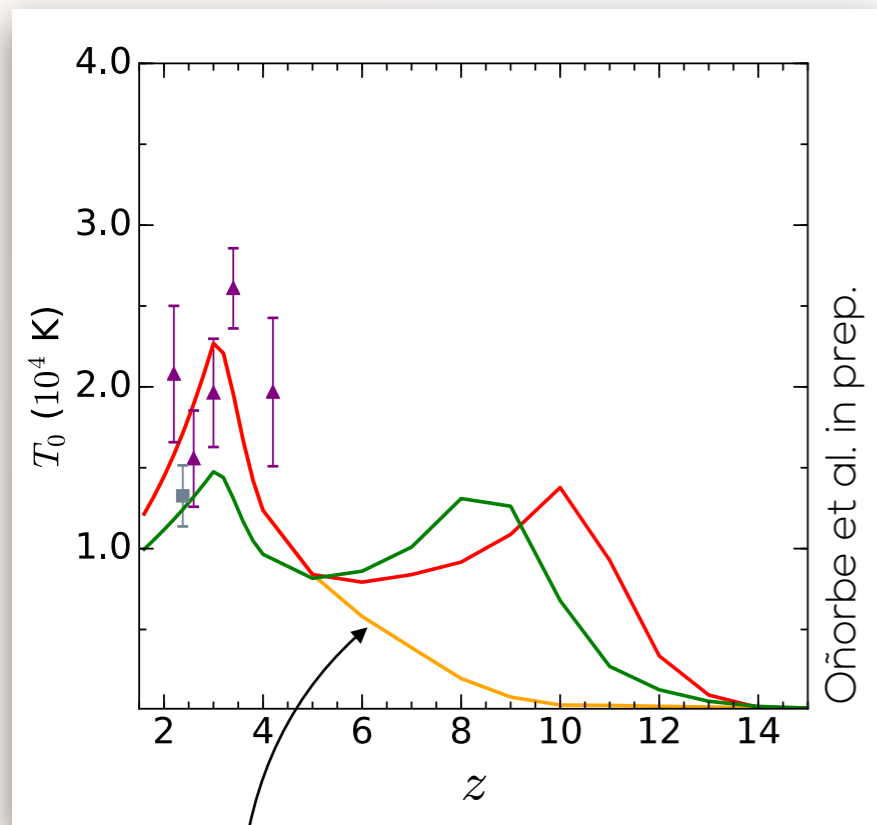


inhomogeneous UV
background radiation

(e.g. D'Aloisio et al. 2015,
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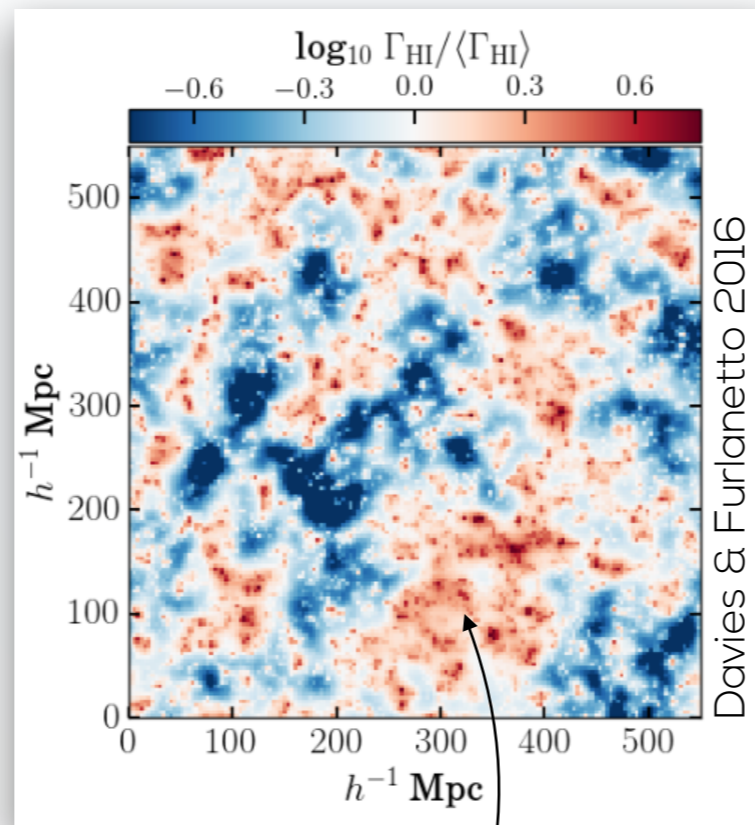
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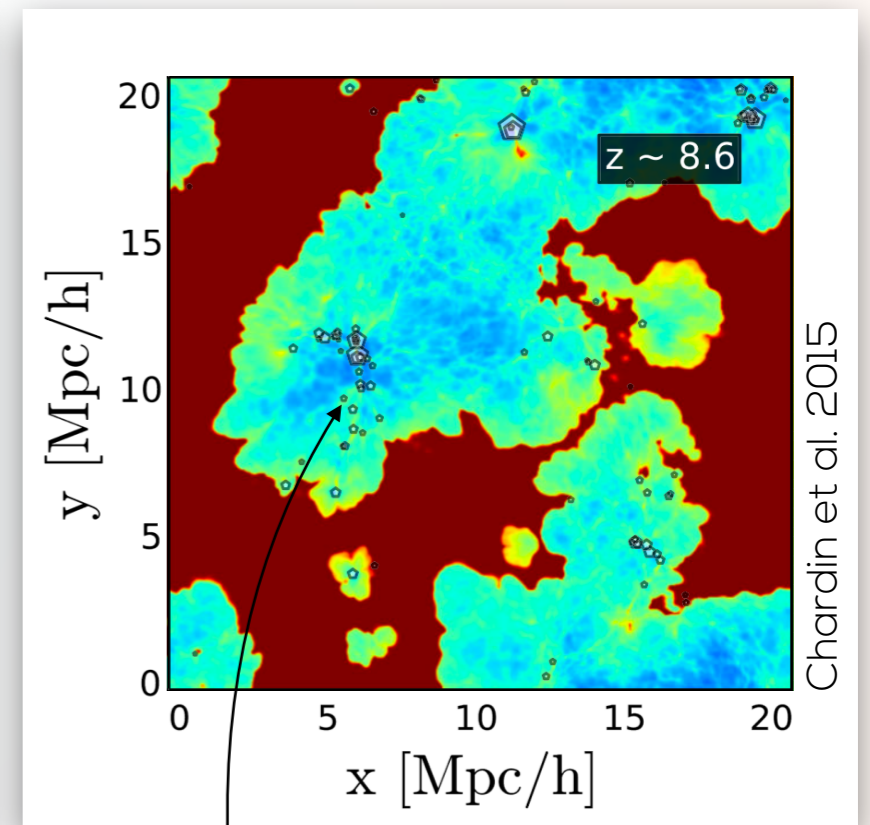
morphology of
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sources of
reionization?



abundant faint or
rare bright ionizing
sources?

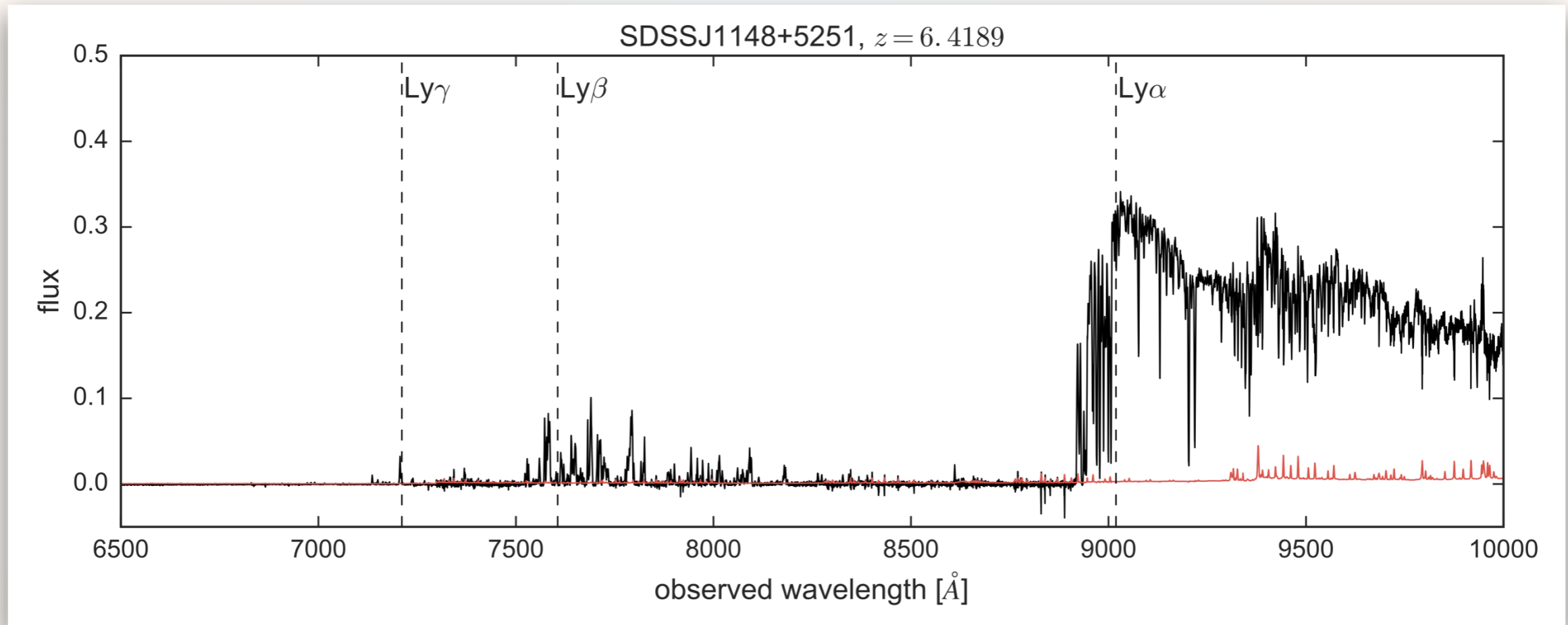
(e.g. Madau & Haardt 2015, Bouwens
et al. 2015, Mitra et al. 2016, ...)

A NEW DATA SET OF QUASAR SPECTRA

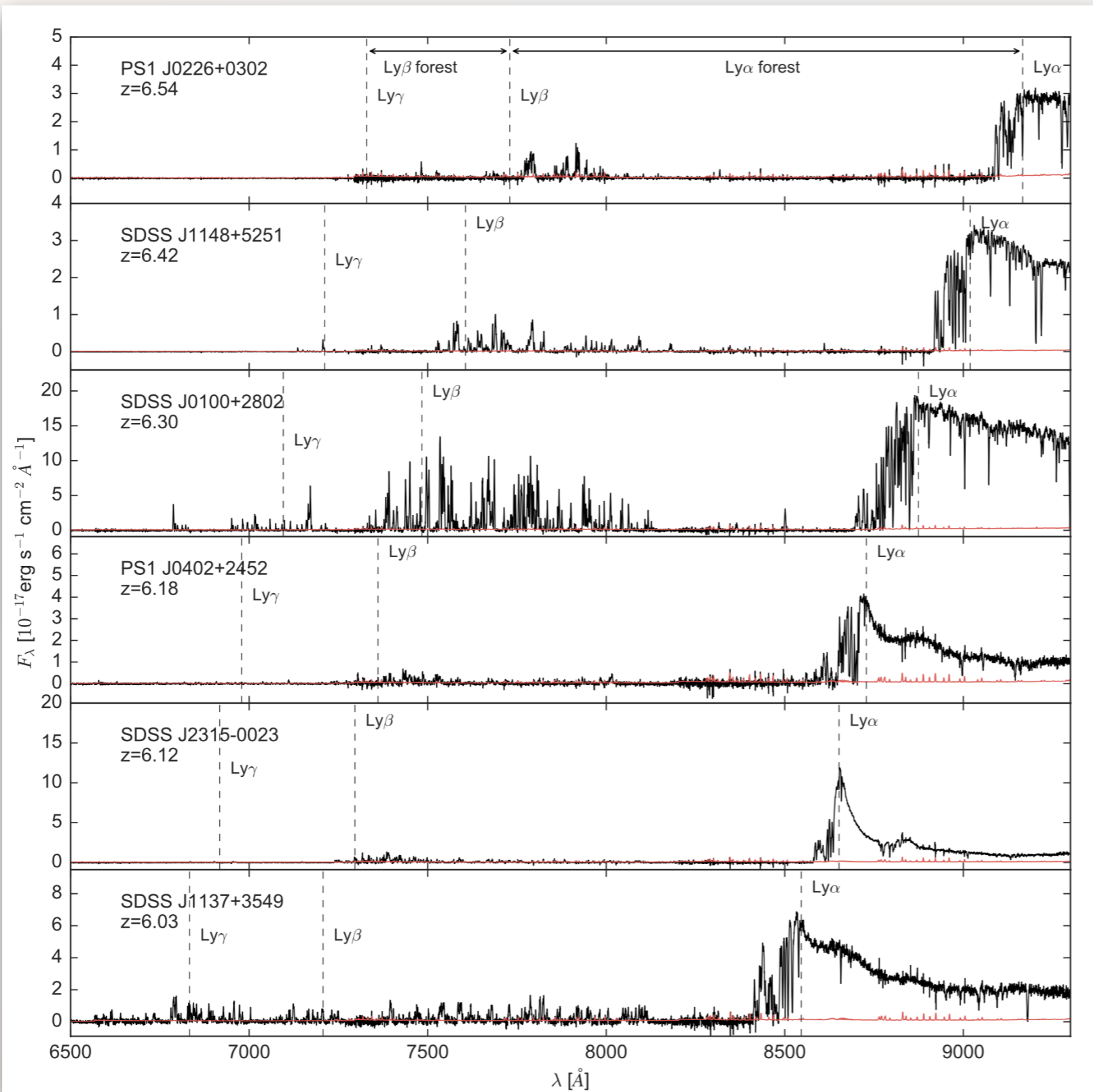
- ◆ 32 quasar spectra (~10 of them unpublished)
- ◆ redshift range: $z \sim 5.78-6.54$
- ◆ Echellette Spectrograph and Imager (ESI) on the Keck telescopes
- ◆ resolution: $R \sim 5000$
- ◆ homogeneous data reduction
- ◆ co-adding of all exposures (~188 hours of telescope time)



25 HOURS OF EXPOSURE TIME



A FEW EXAMPLE SPECTRA



two new Pan-STARRS objects
(Bañados et al. 2014,
Venemans et al. 2015)

SCIENCE GOALS

- I. measurements of the **optical depths** of the intergalactic medium along the line of sight
(e.g. Fan et al. 2006, Becker et al. 2015)

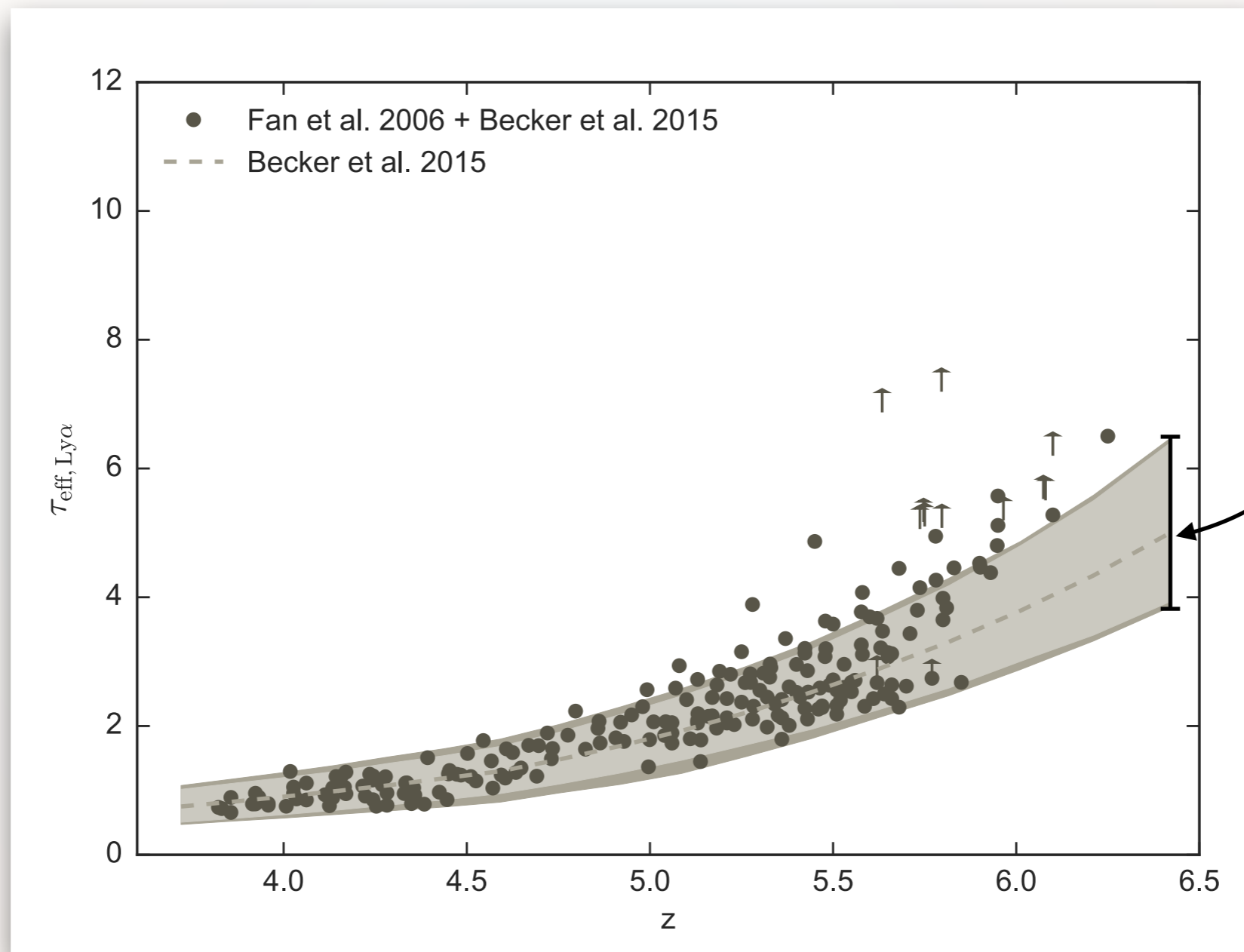
- II. **probability distribution function** of transmitted flux in the Ly α and Ly β forest

- III. measure sizes of **quasar proximity zones**
(e.g. Fan et al. 2006, Carilli et al. 2010, Venemans et al. 2015)

MEASUREMENTS OF THE OPTICAL DEPTH

$$\tau_{\text{eff}} = -\ln(\langle F \rangle)$$

mean flux averaged over chunks of 50 cMpc/h

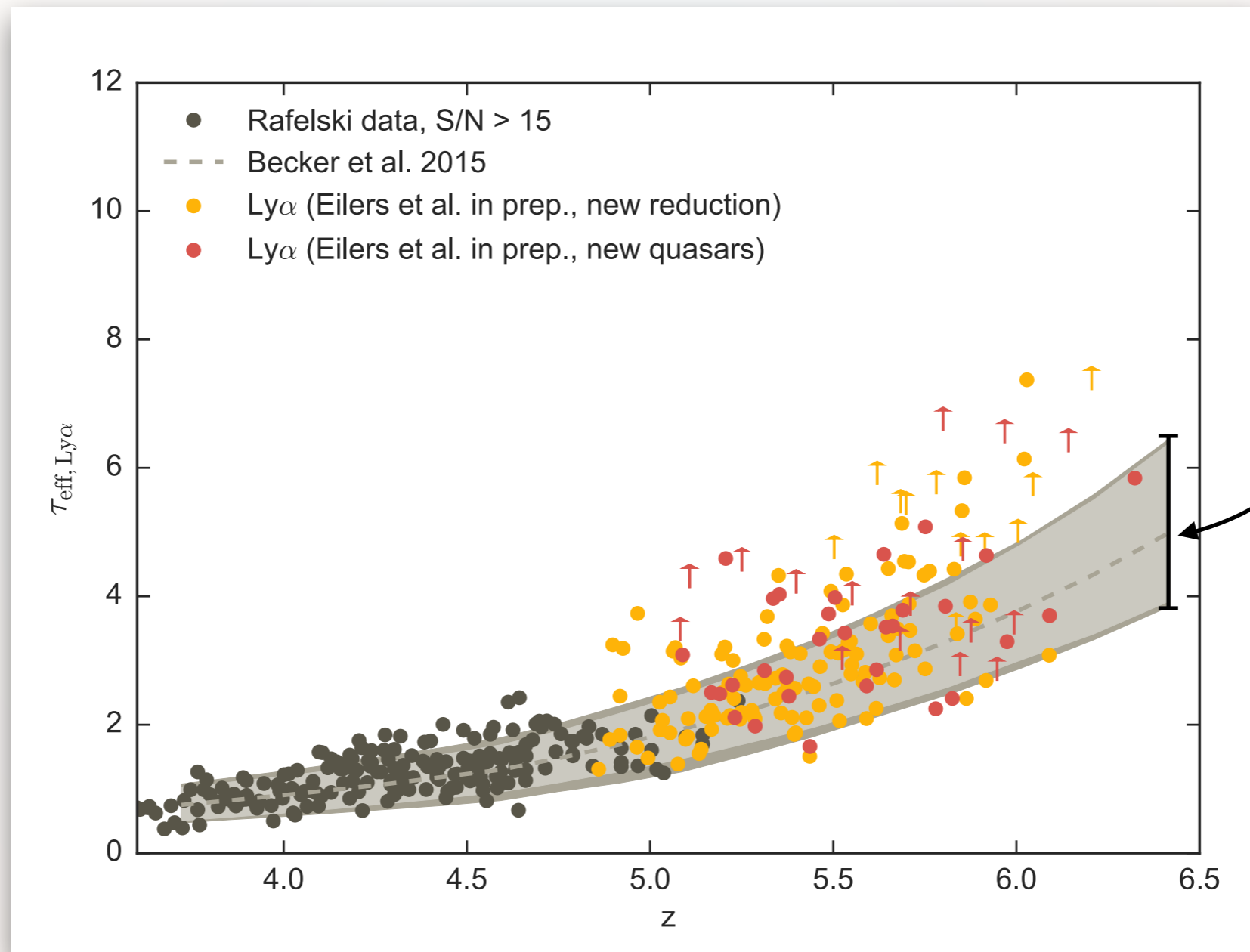


expected density fluctuations

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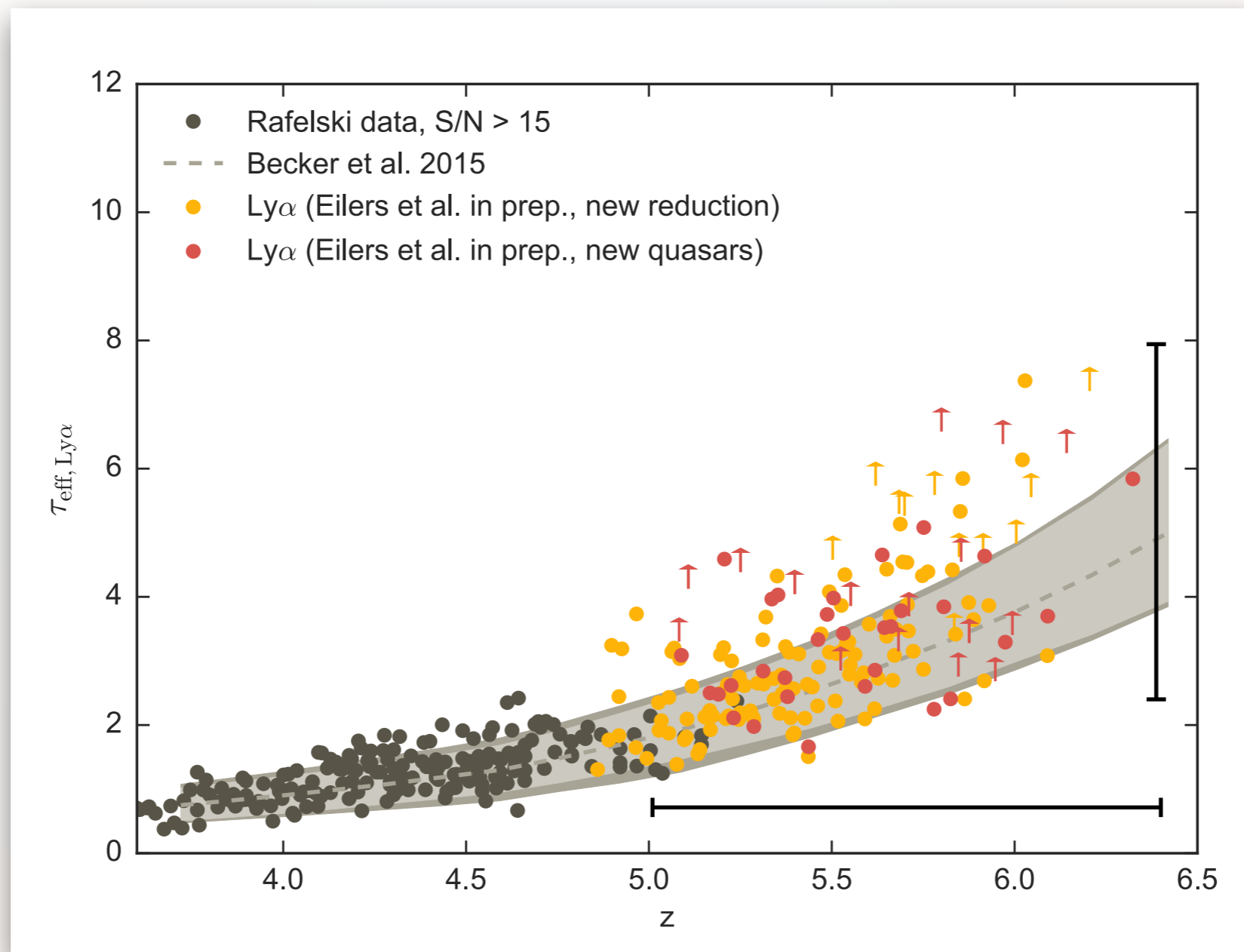


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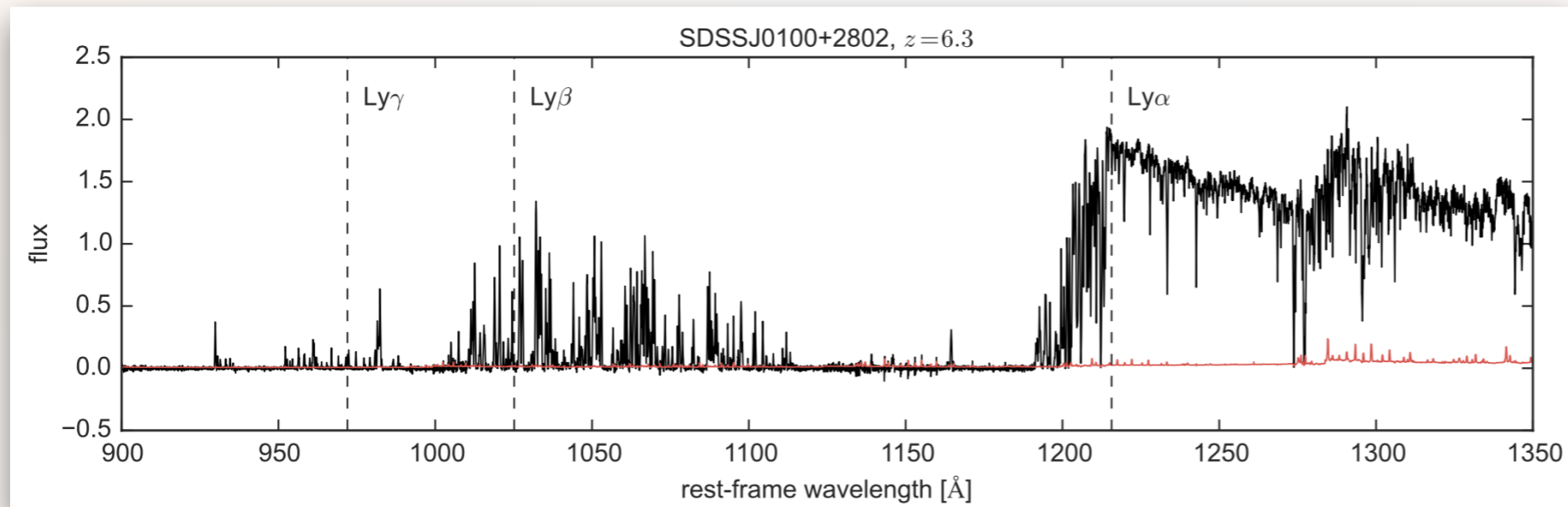
mean flux averaged over chunks of 50 cMpc/h



fluctuating
UV back-
ground?

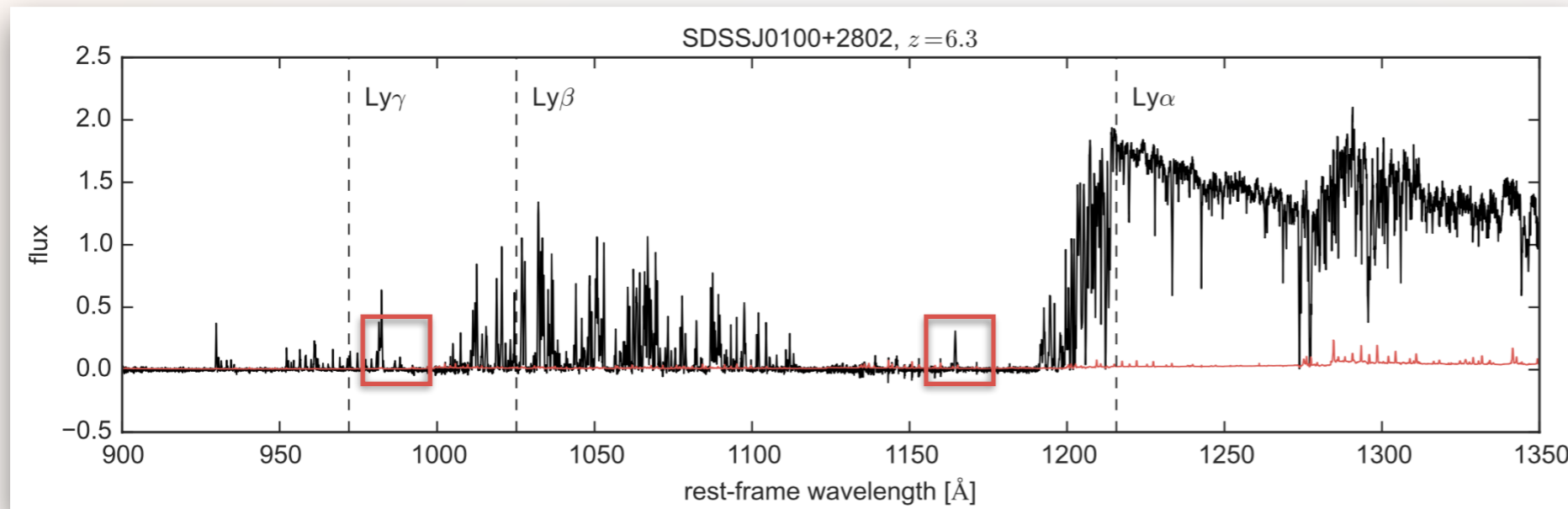
post-
reionization
IGM

INCREASE IN SENSITIVITY FOR LYMAN-BETA

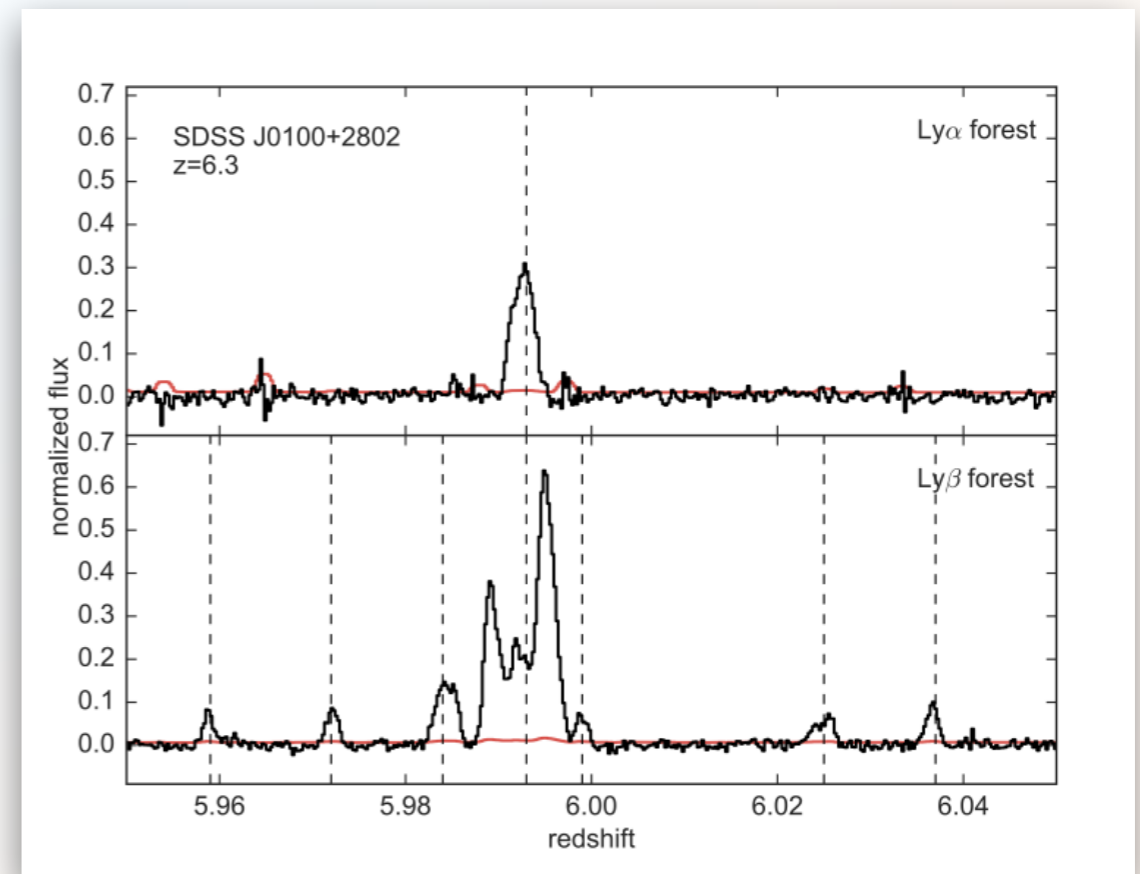


- ◆ Ly α is extremely sensitive and saturates already for volume averaged neutral fractions of $\langle x_{\text{HI}} \rangle \gtrsim 10^{-4}$

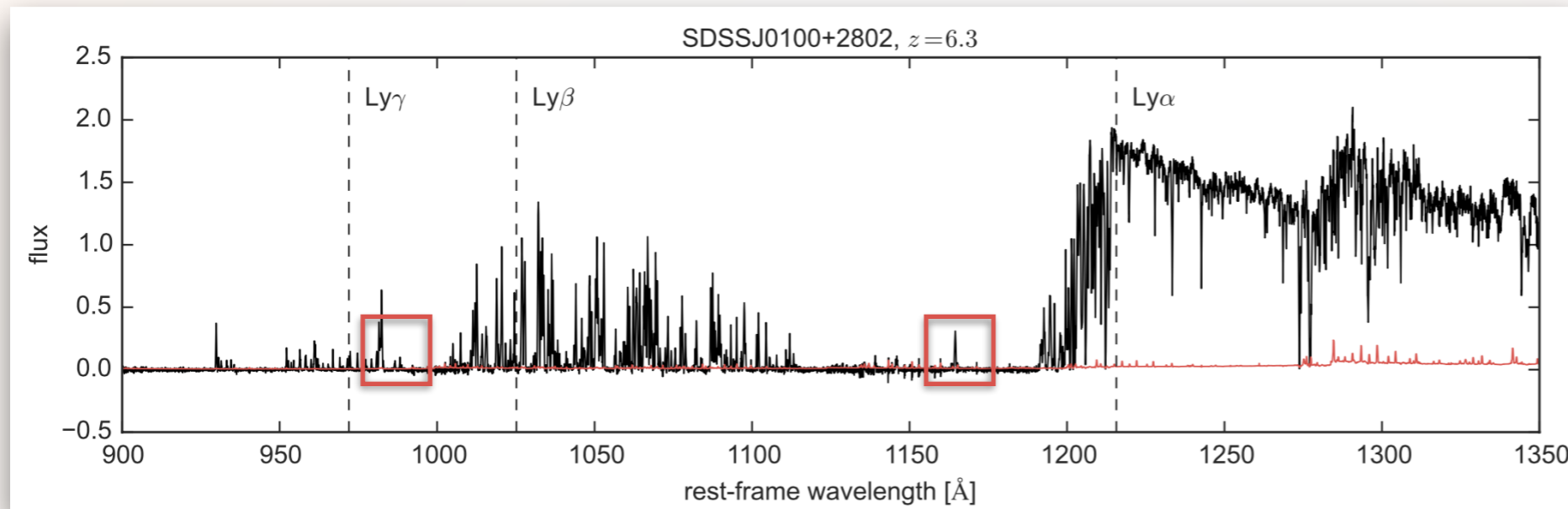
INCREASE IN SENSITIVITY FOR LYMAN-BETA



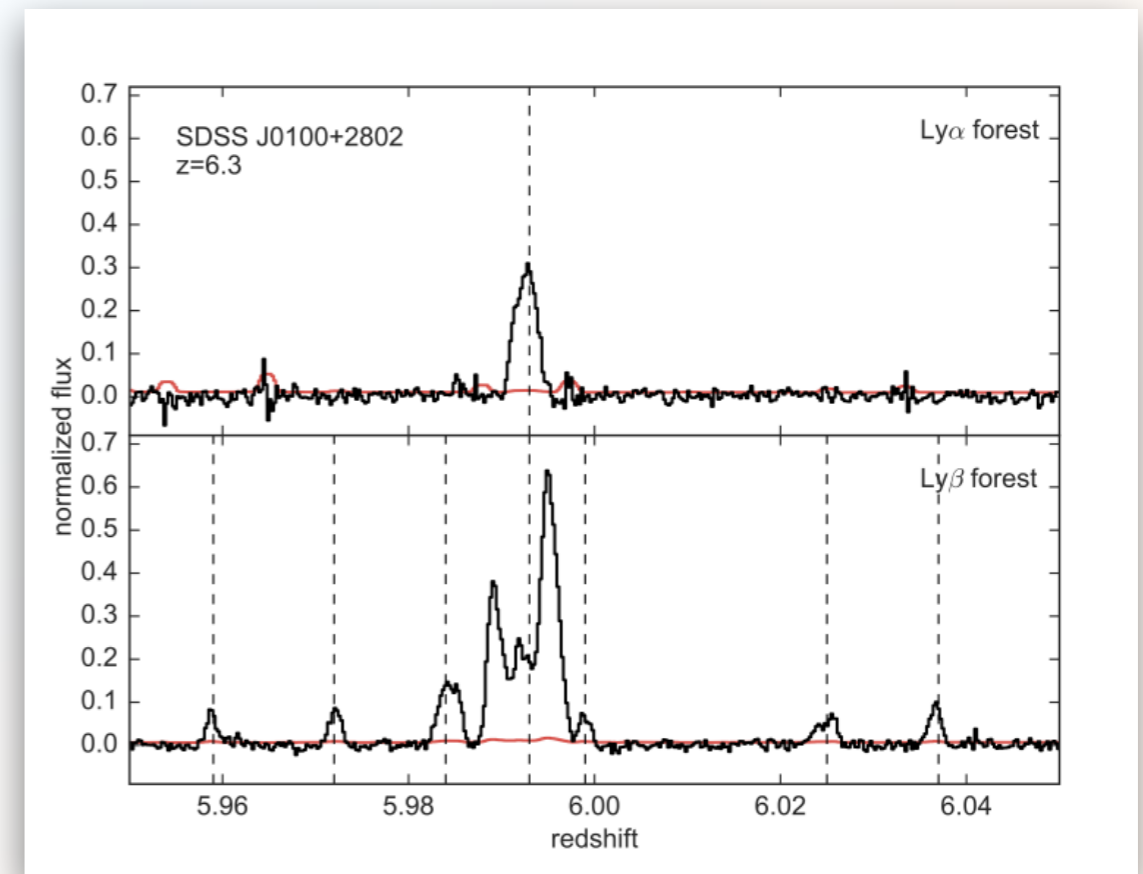
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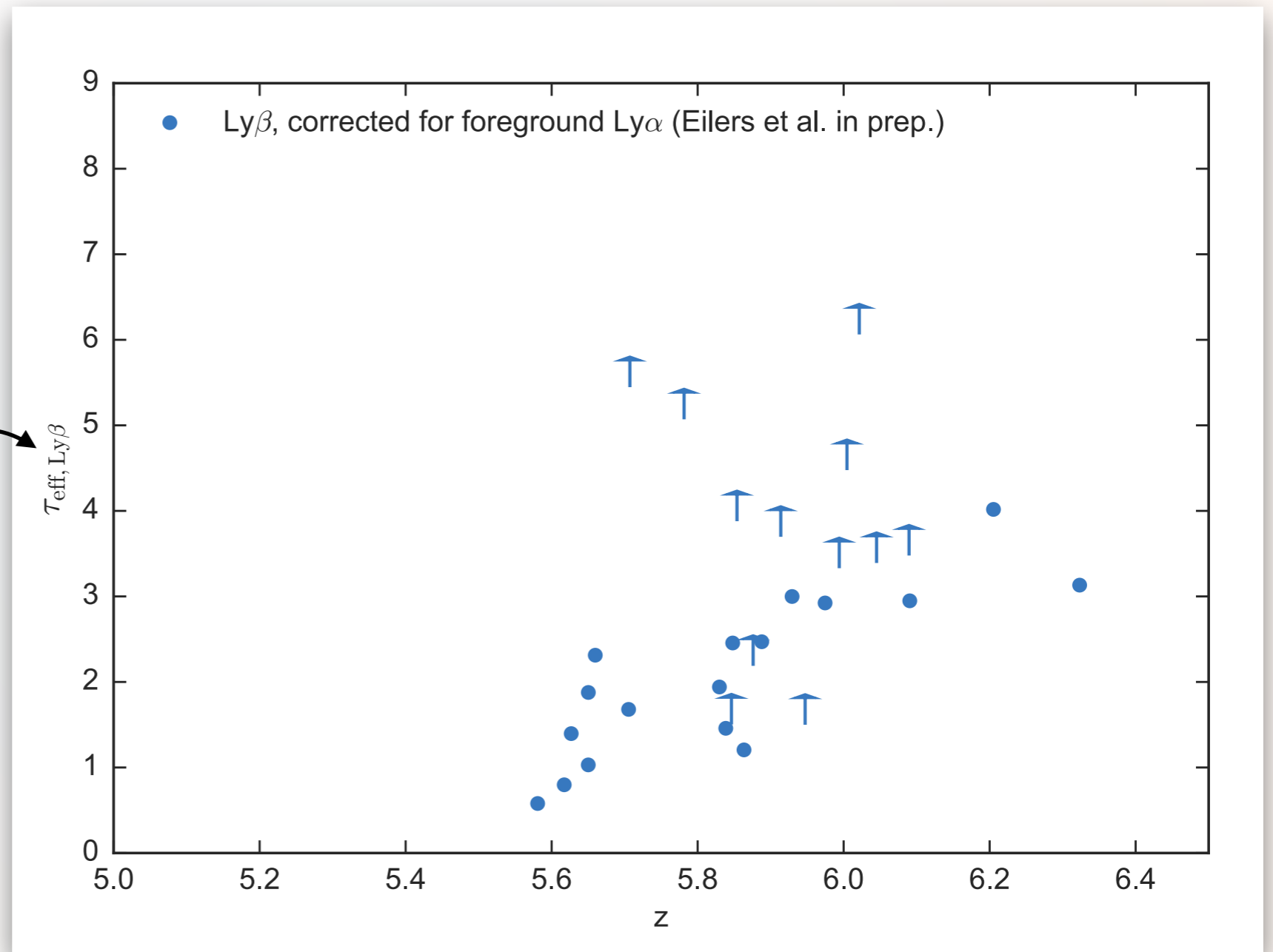


- ◆ Ly α is extremely sensitive and saturates already for volume averaged neutral fractions of $\langle x_{\text{HI}} \rangle \gtrsim 10^{-4}$
- ◆ optical depth scales with the oscillator strength of transition: $\tau \propto f\lambda$
- ◆ ~5 times more sensitivity to the neutral gas content with the Ly β forest

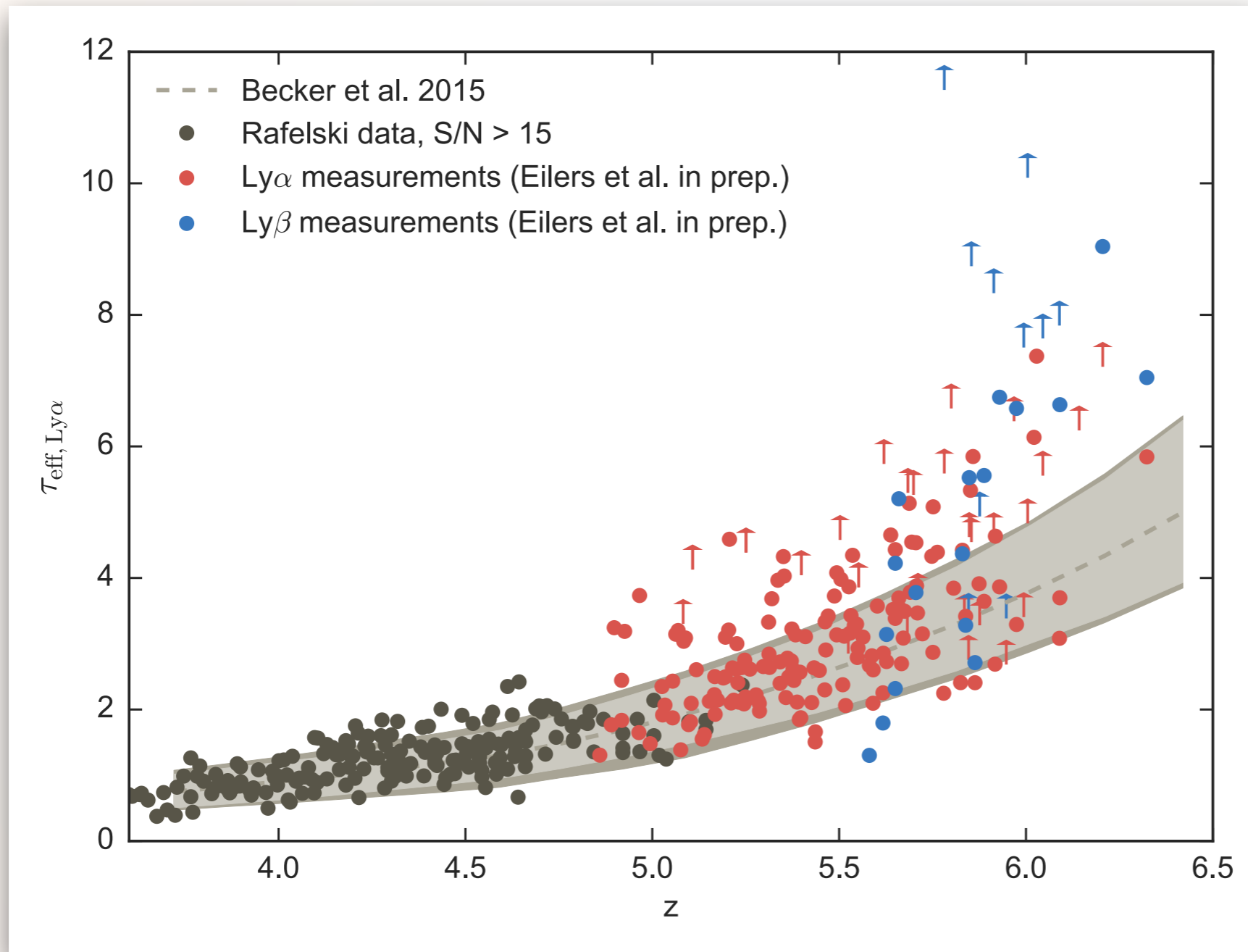


MEASUREMENTS OF THE OPTICAL DEPTH

Optical depth of $\text{Ly}\beta$
(foreground $\text{Ly}\alpha$
contamination statistically
subtracted)



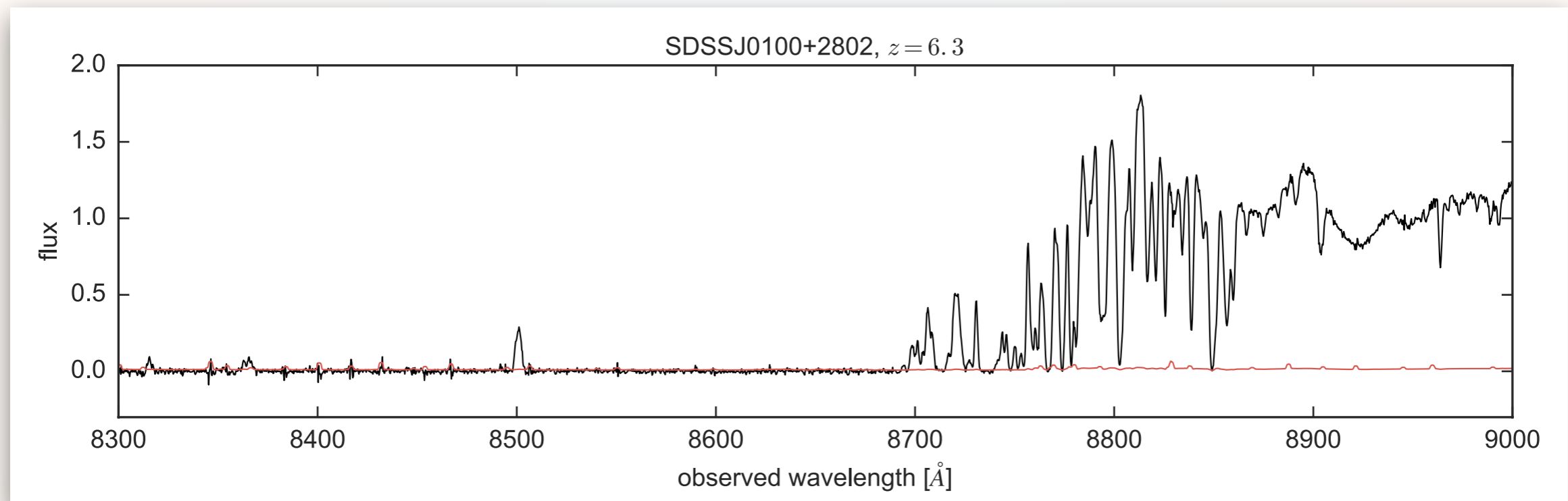
MEASUREMENTS OF THE OPTICAL DEPTH



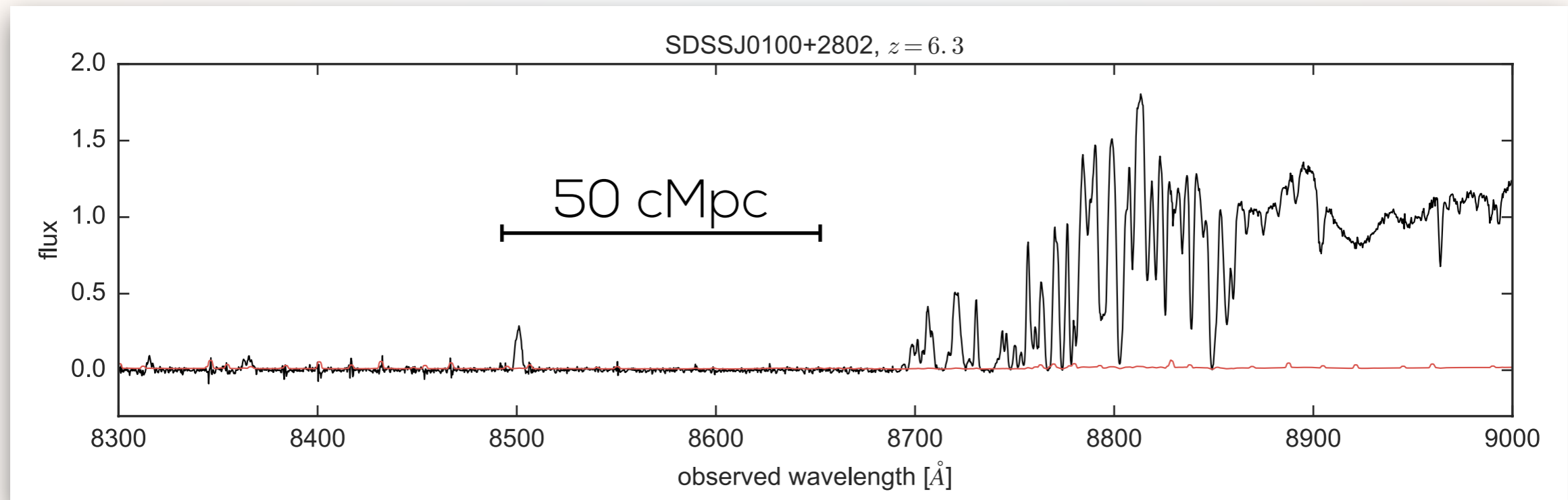
re-scaling Ly β optical depths to Ly α :

$$\tau_{\text{Ly}\alpha} / \tau_{\text{Ly}\beta} \approx 2.25$$

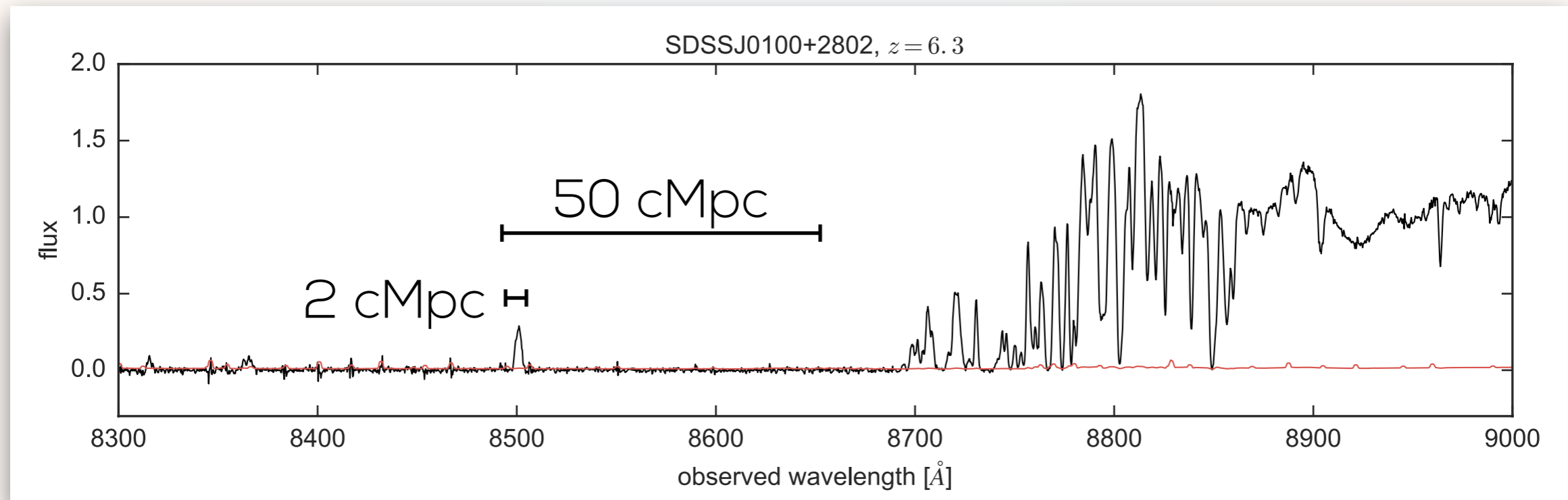
PROBABILITY DISTRIBUTION FUNCTIONS



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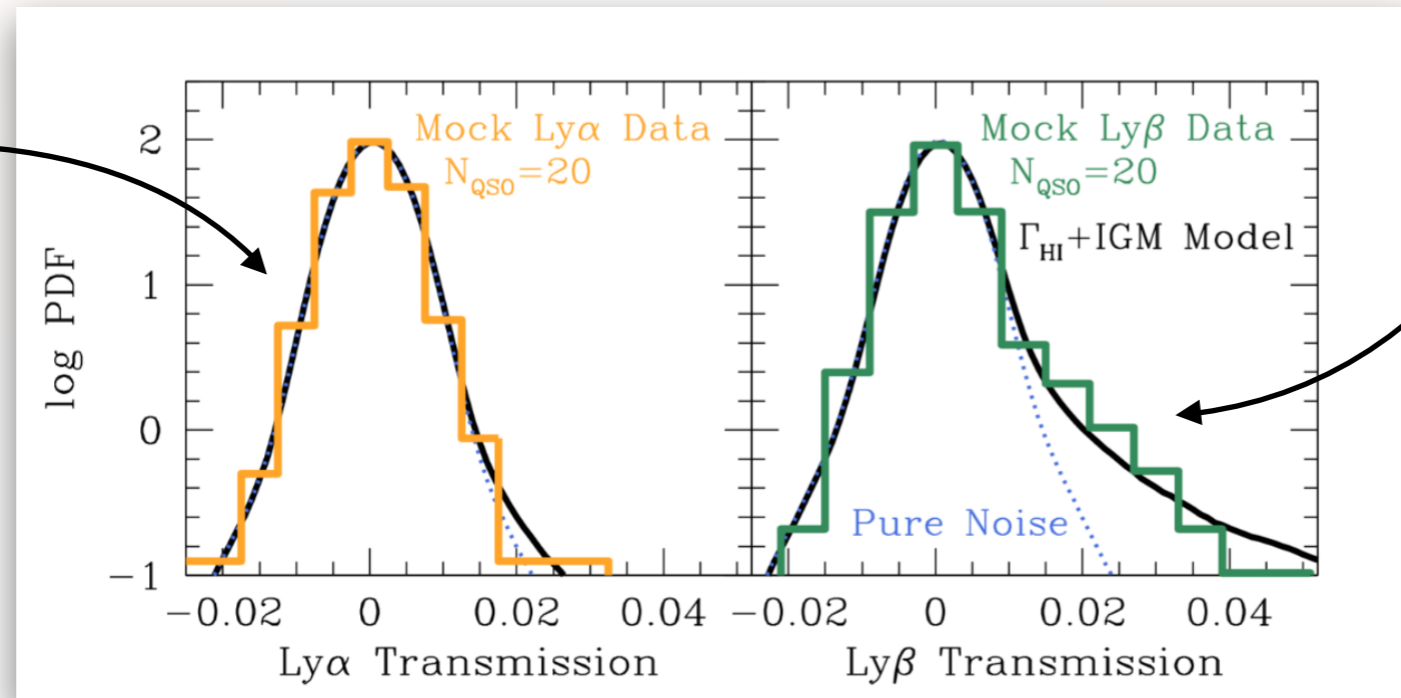


PROBABILITY DISTRIBUTION FUNCTIONS



PROBABILITY DISTRIBUTION FUNCTIONS

Ly α PDF

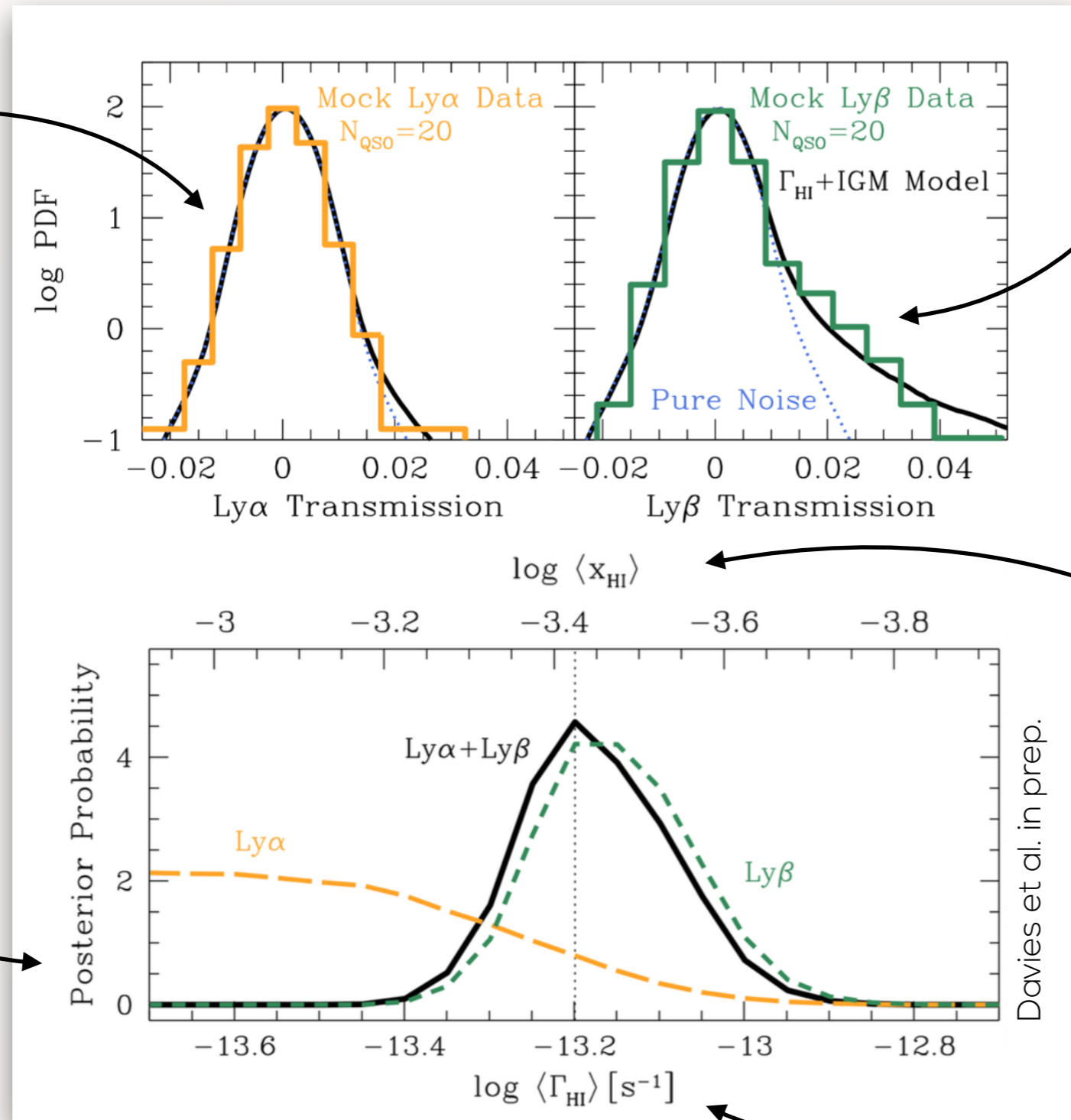


Ly β PDF

PROBABILITY DISTRIBUTION FUNCTIONS

Ly α PDF

Ly β PDF



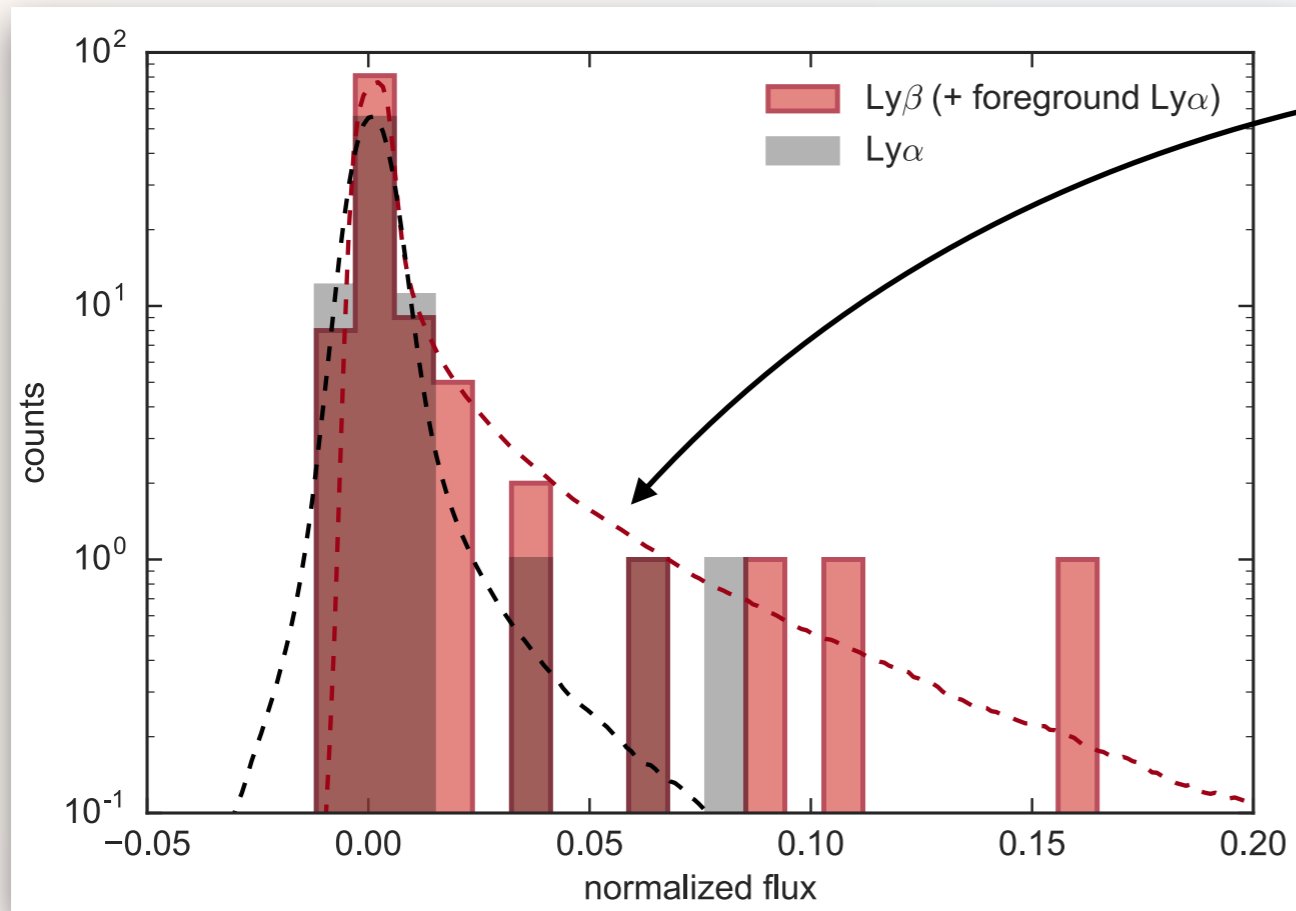
posterior probability distribution functions

neutral gas fraction

strength of the UV background

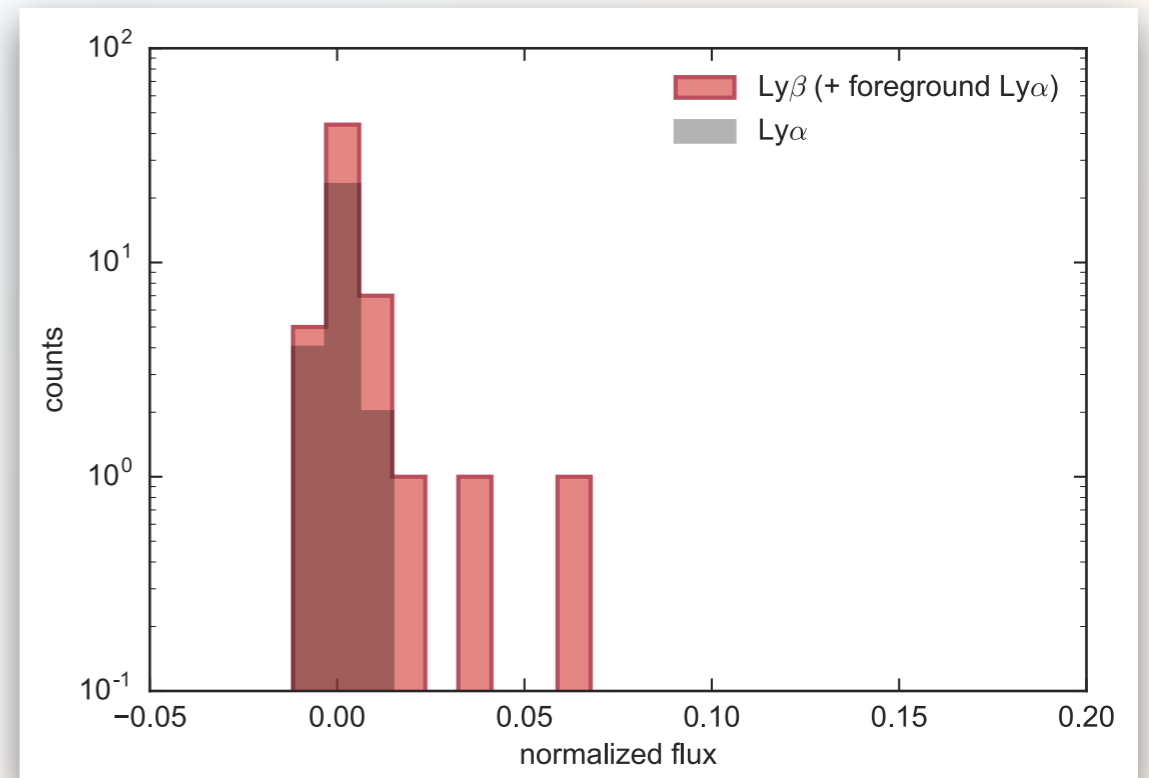
PROBABILITY DISTRIBUTION FUNCTIONS

5.9 < z < 6.1

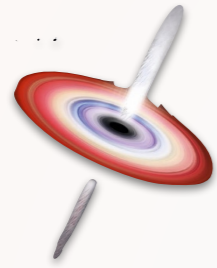


models: strongly fluctuating
UV background
with $\langle \Gamma_{\text{HI}} \rangle \approx 1.8 \cdot 10^{-13} \text{ s}^{-1}$

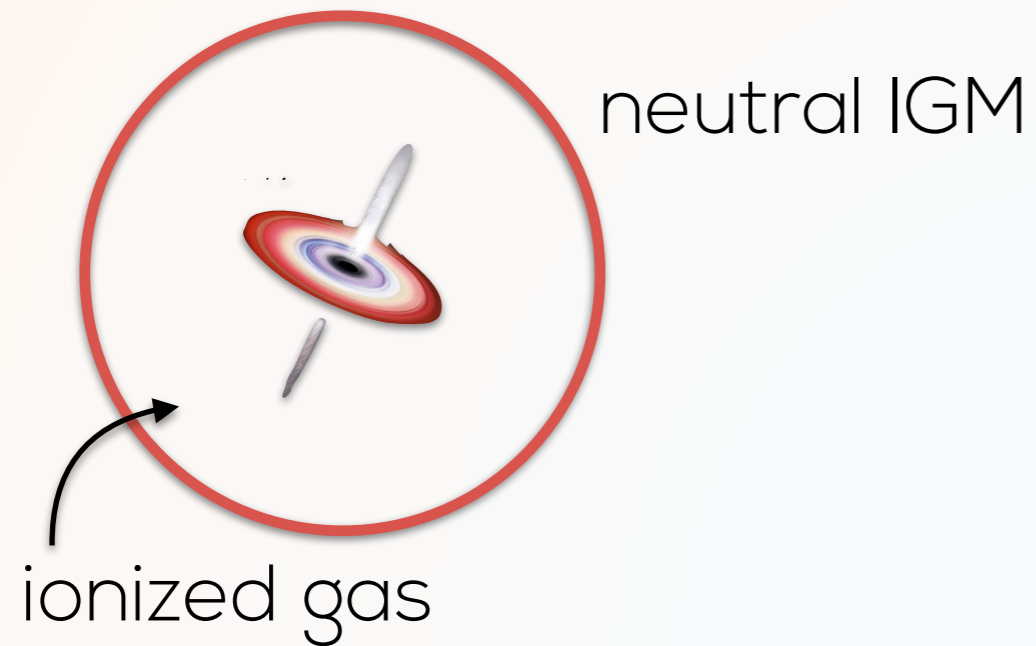
6.1 < z < 6.3



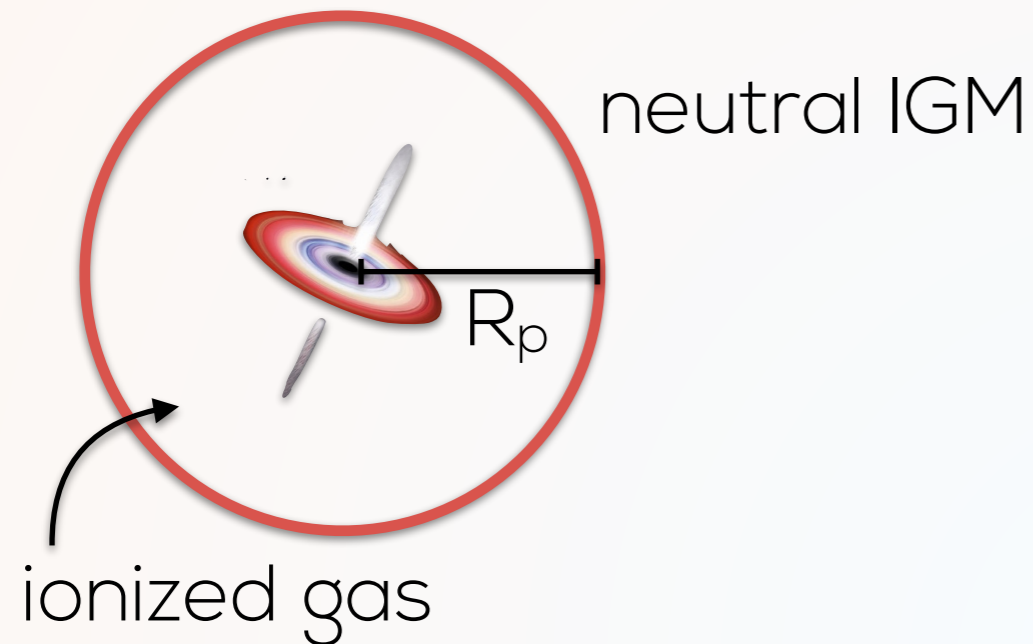
THE PHYSICS OF PROXIMITY ZONES



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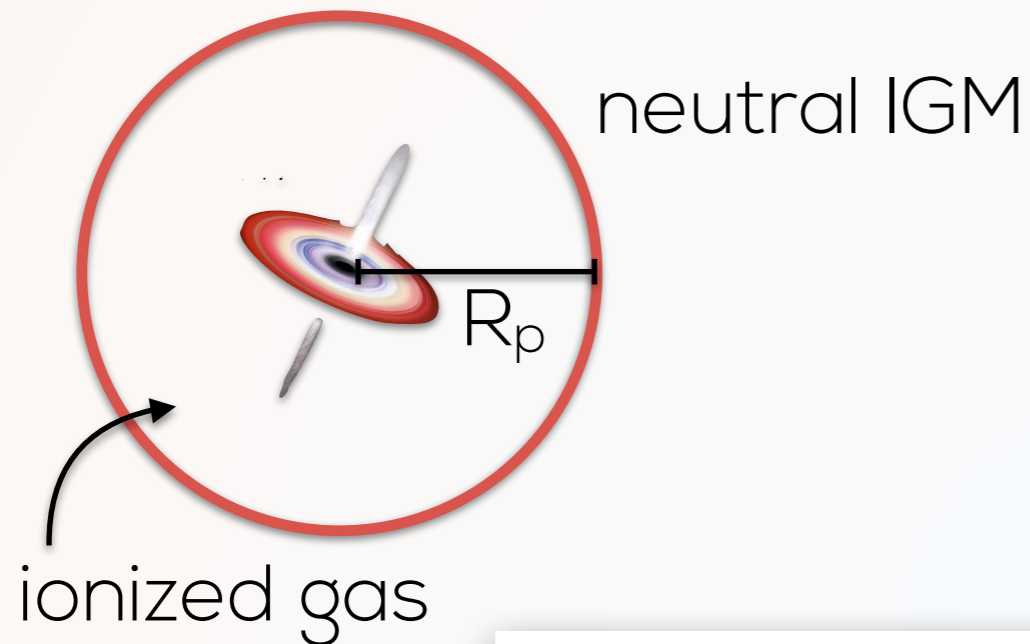


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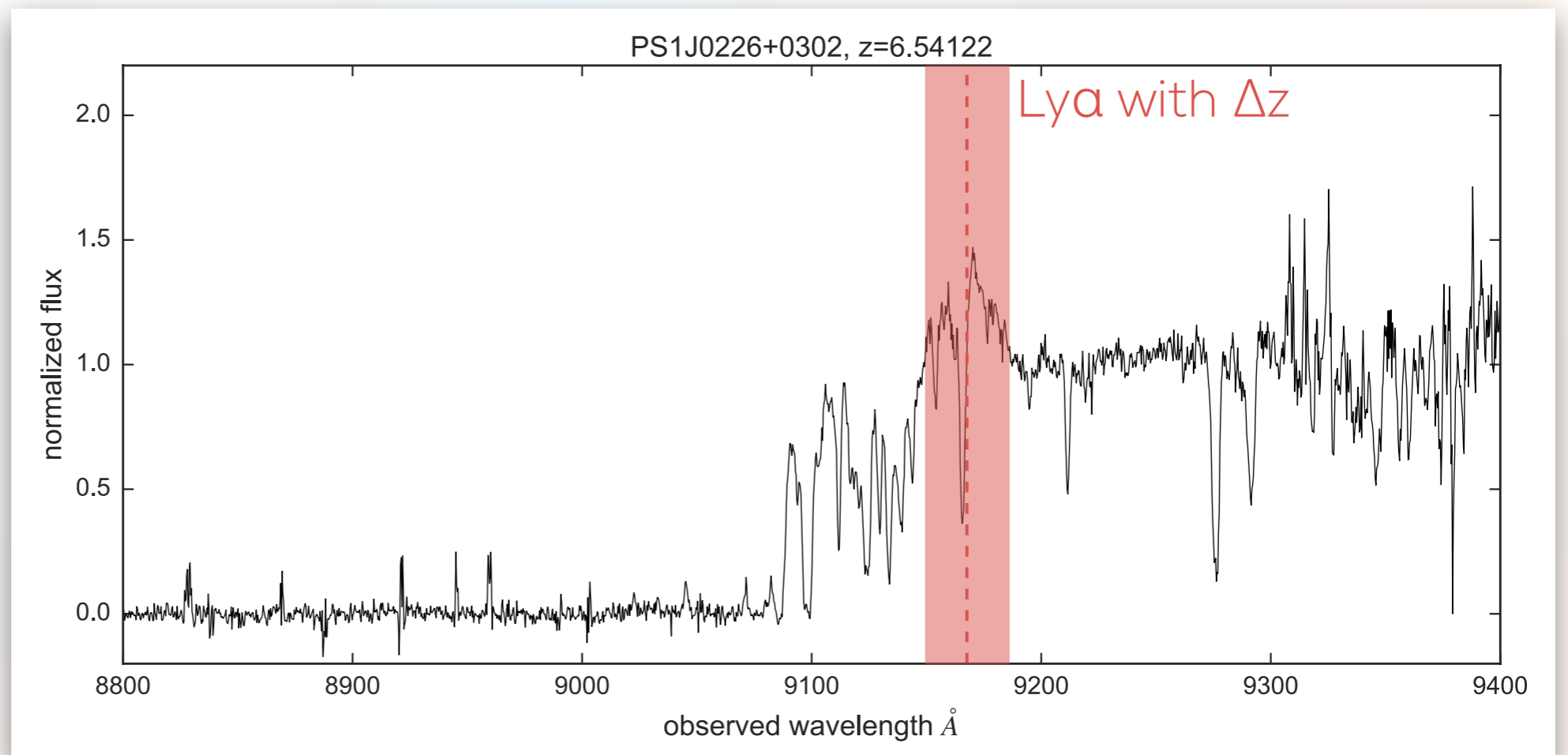


$$R_p \propto \left(\frac{\dot{N}_Q}{x_{HI}} \right)^{1/3}$$

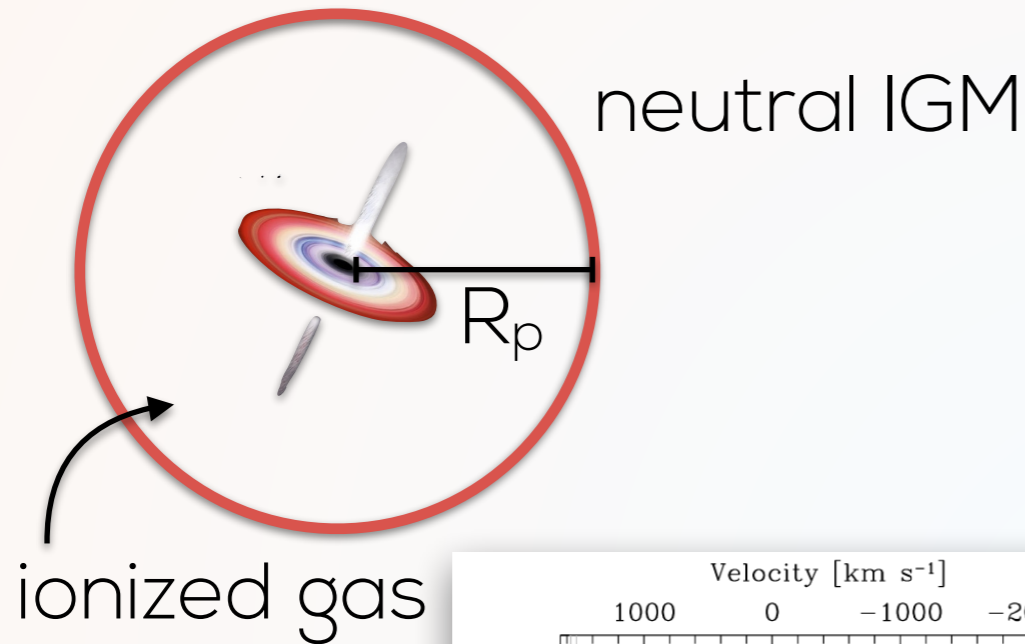
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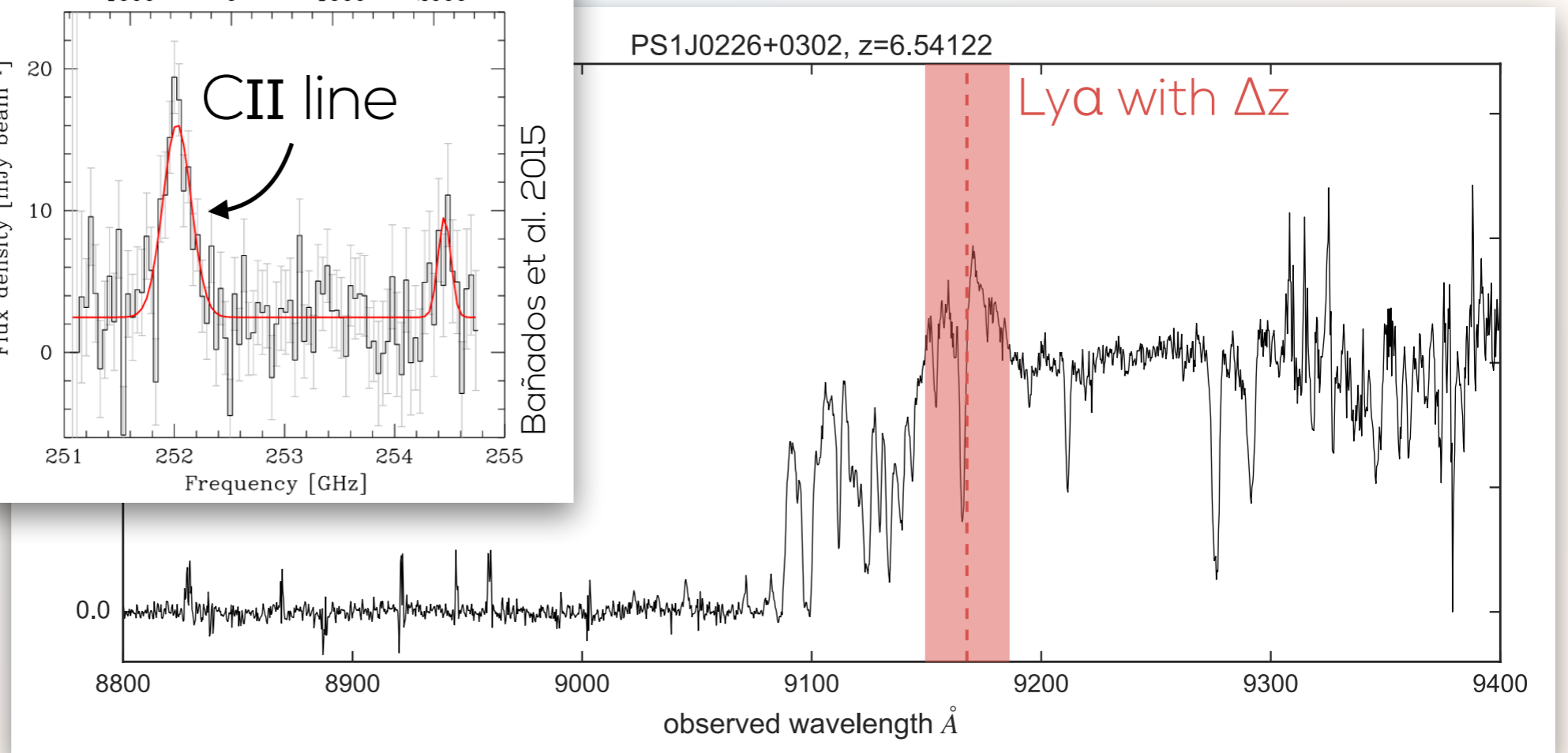
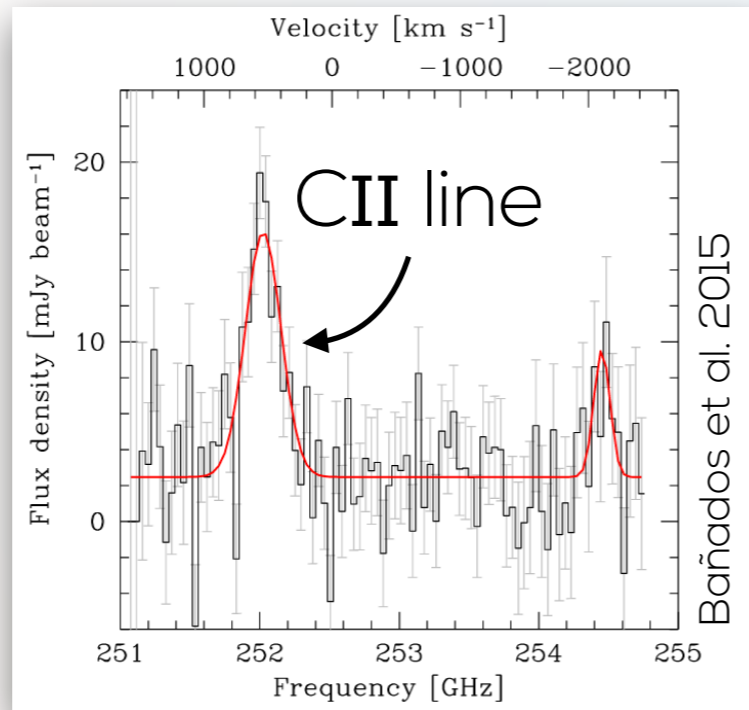
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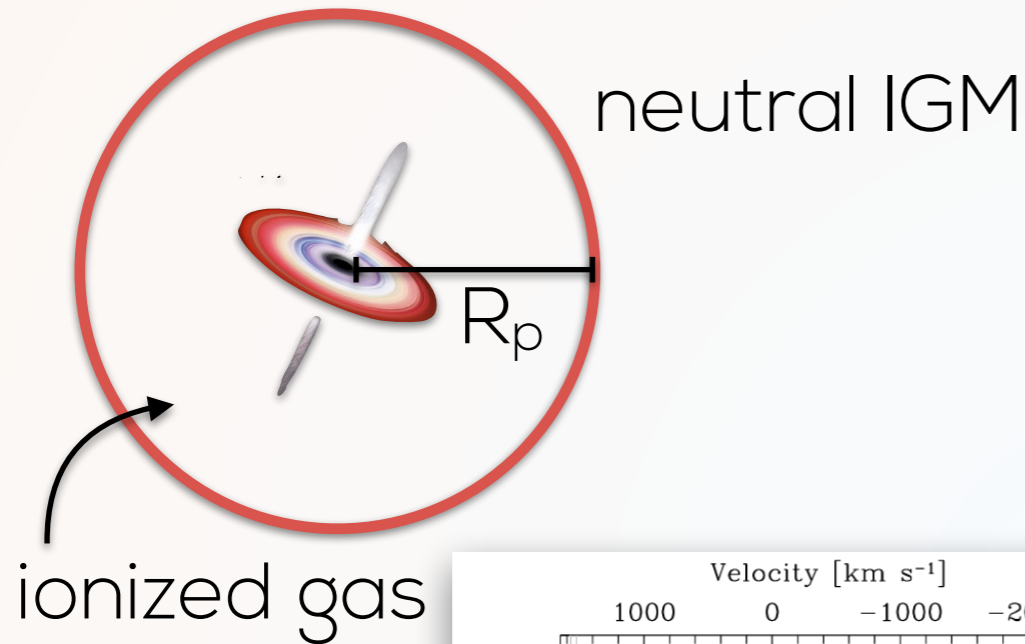
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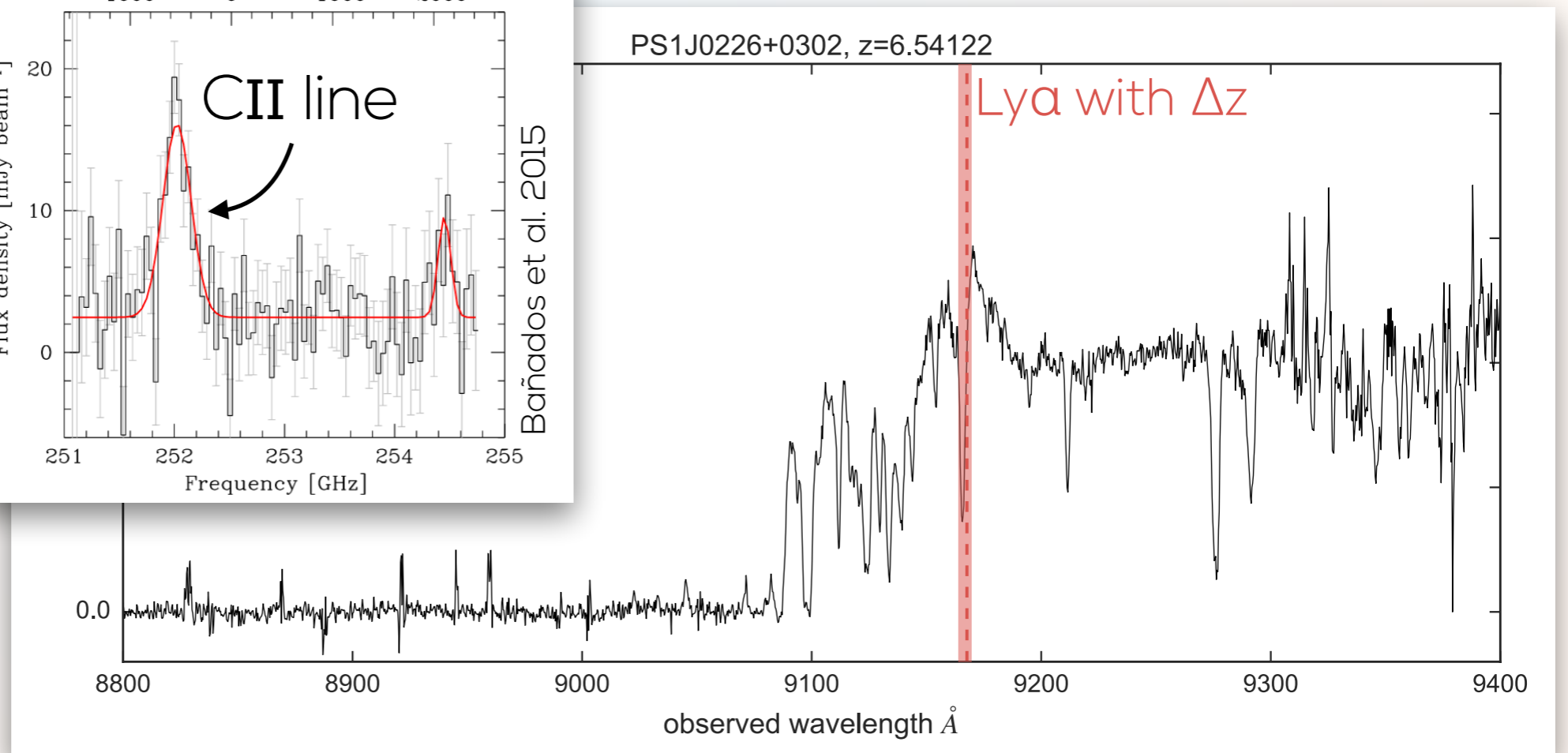
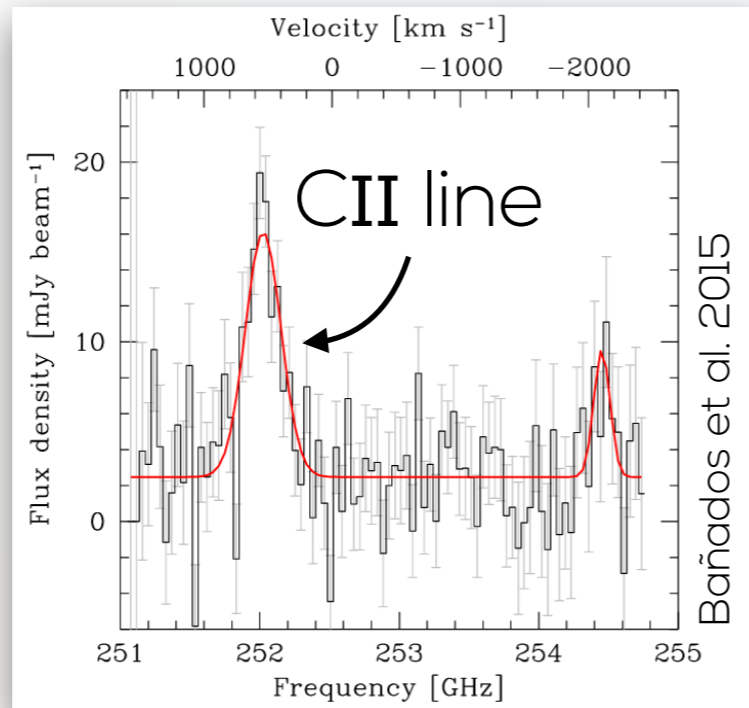
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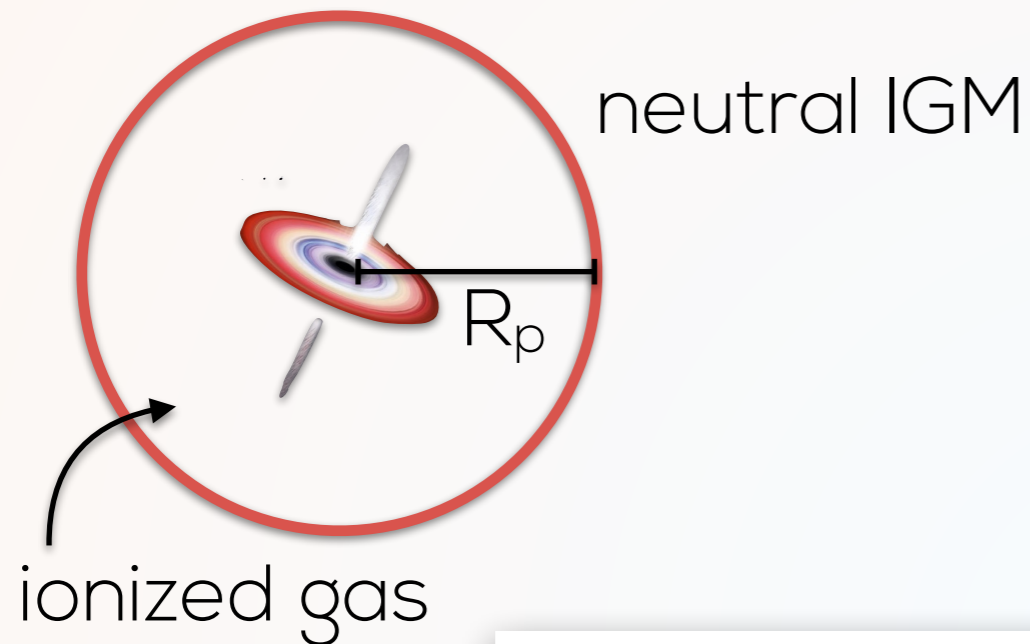
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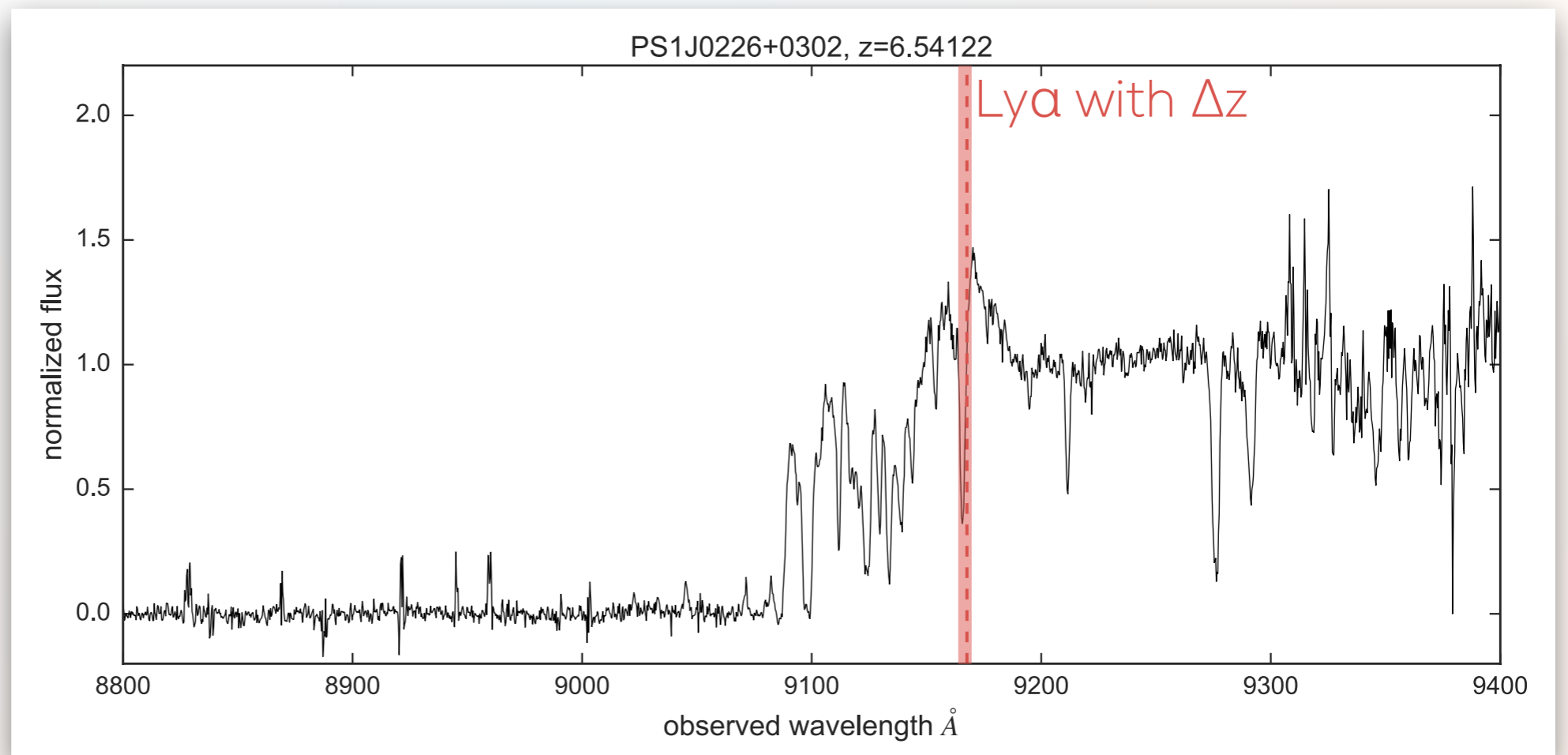
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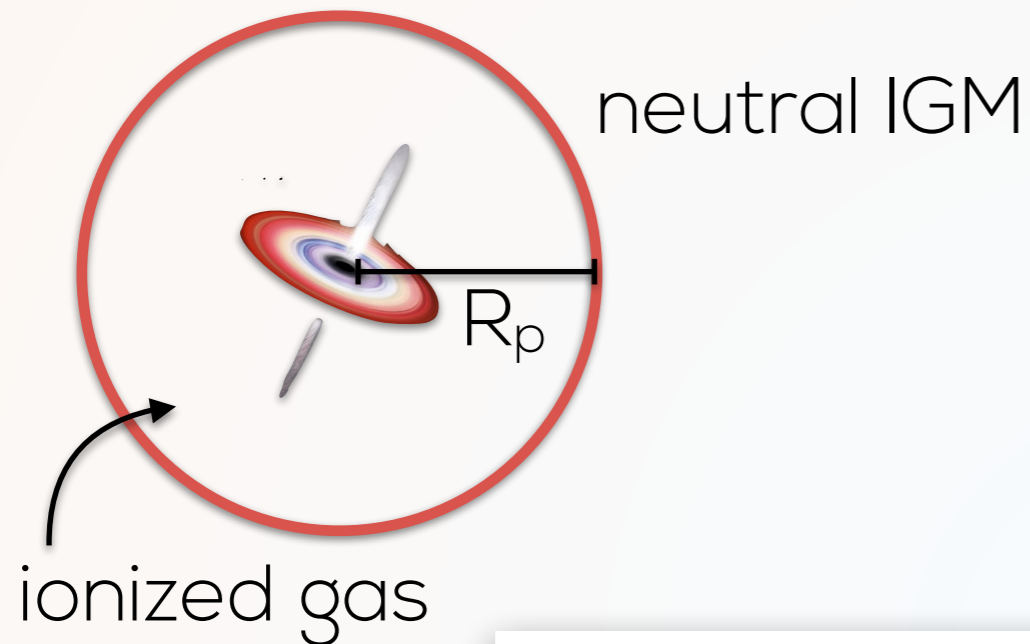
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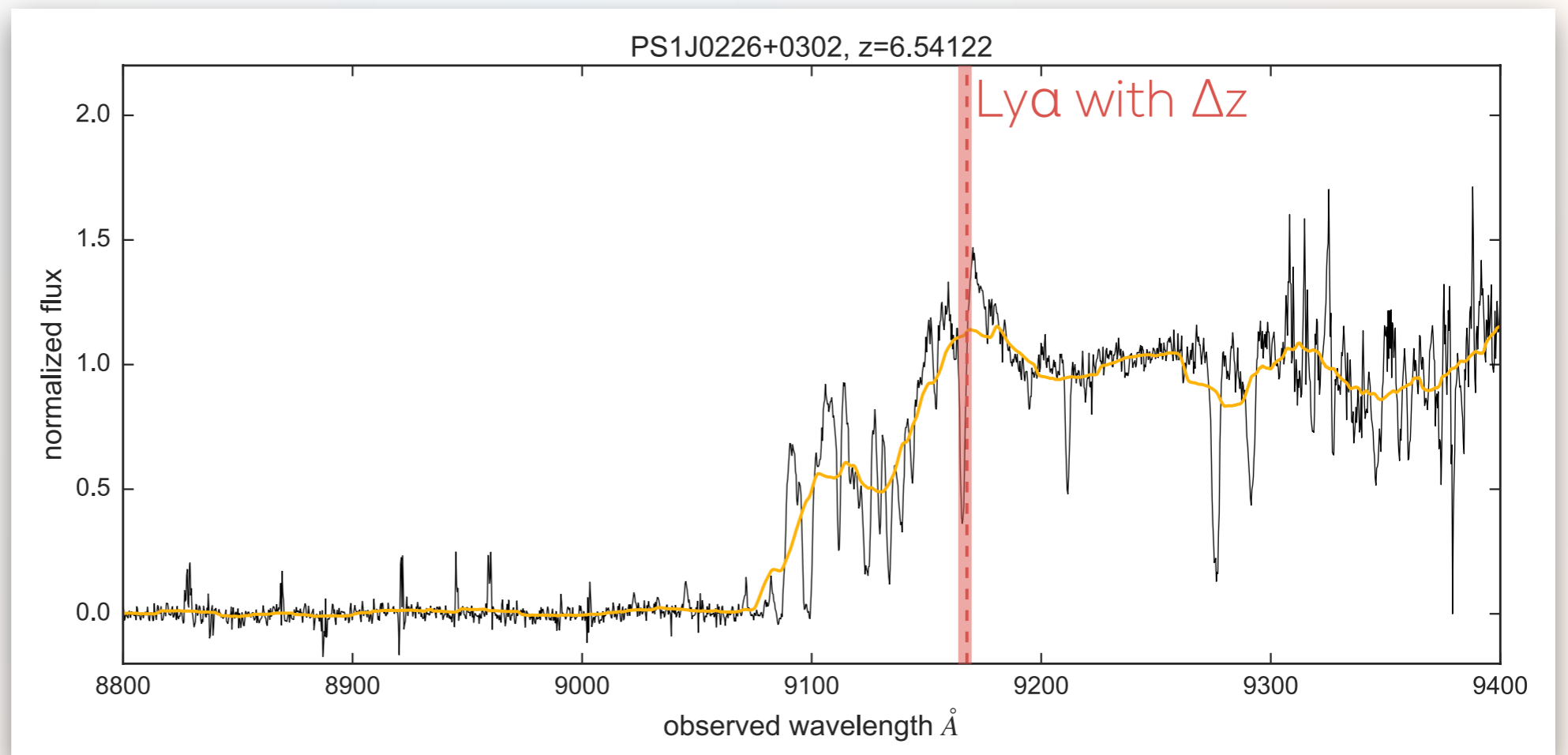
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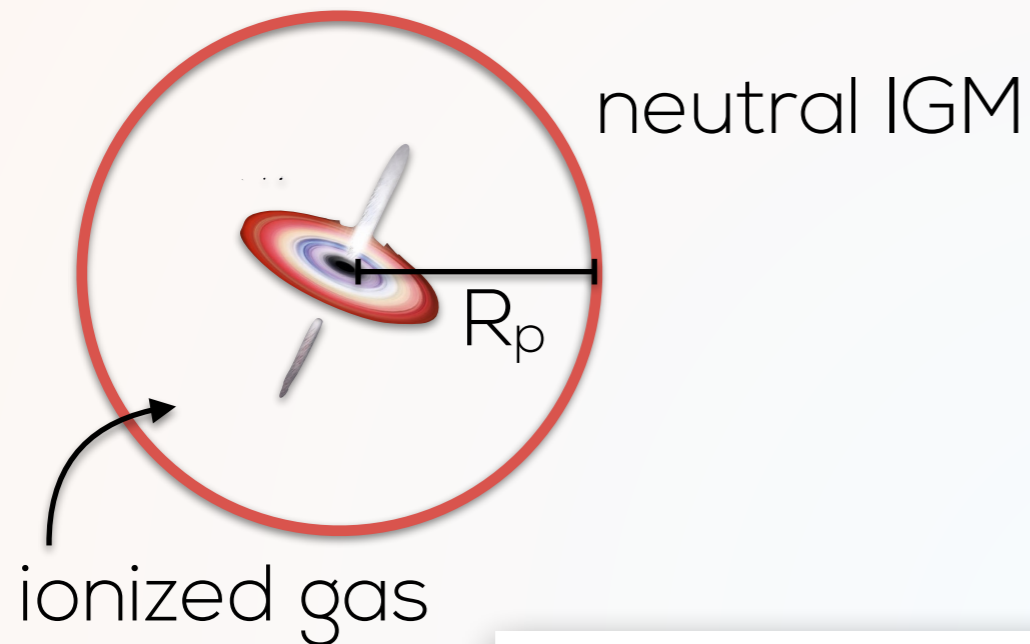
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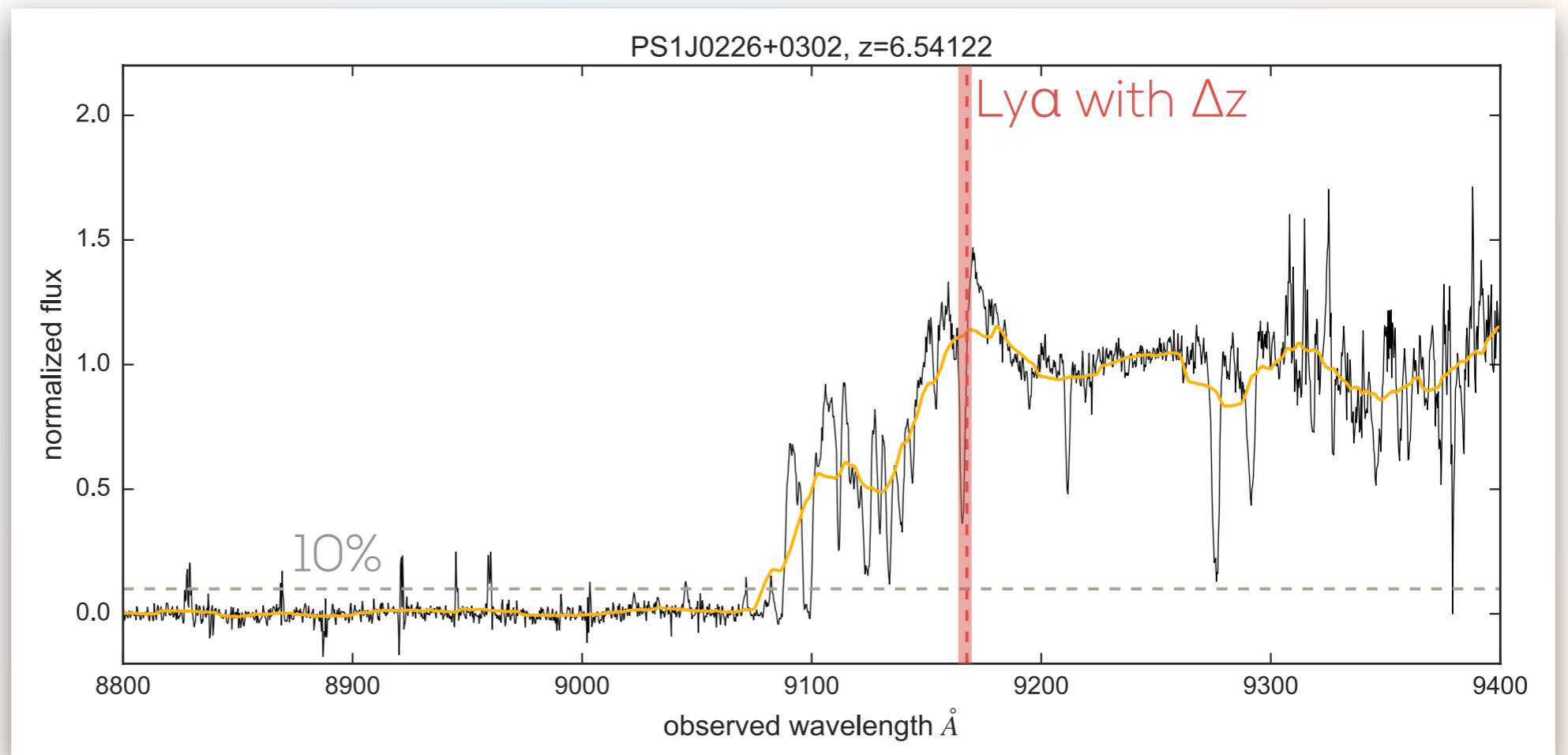
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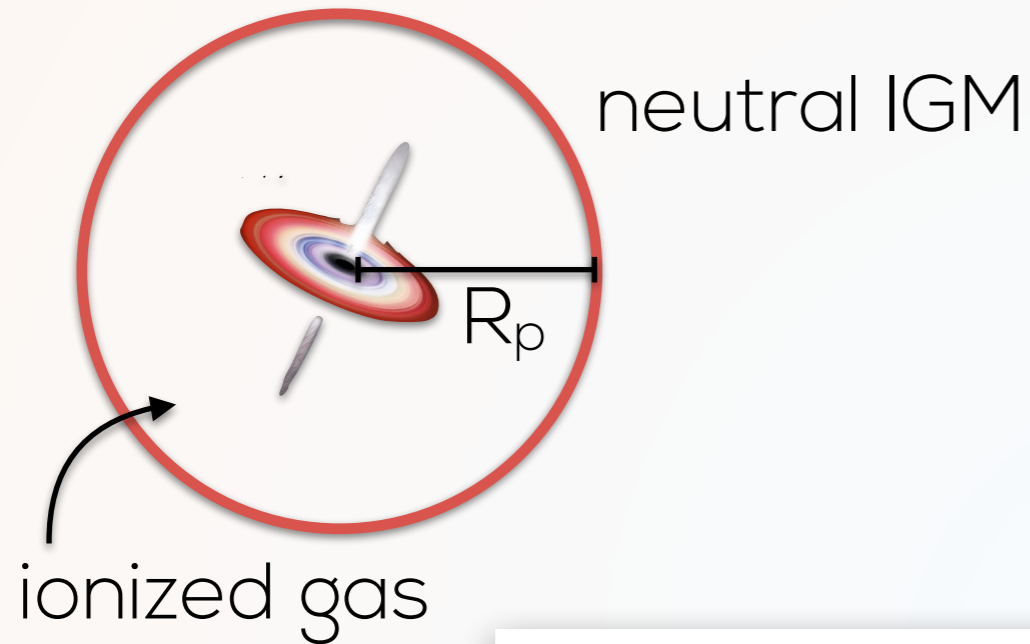
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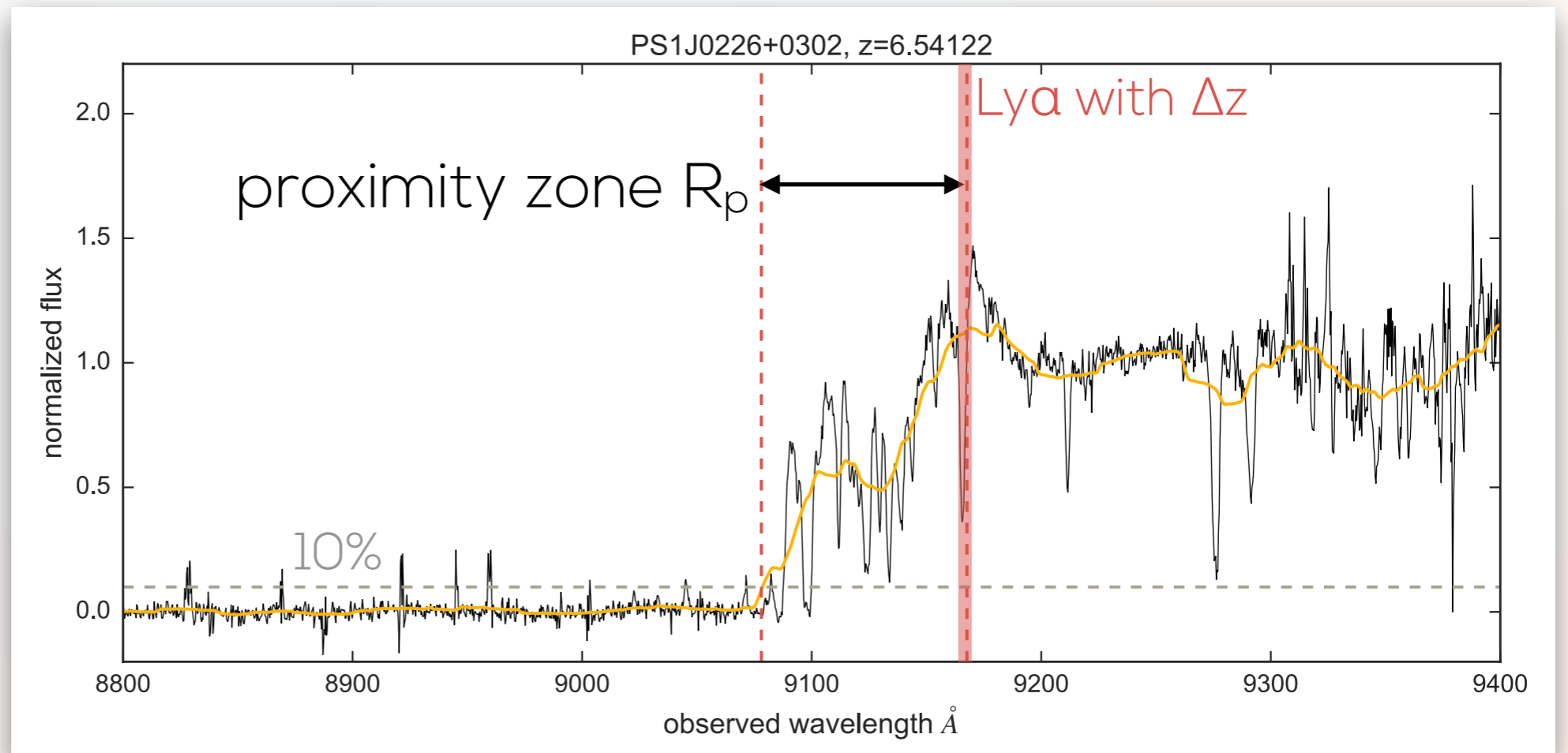
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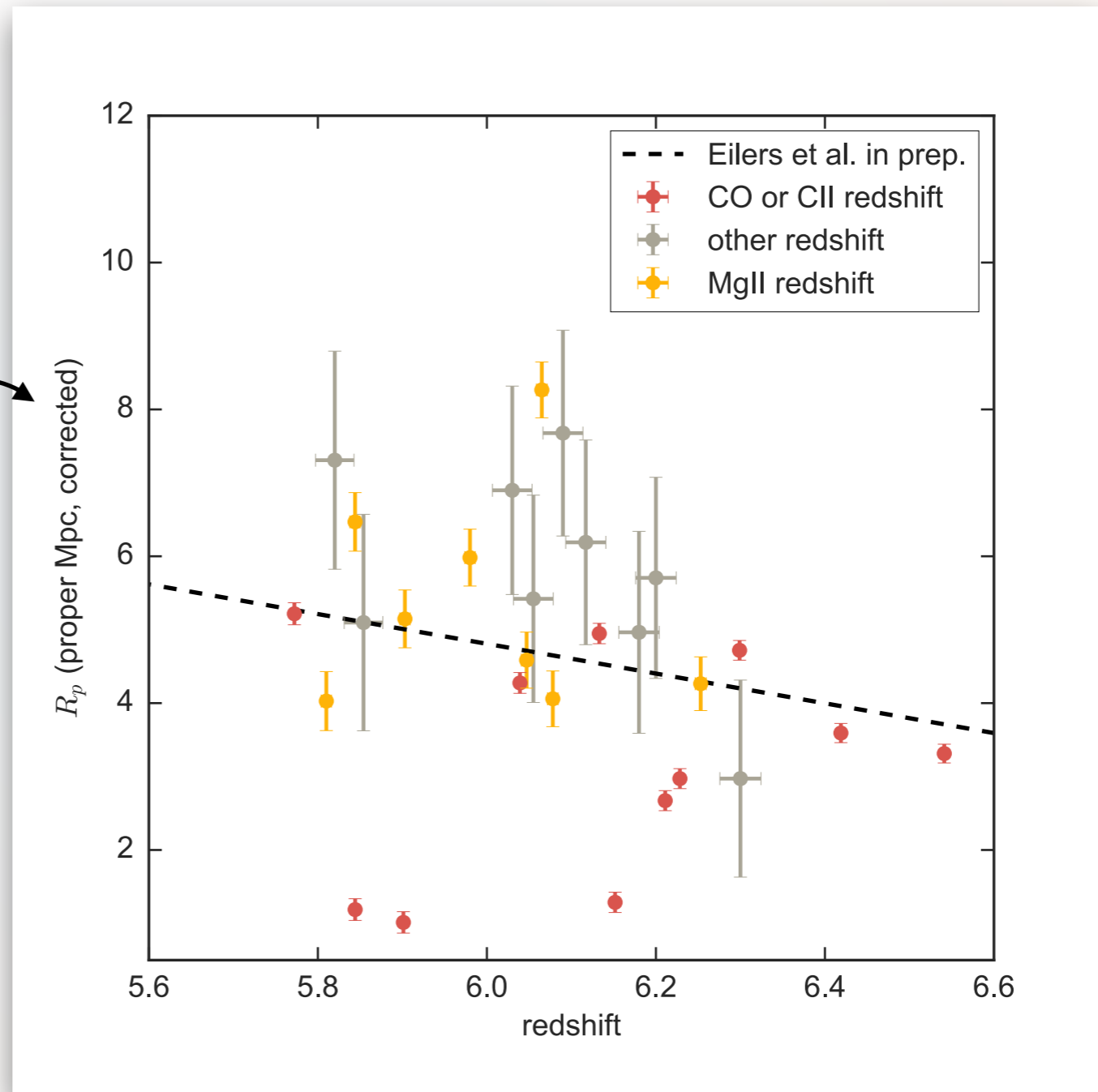
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PROXIMITY ZONE MEASUREMENTS

all quasars are normed
to the same luminosity:

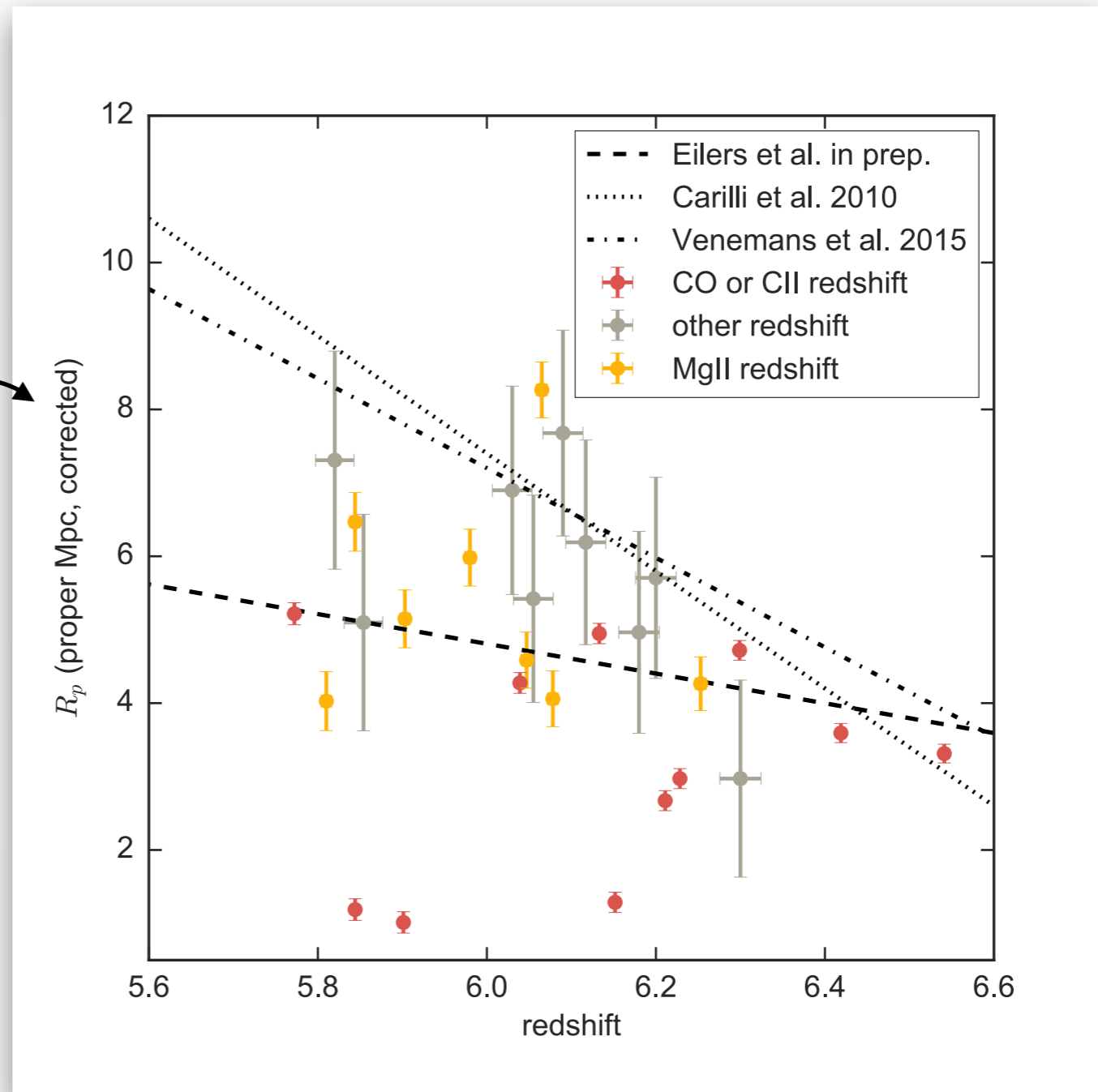
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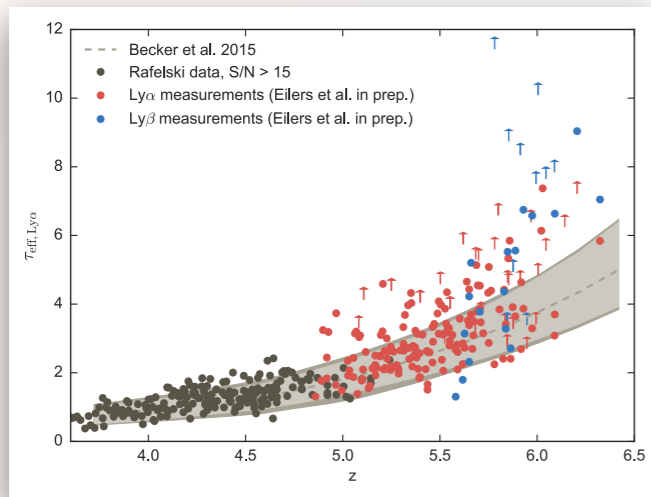


CONCLUSIONS

- ◆ we compiled a new data set of **32 quasar spectra** and reduced them in a homogeneous way

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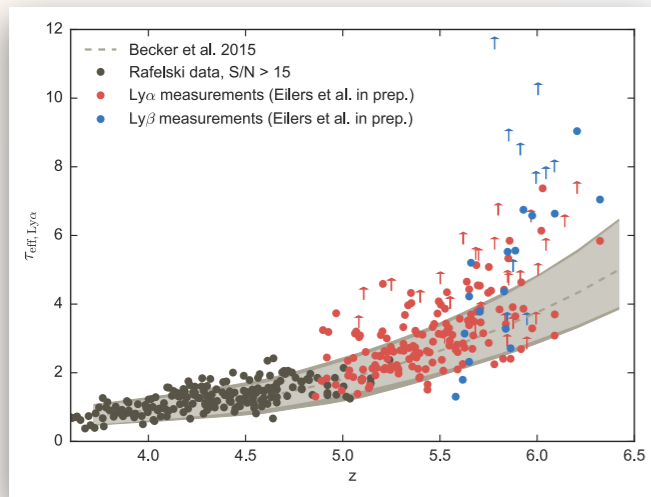
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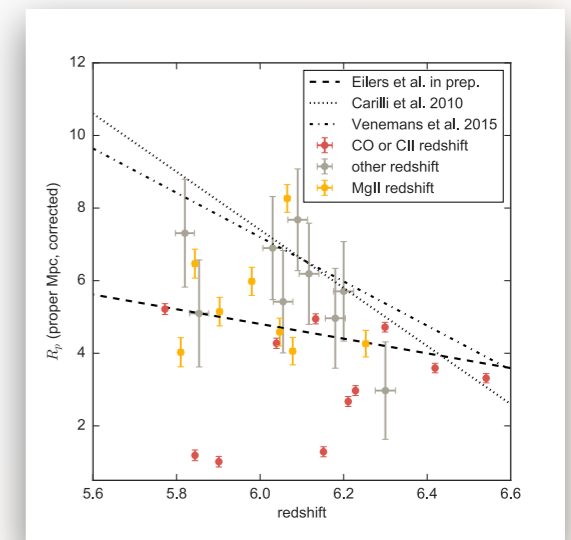
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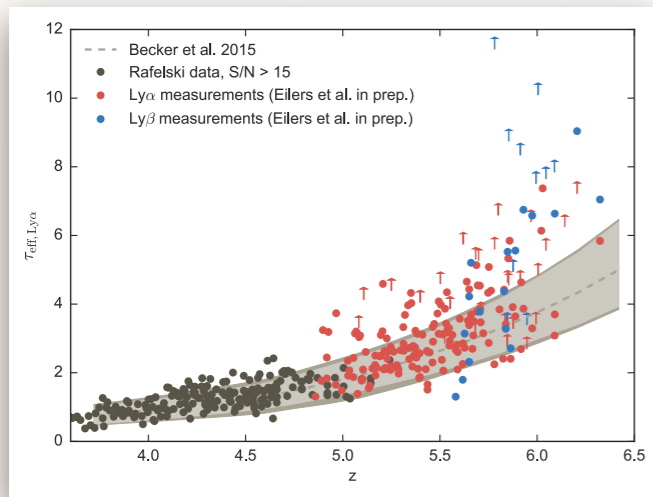
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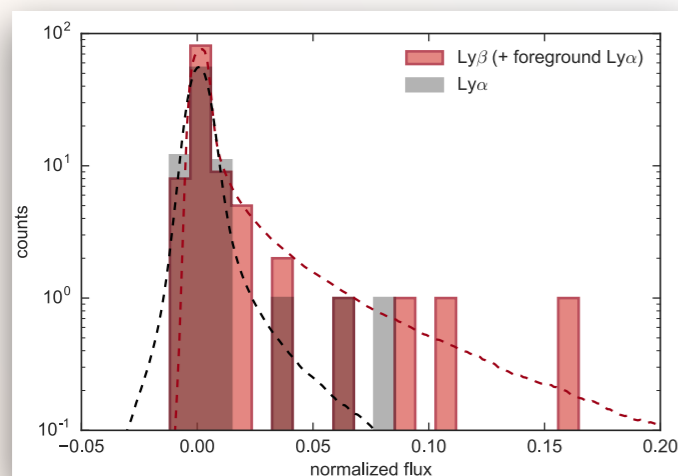
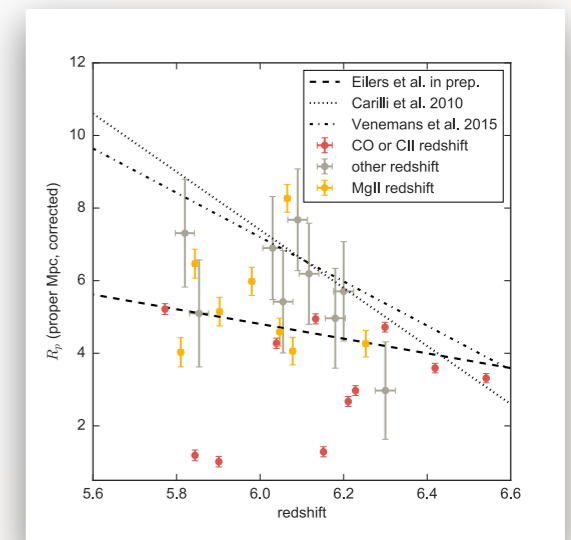
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- ◆ future work: measure **probability distribution function** of Ly-alpha and Ly-beta and compare to simulations