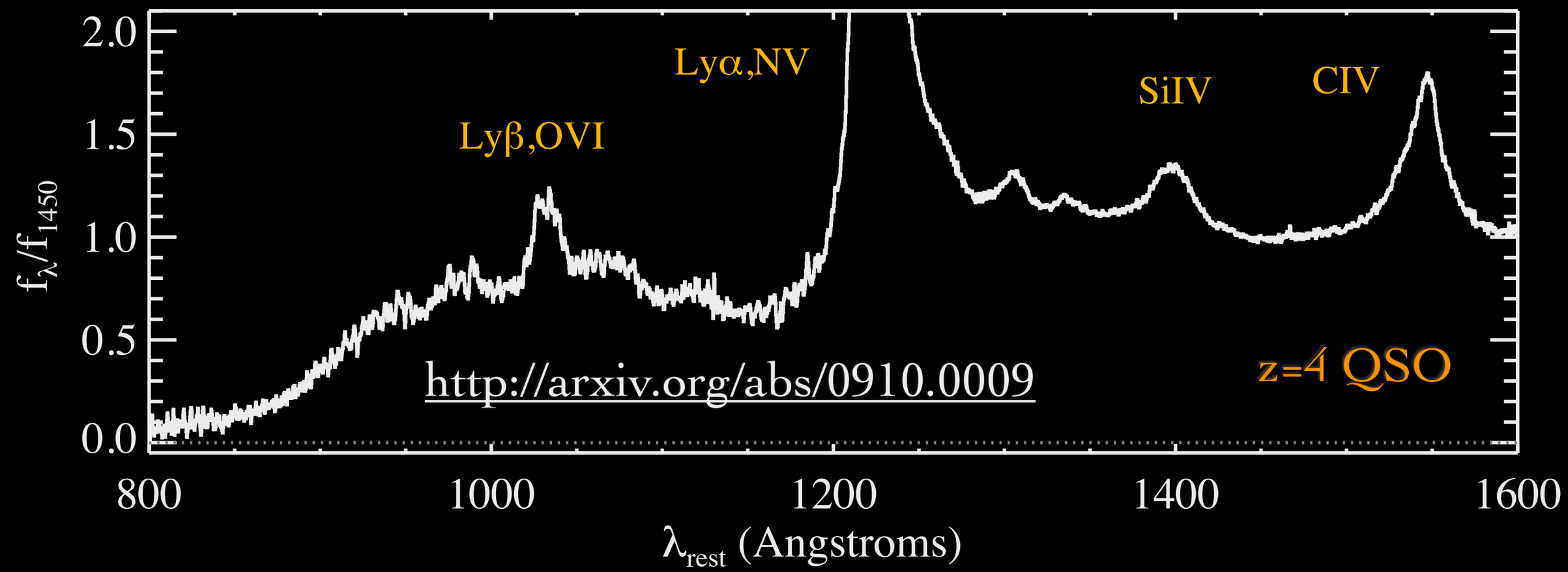
Opacity of the IGM to Ionizing Radiation

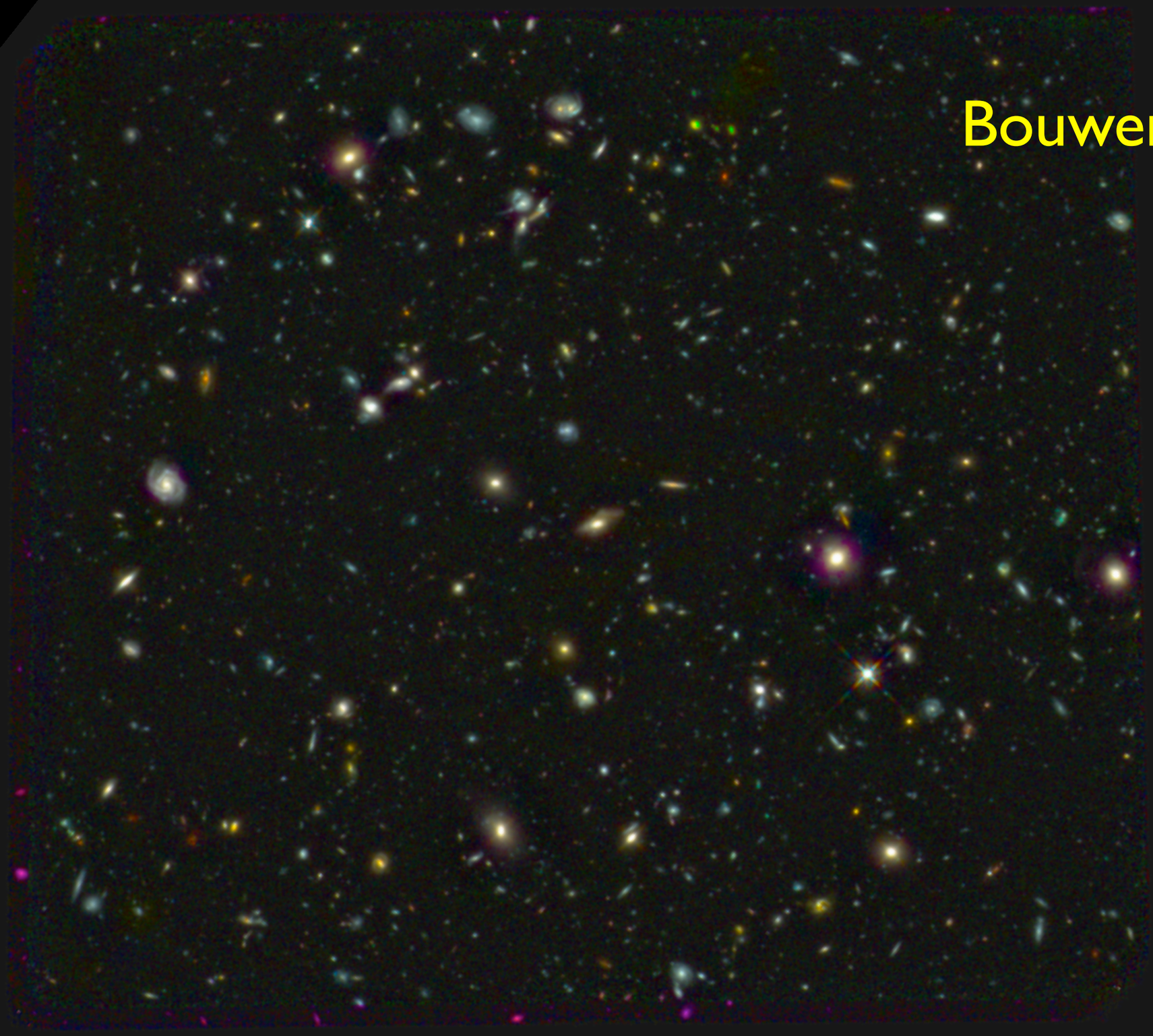


J. Xavier Prochaska (IMPS, UCO, UC Santa Cruz)

Gabor Worseck (IMPS, UCO)

John O'Meara (St. Michael's)

Probing into the HI Reionization Epoch

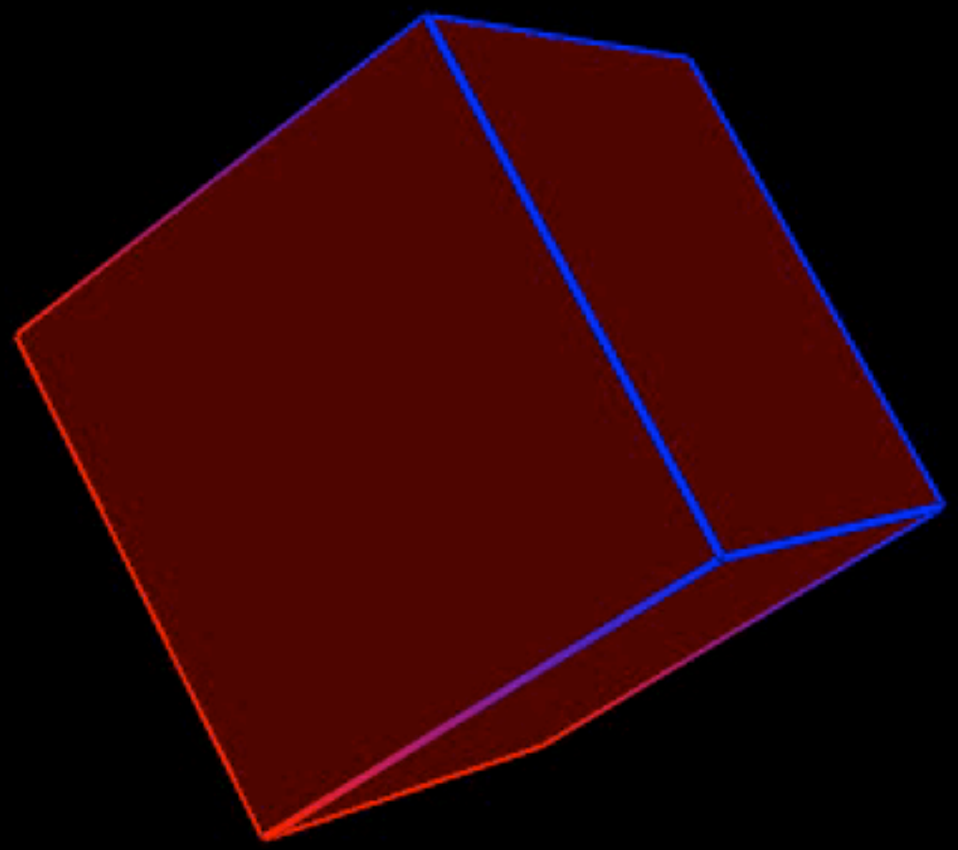


Bouwens+09

HUDF with WFC3

HI Reionization

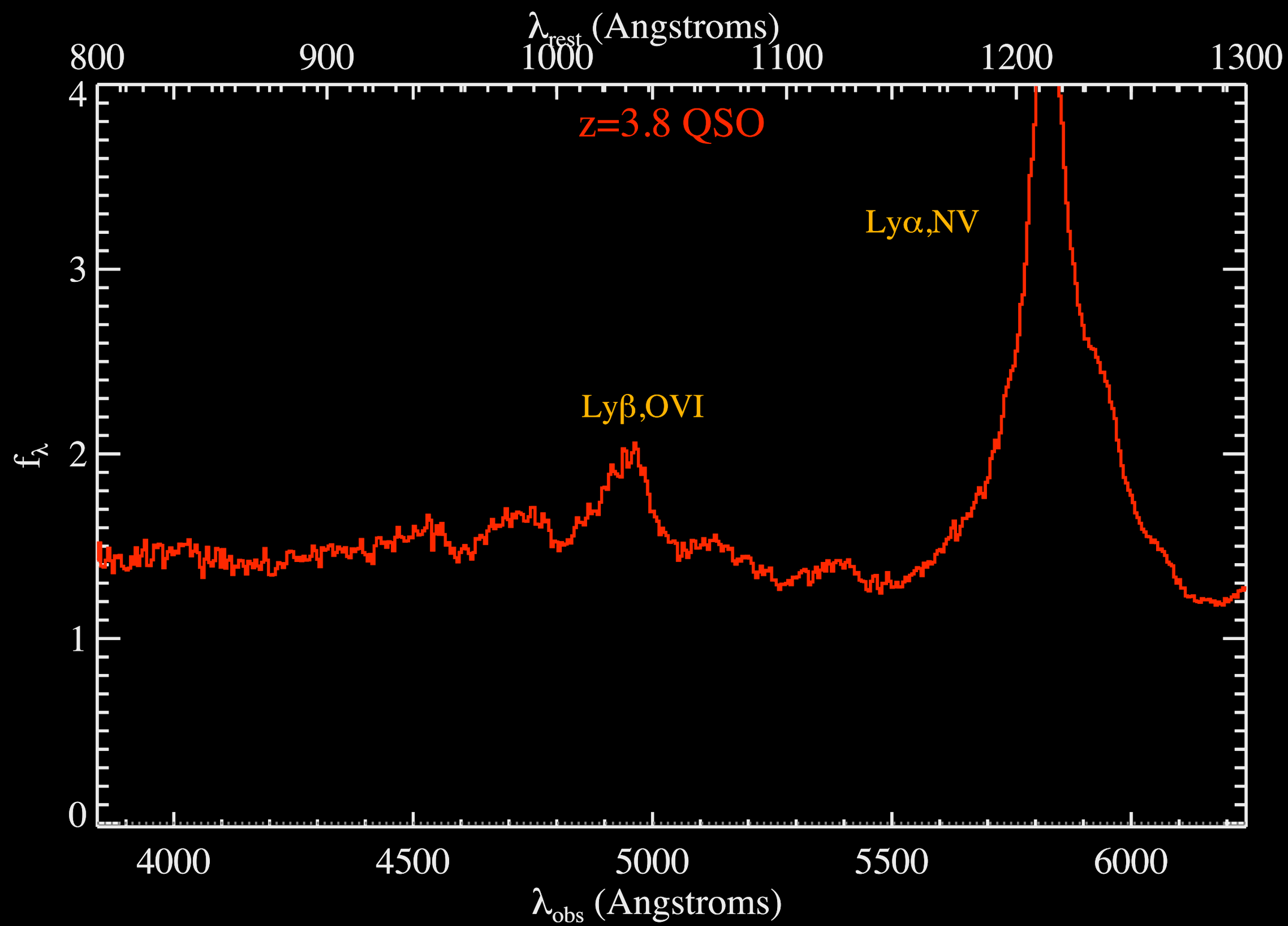
McQuinn et al.



Gnedin et al.

Calculations (cartoons) of Reionization

Did HI Reionization Occur?



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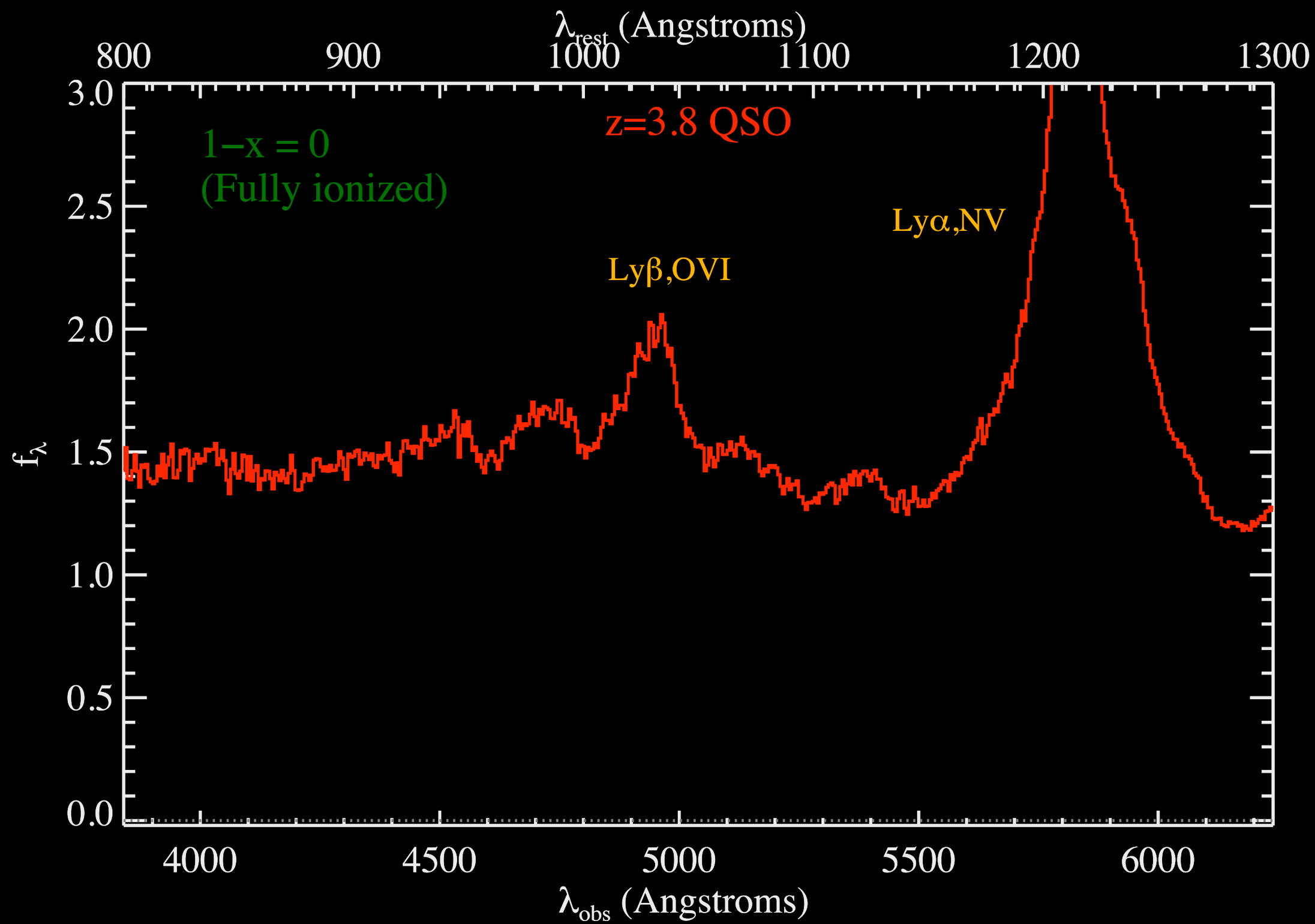

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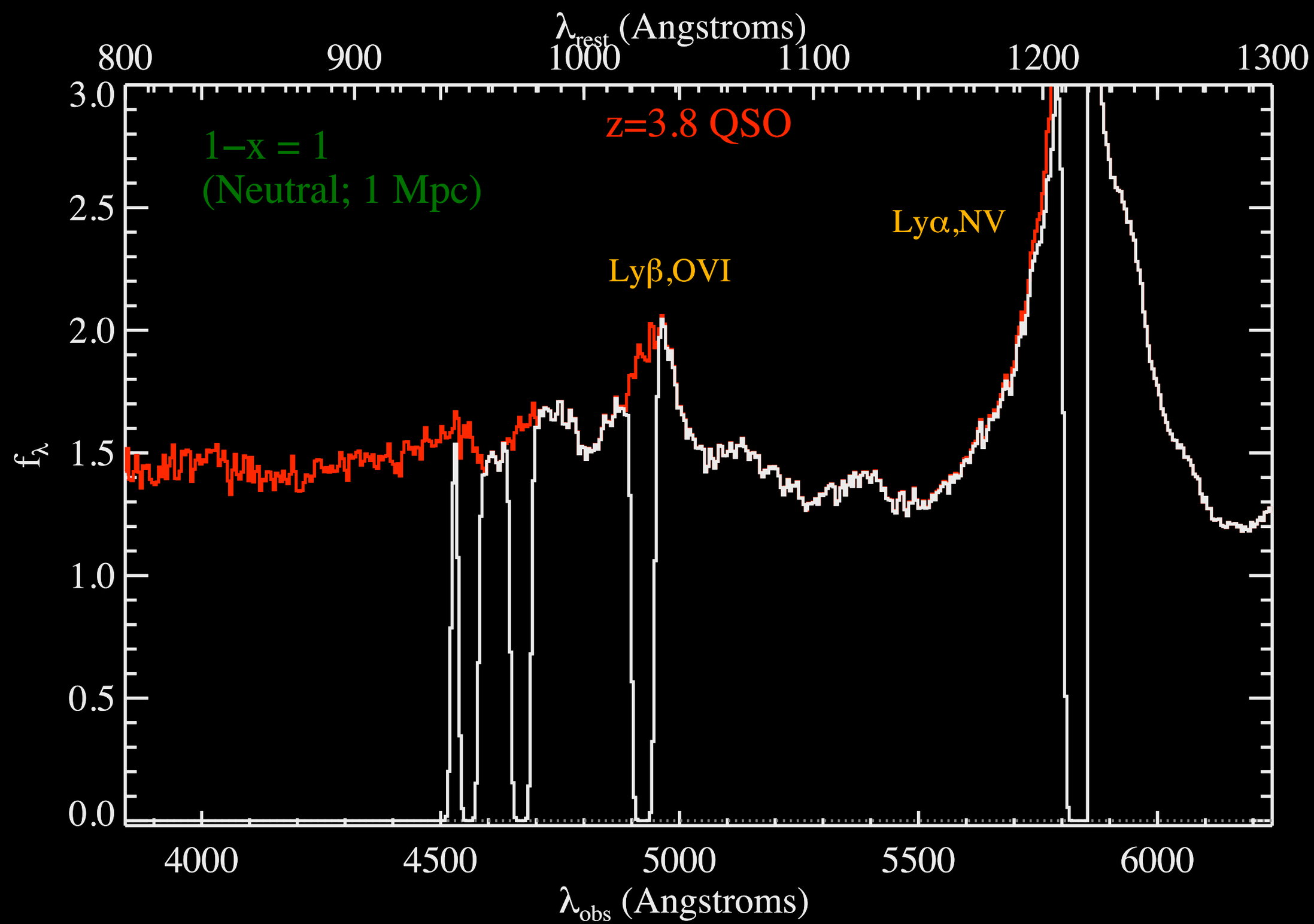

$$N_{HI} = \Omega_b (1+z)^3 n_c \ (1 \text{ Mpc}) \sim 10^{20} \text{ cm}^{-2}$$

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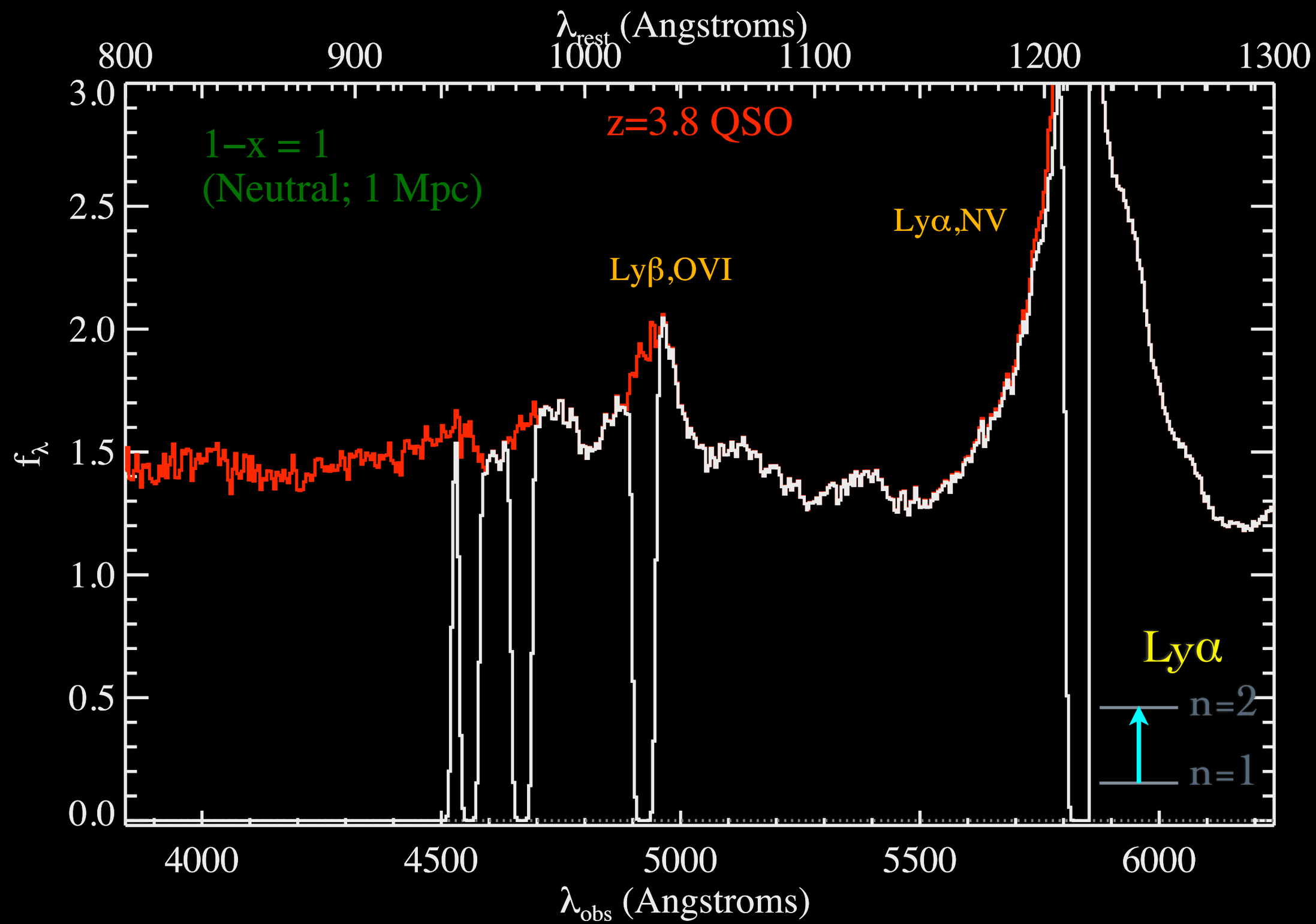

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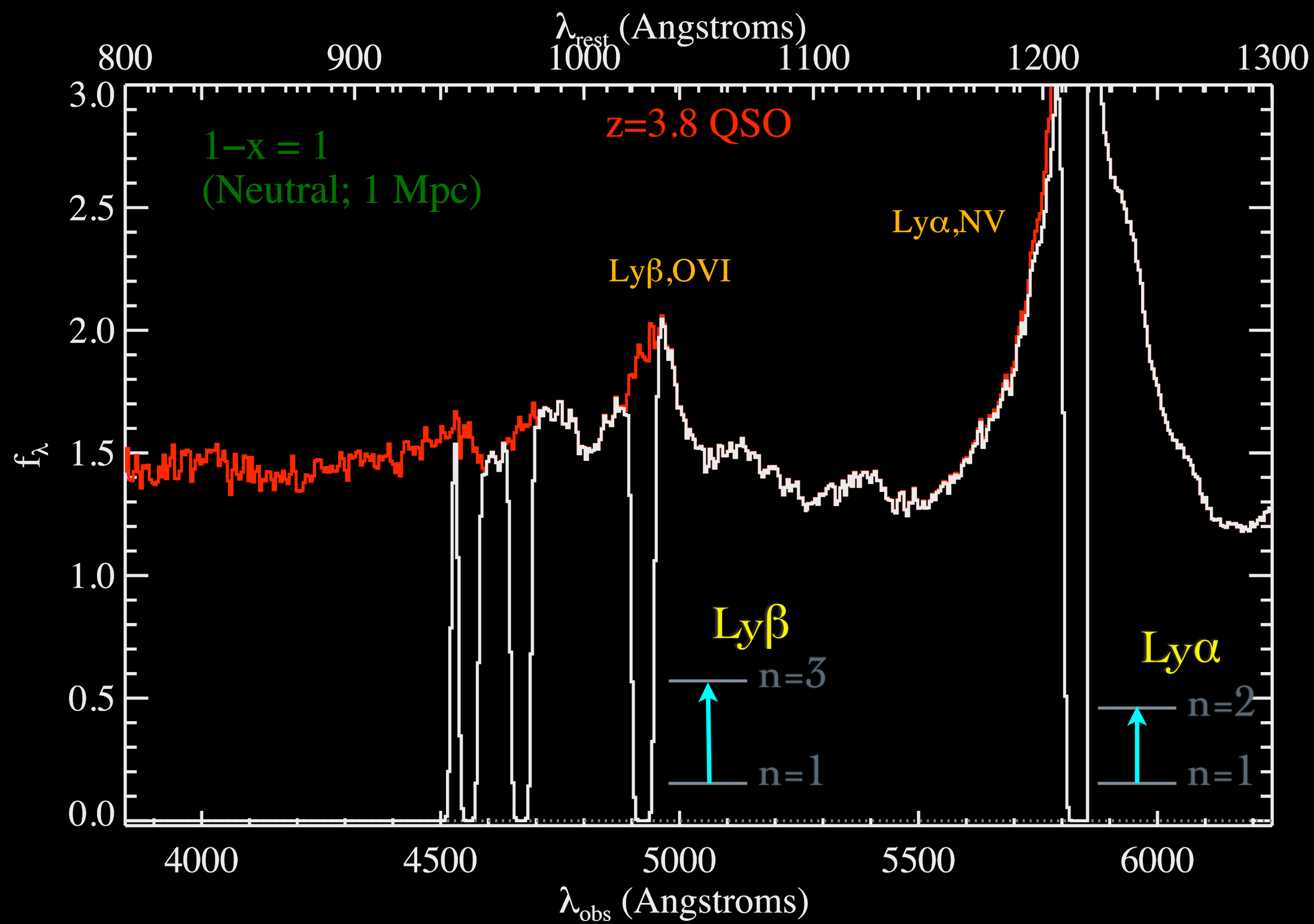

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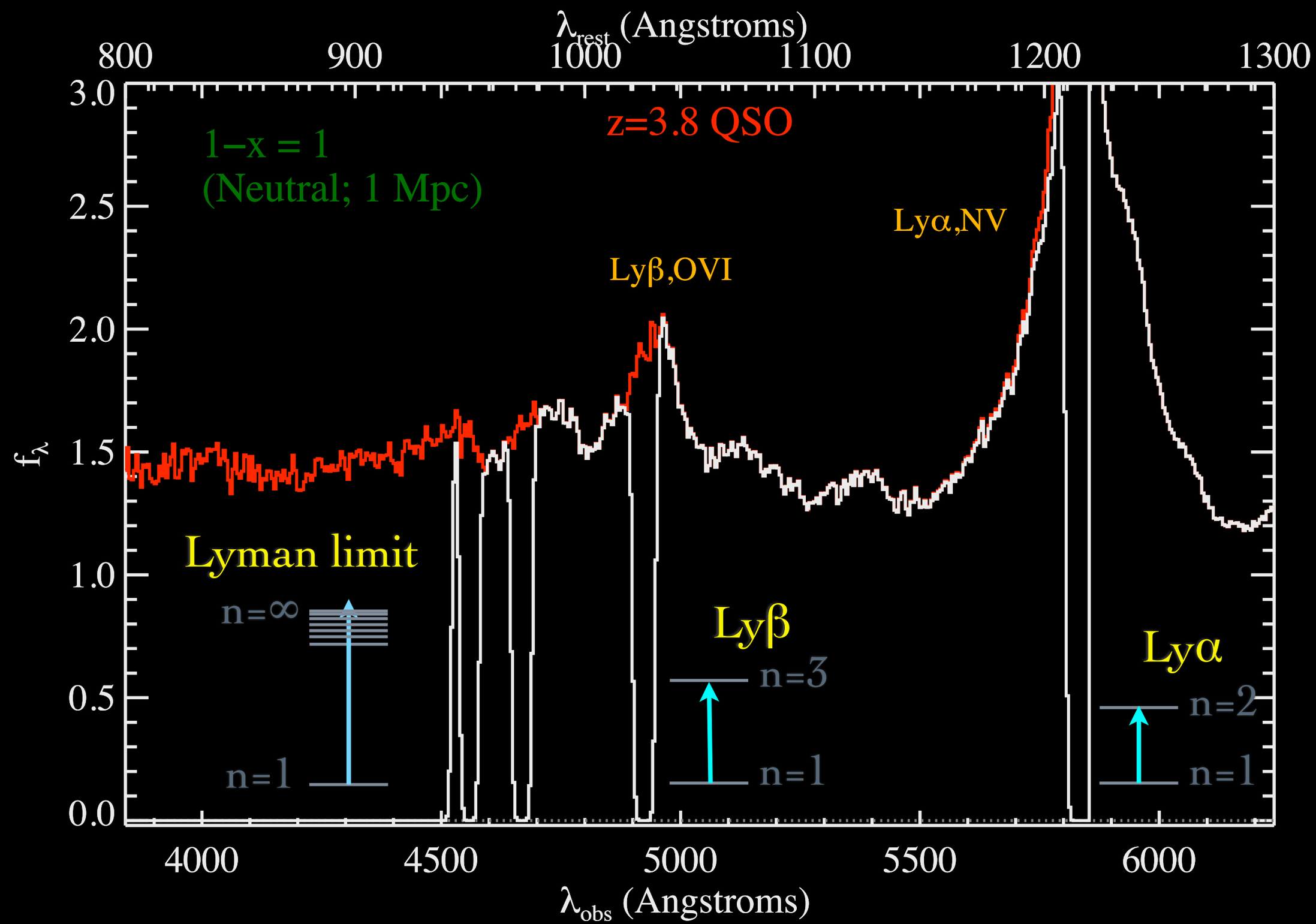

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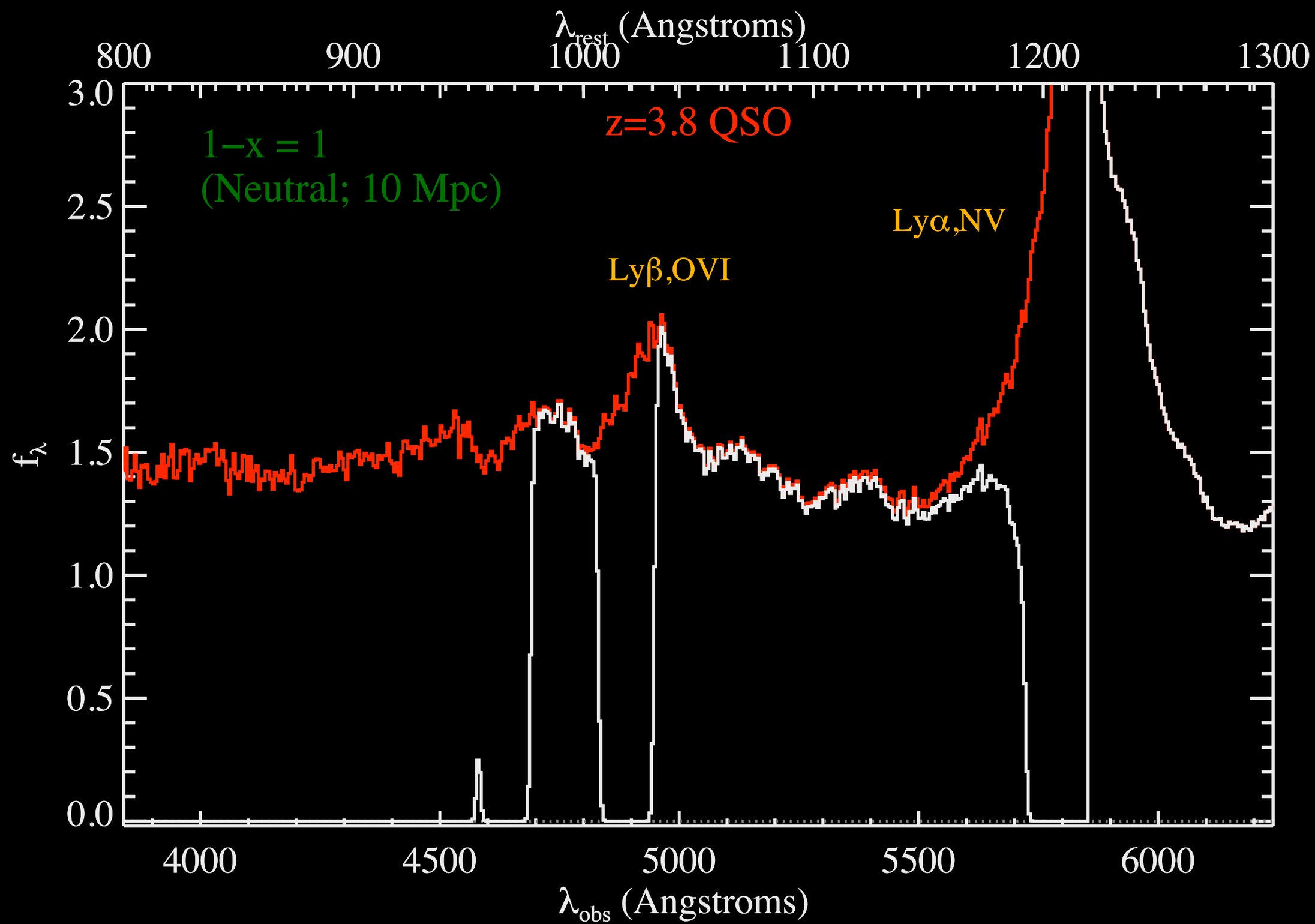

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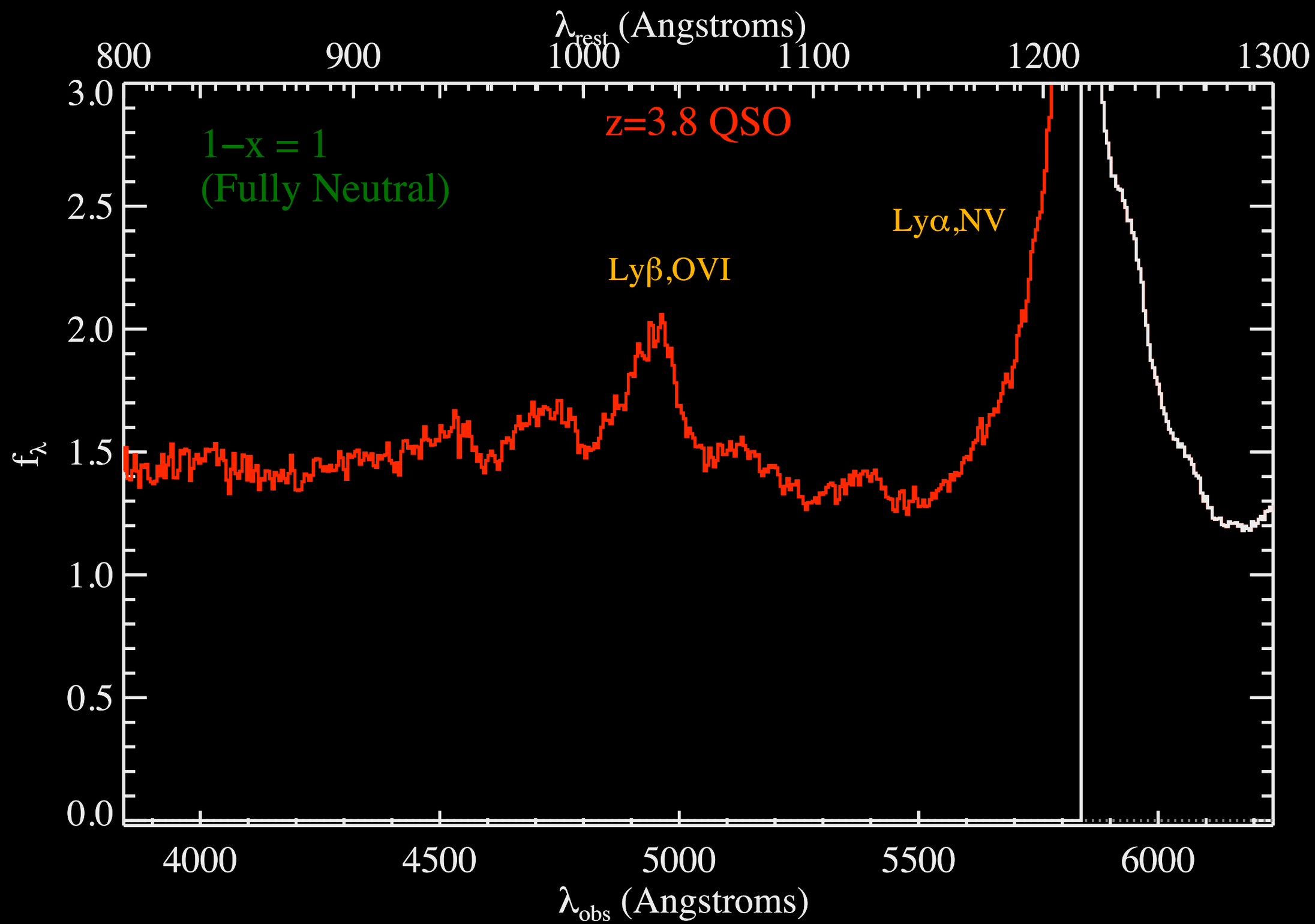

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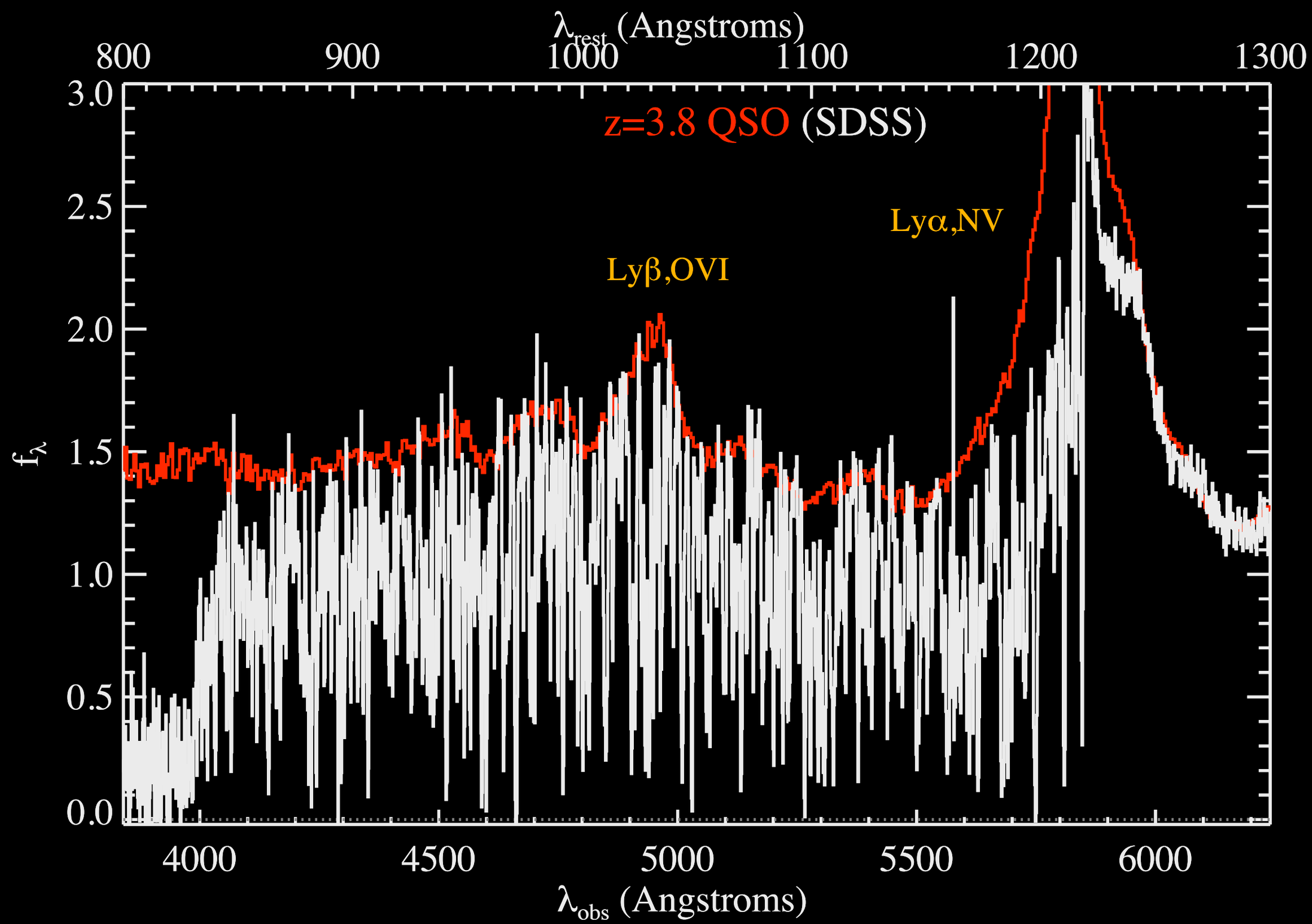

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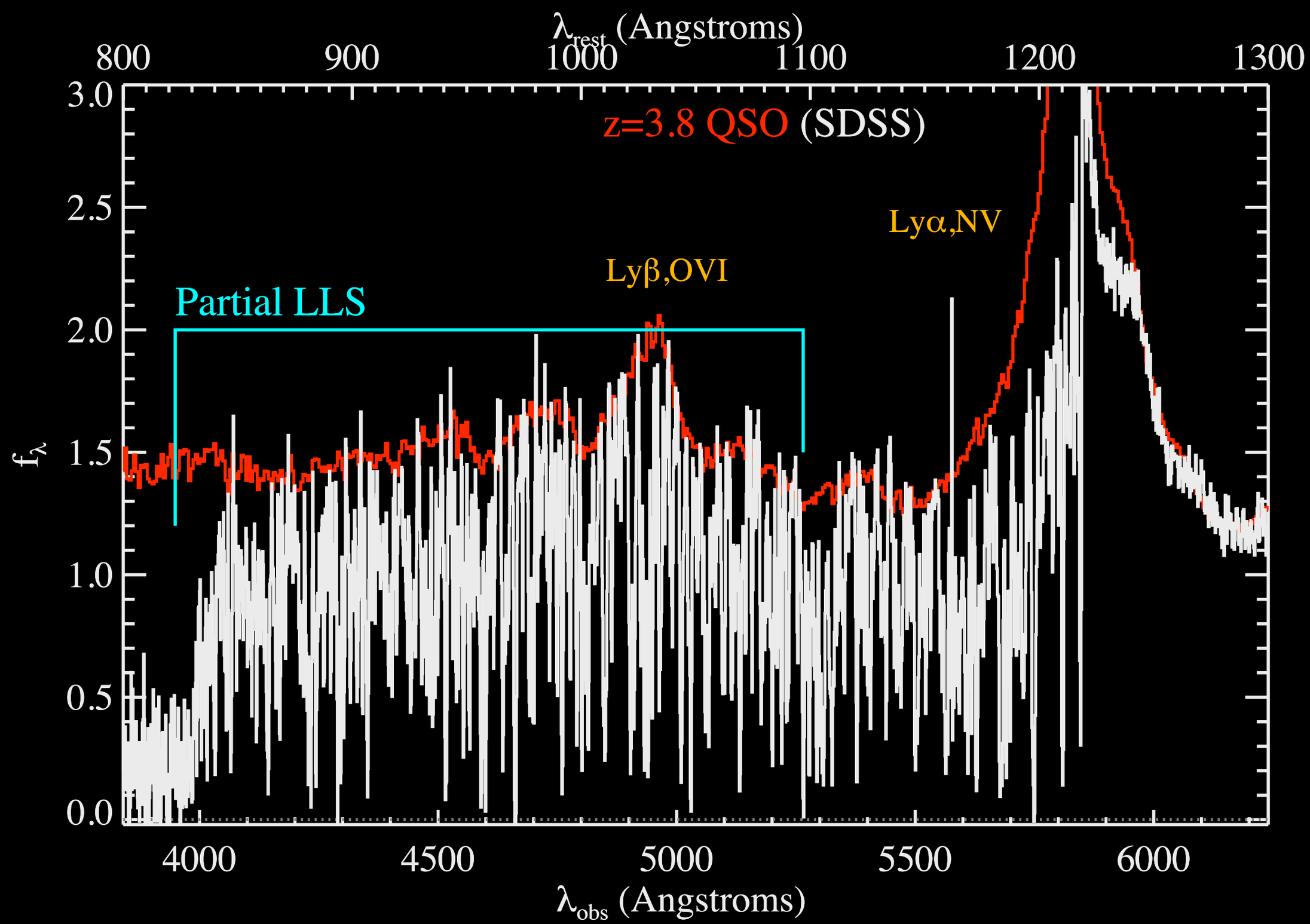

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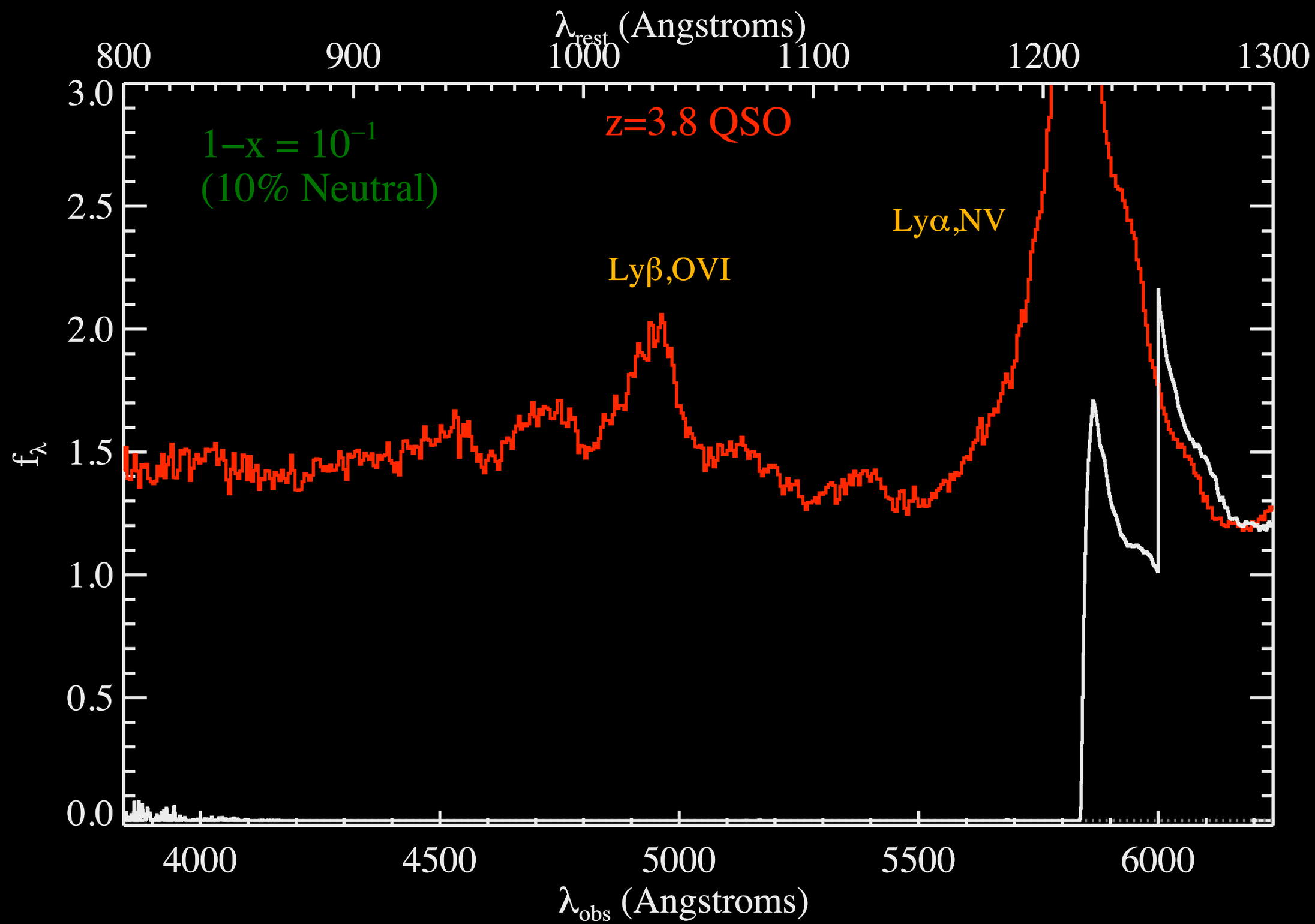

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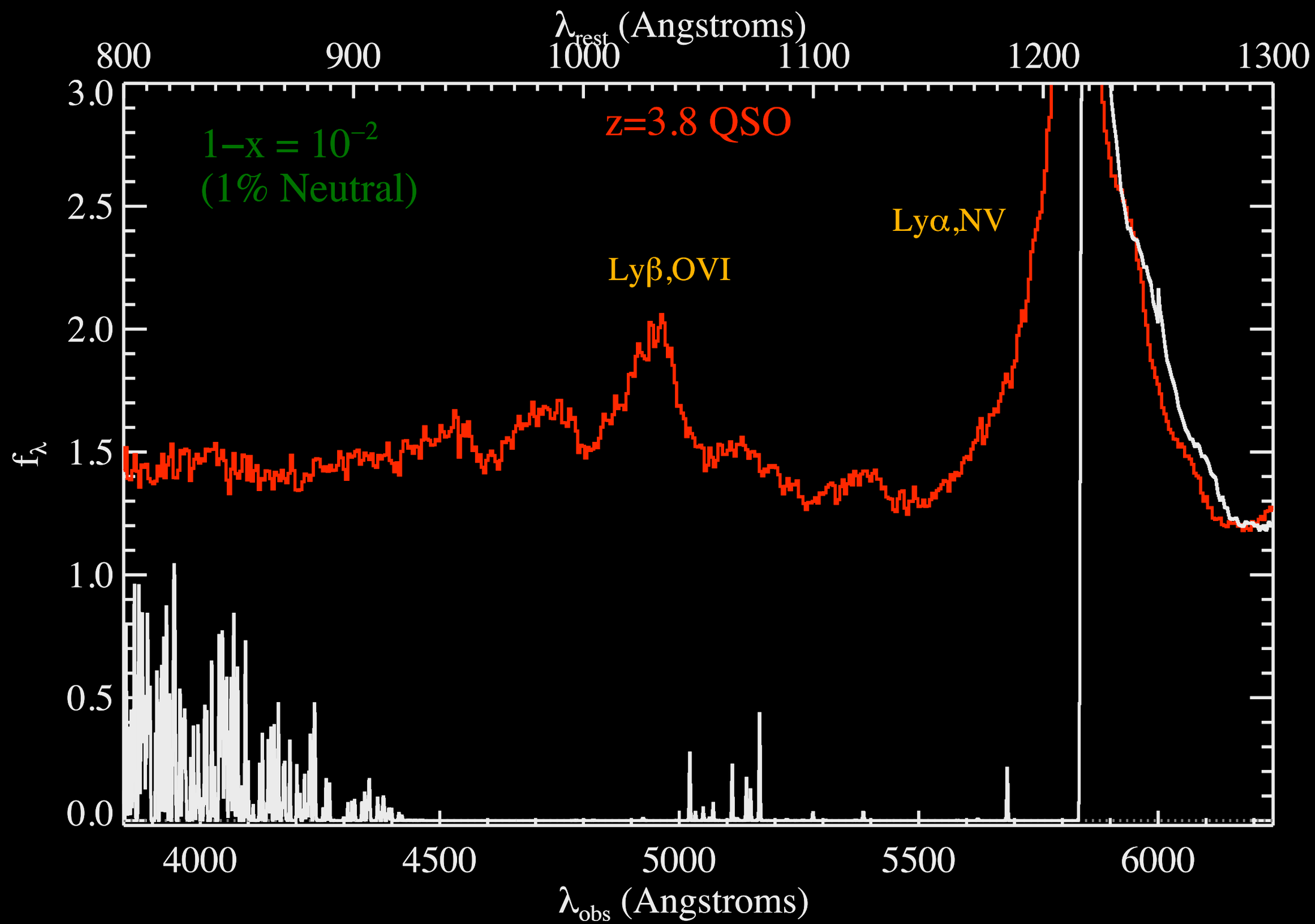

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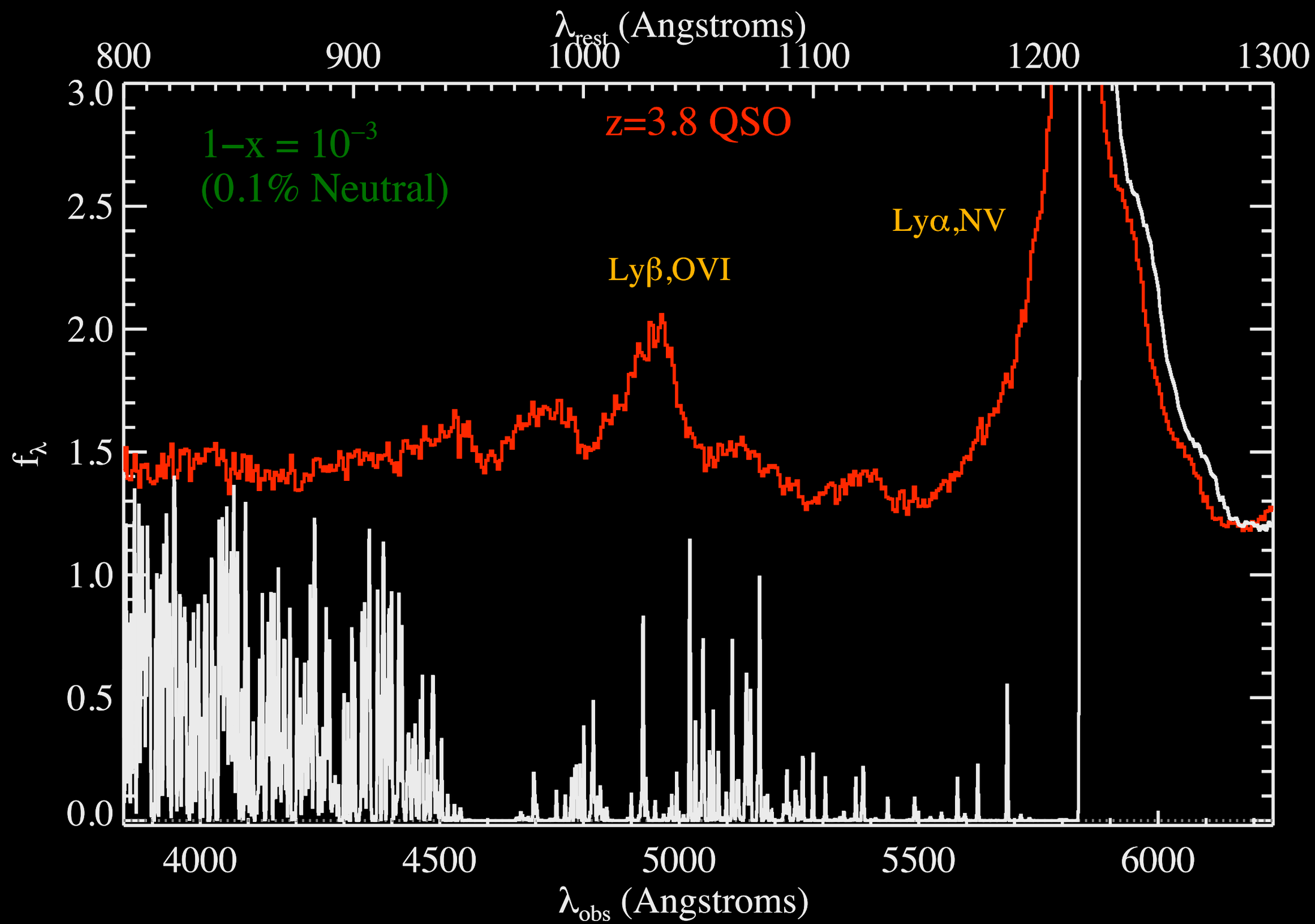

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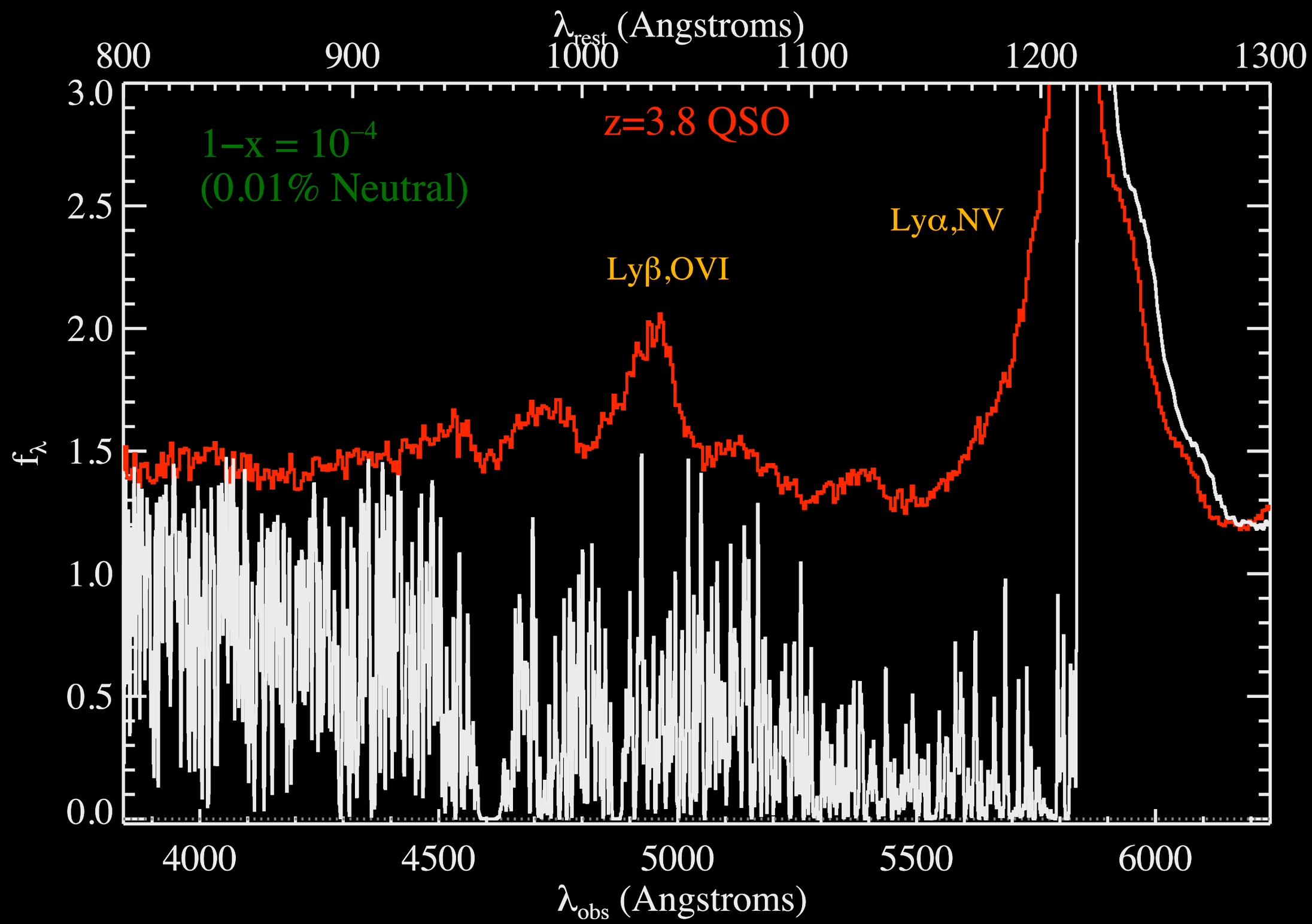

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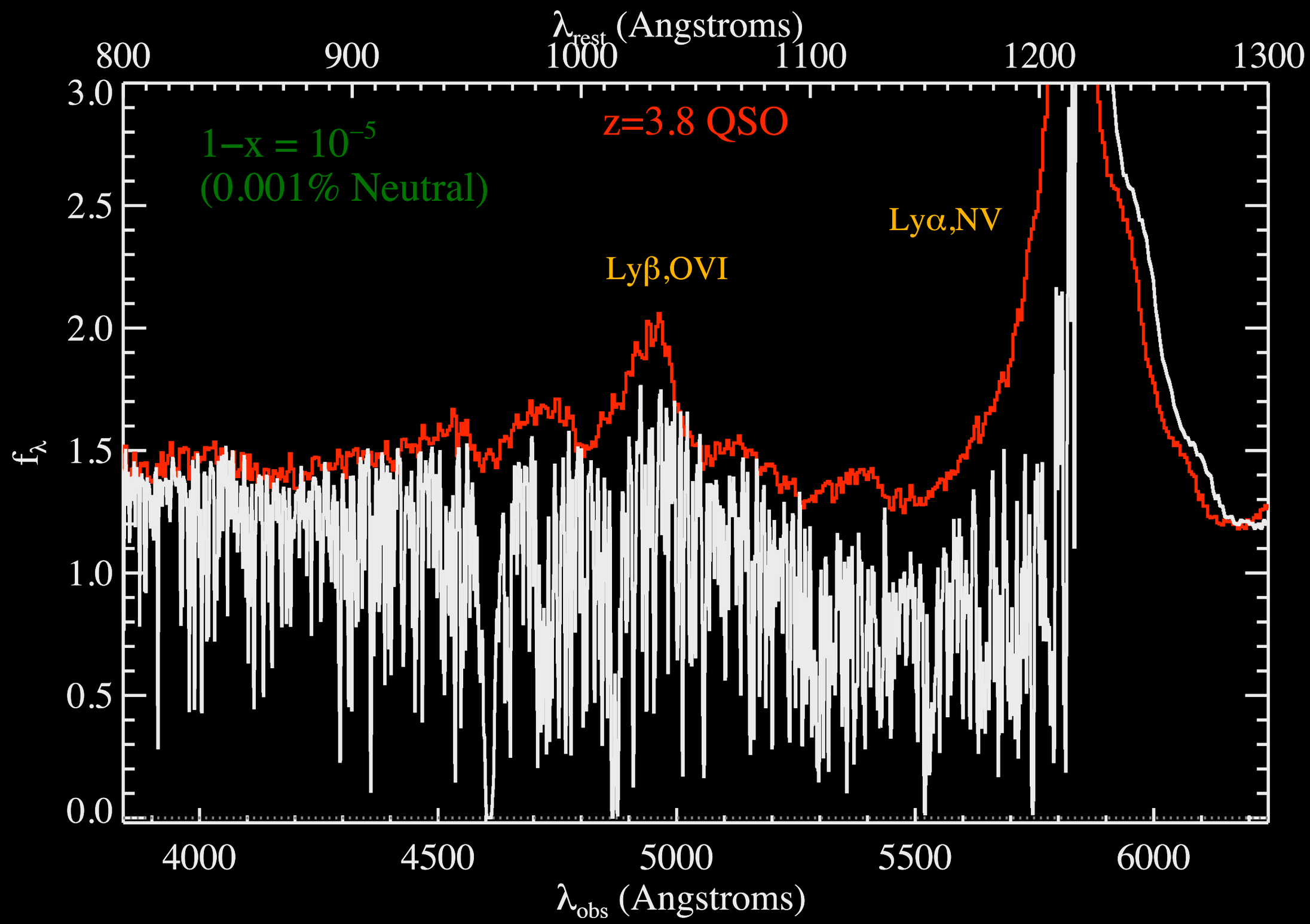

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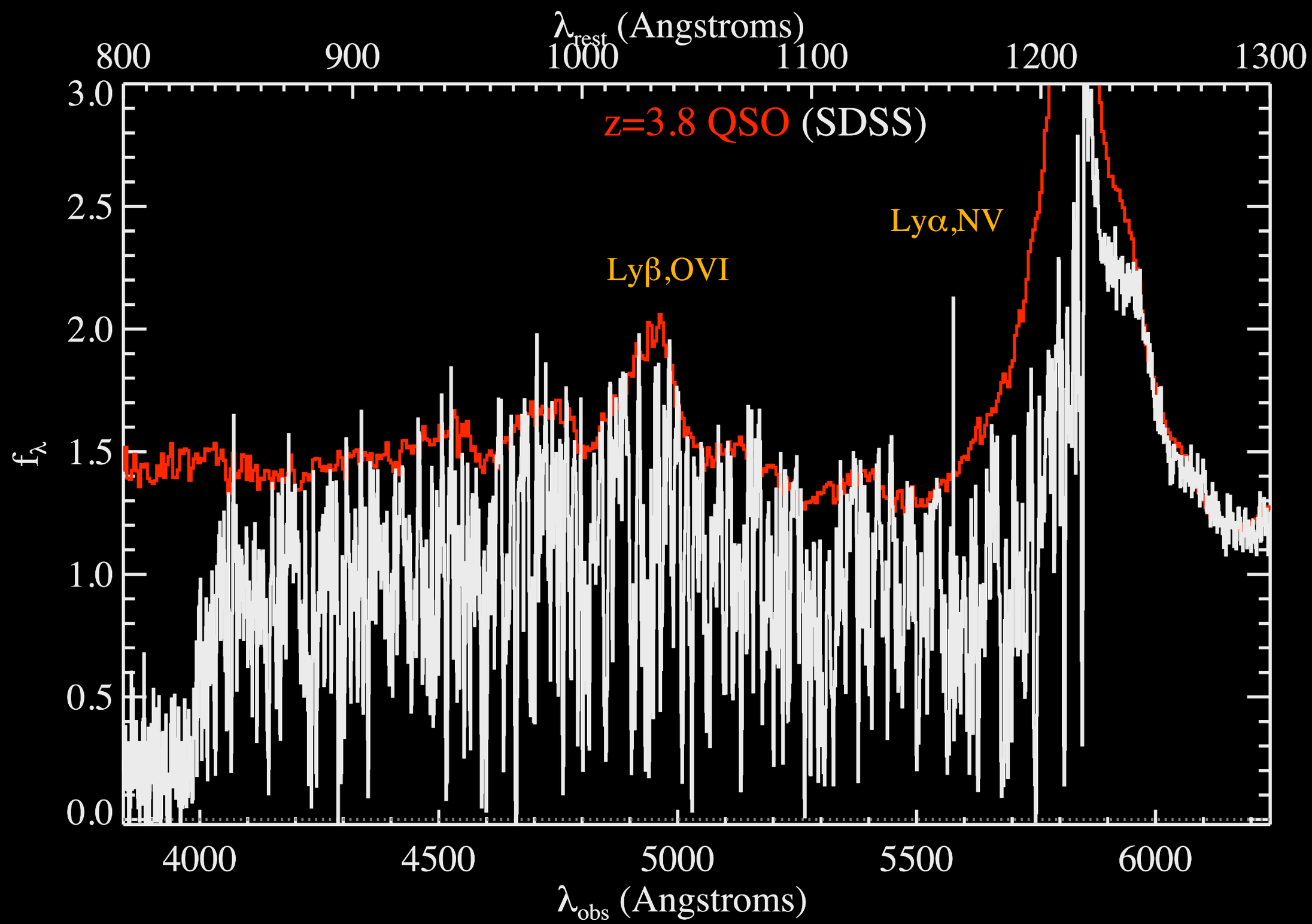
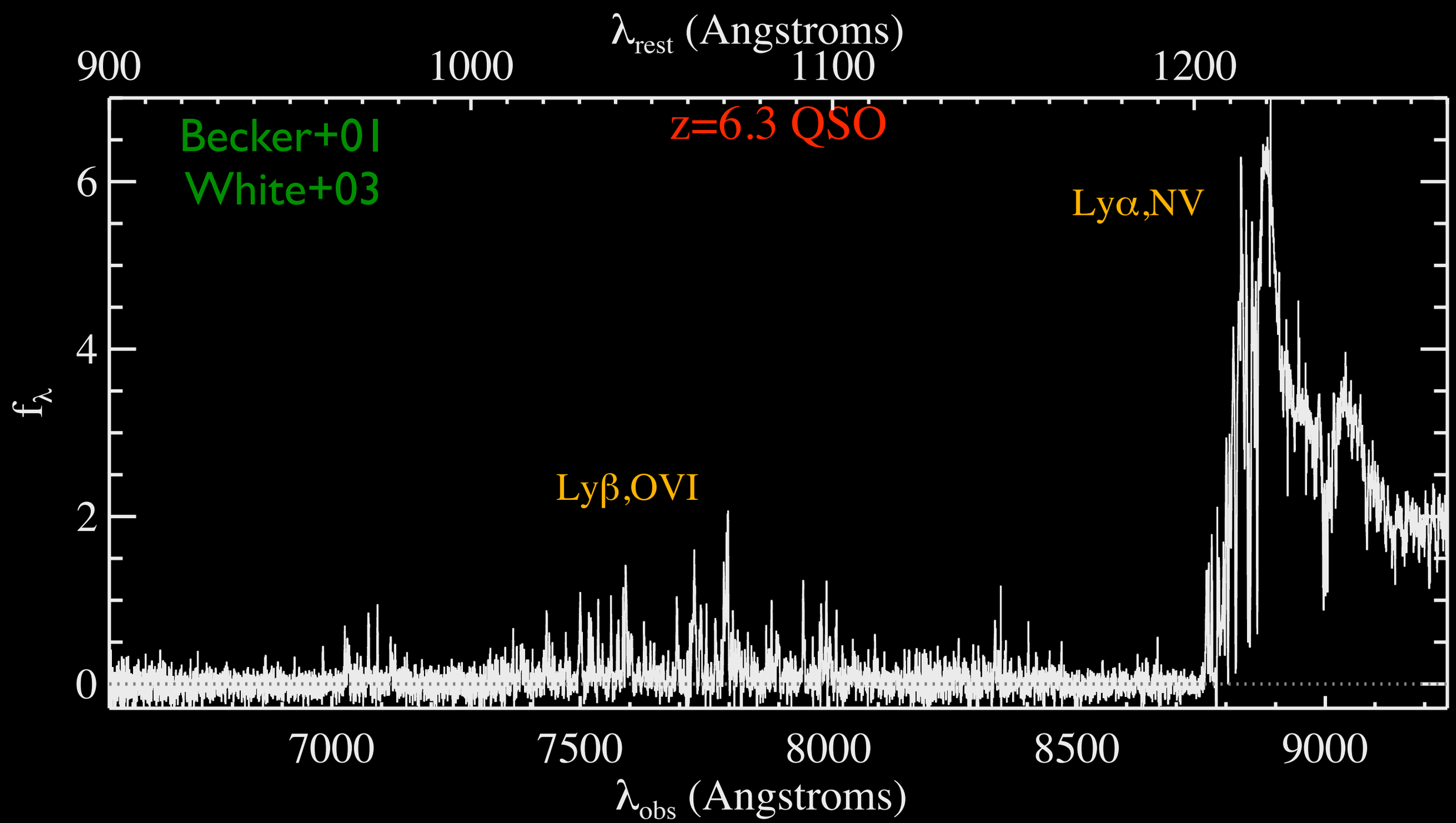
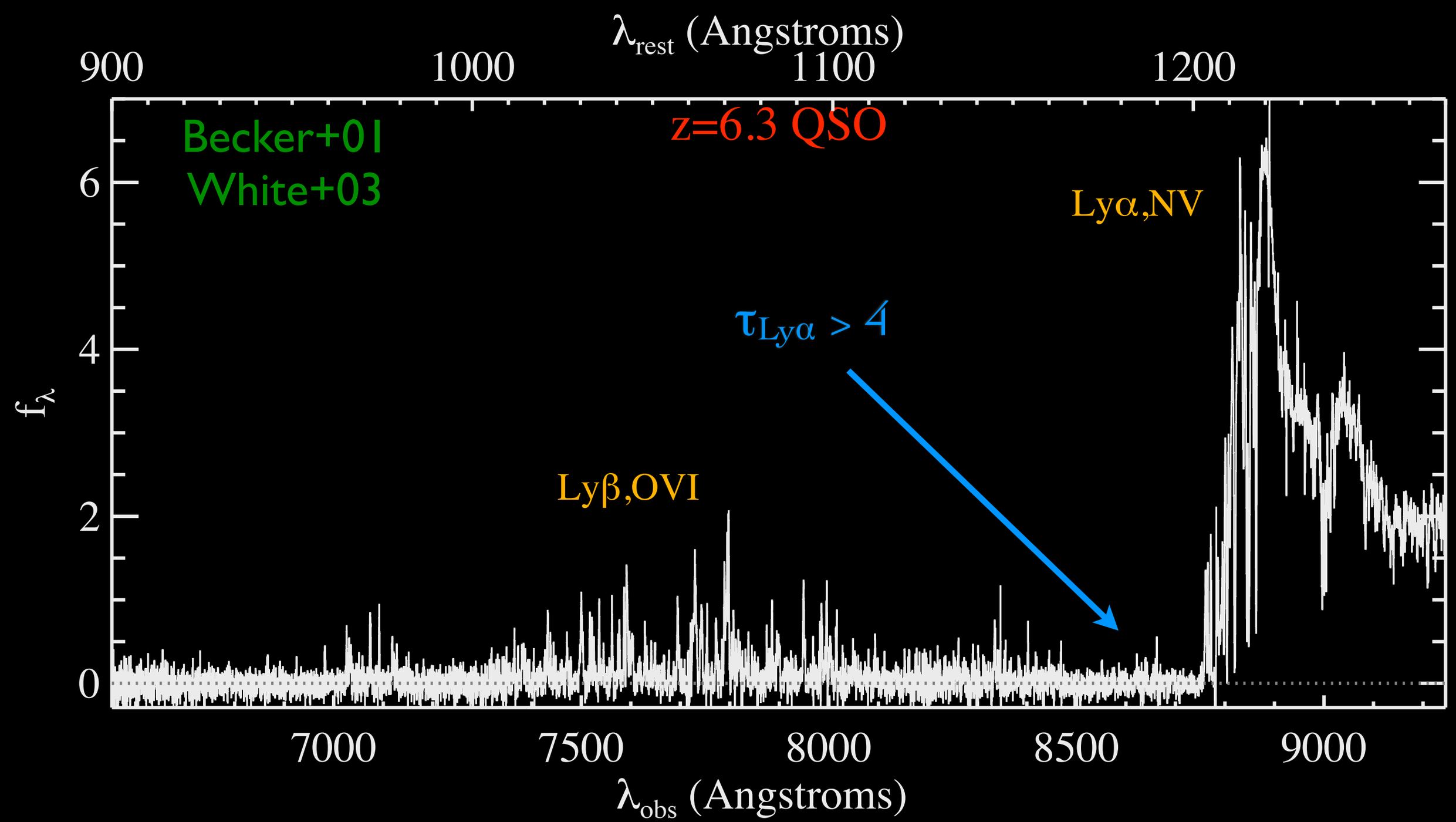


Yes, it did!

z=6.28 Quasar


λ_{rest} (Angstroms)
900
1000
1100
1200
Becker+01
White+03
z=6.3 QSO
Lyα,NV
Lyβ,OVI
f_λ
0
2
4
6
7000
7500
8000
8500
9000
λ_{obs} (Angstroms)

z=6.28 Quasar


λ_{rest} (Angstroms)
900
1000
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Becker+01
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z=6.3 QSO
Lyα,NV
$\tau_{Ly\alpha} > 4$
Lyβ,OVI
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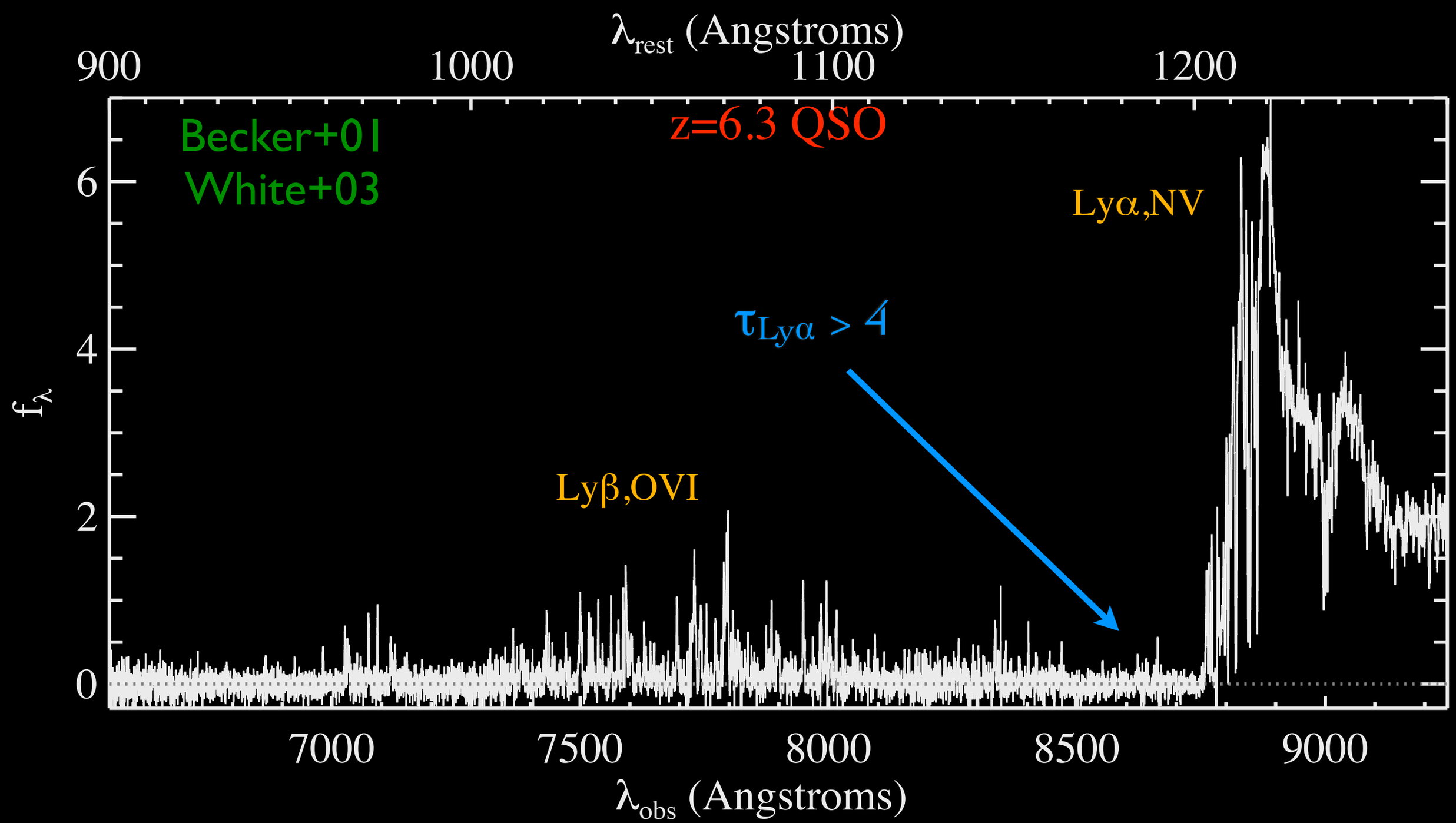
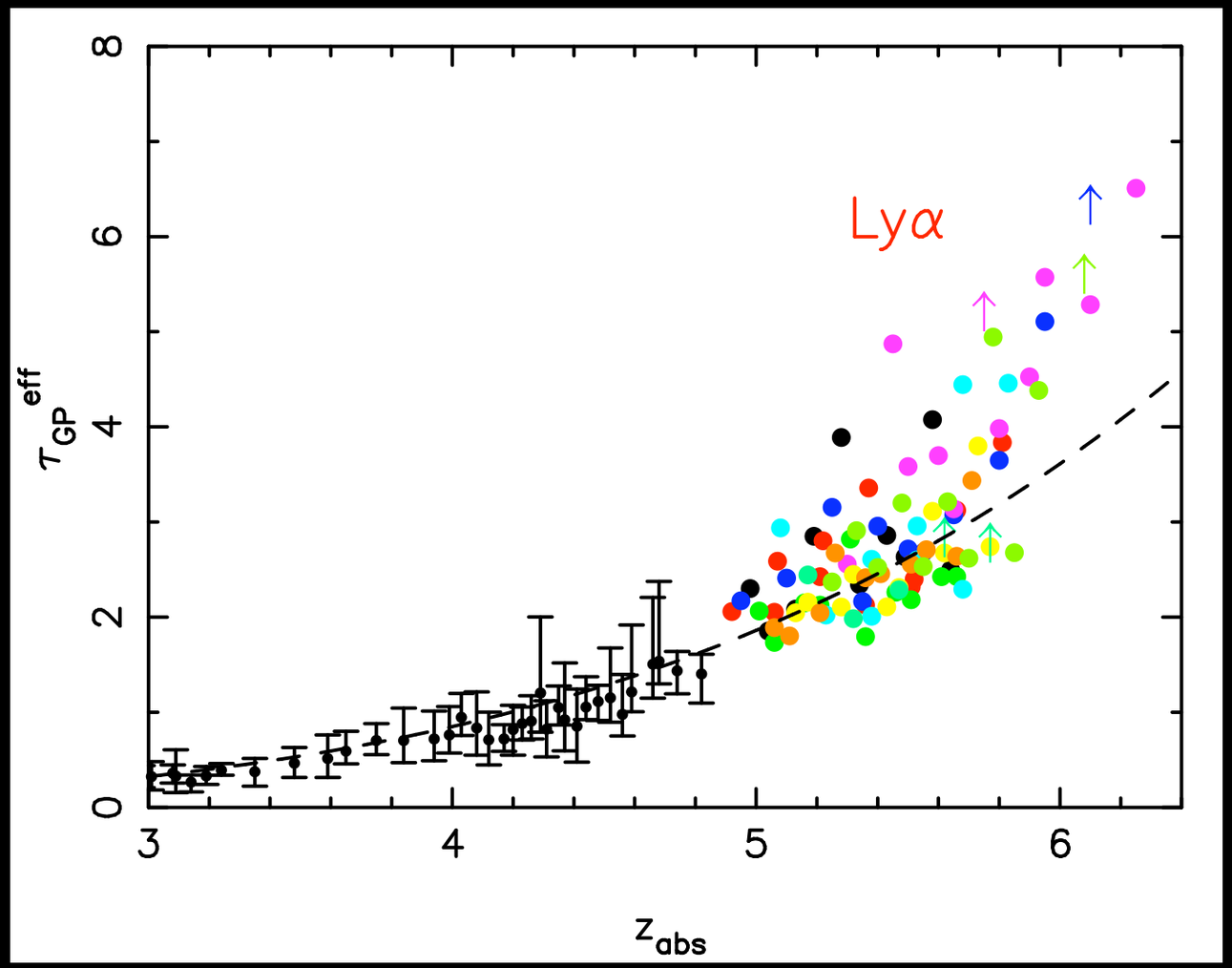


Is this high Lyα opacity a definitive signature of reionization at z~6?

Reionization at z~6?

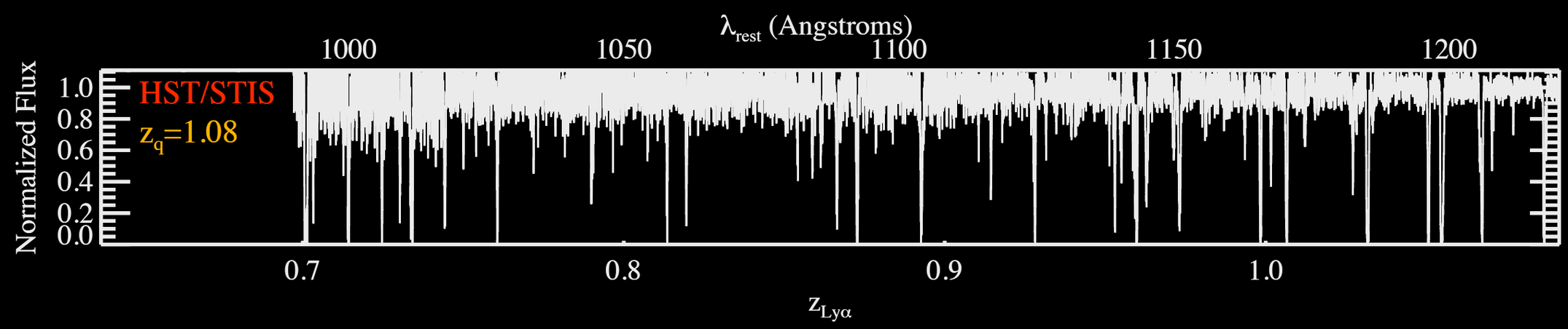
$$\tau_{\rm GP} \equiv \tau_{\rm Ly\alpha} = -\ln\left(\frac{f_\nu^{\rm obs}}{f_\nu^{\rm QSO}}\right)$$

- Basic approach (in favor)
  - Measure $\tau_{Ly\alpha}$ at z<5
    - Extrapolate this trend to z>6
  - Measure $\tau_{Ly\alpha}$ at z>6
    - Compare
- 'Phase transition'
  - At z~6, $\tau_{Ly\alpha}$ exceeds the simple extrapolation
  - "The reionization epoch!"



White+03, Fan+06

Evolving Lyα Forest Absorption



The expanding (contracting) universe implies higher Lyα absorption at higher z.

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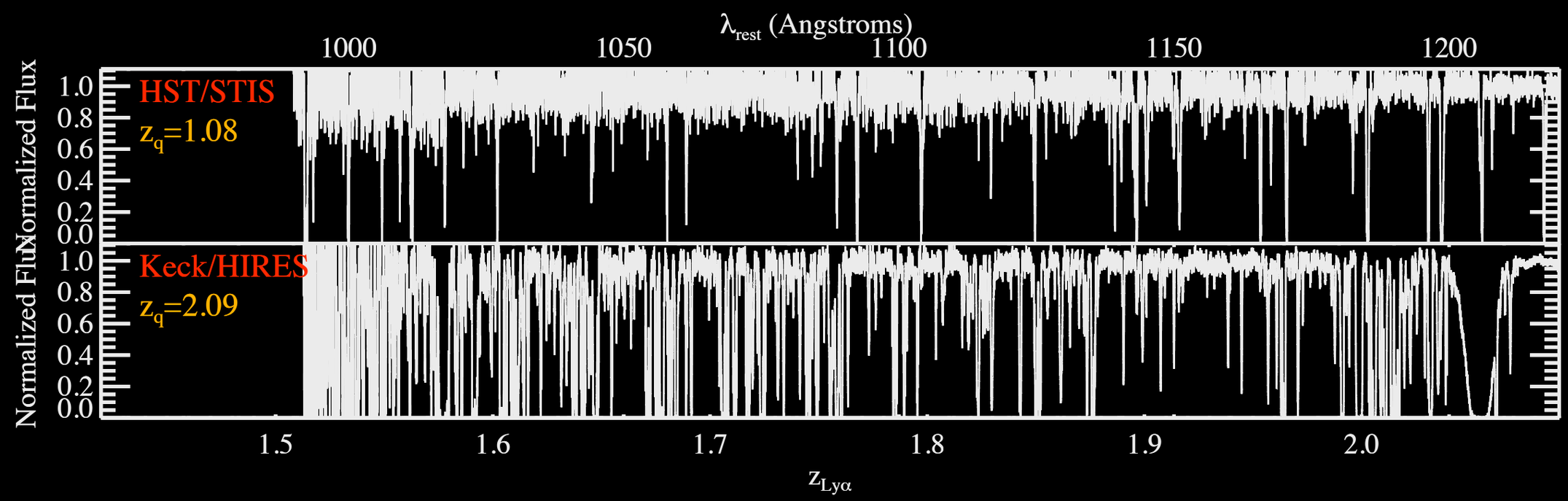

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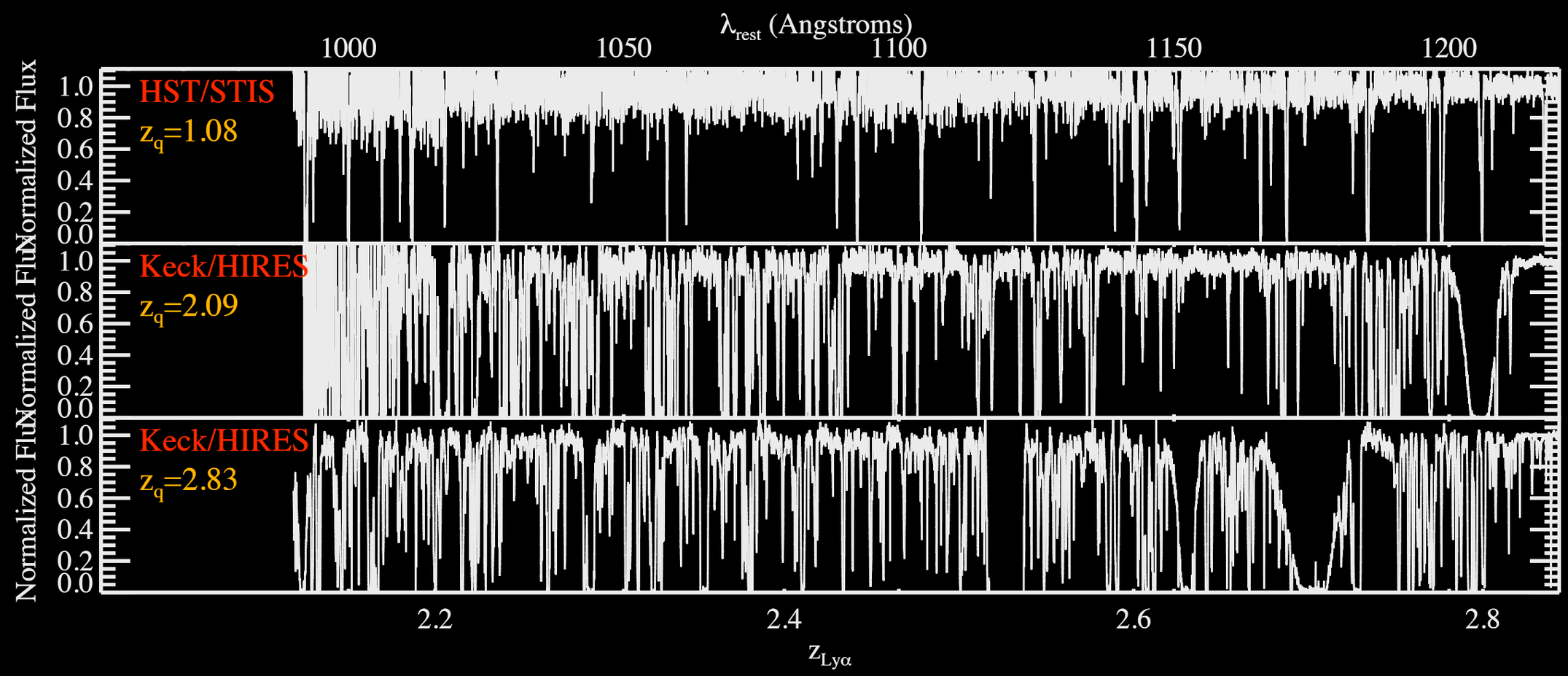

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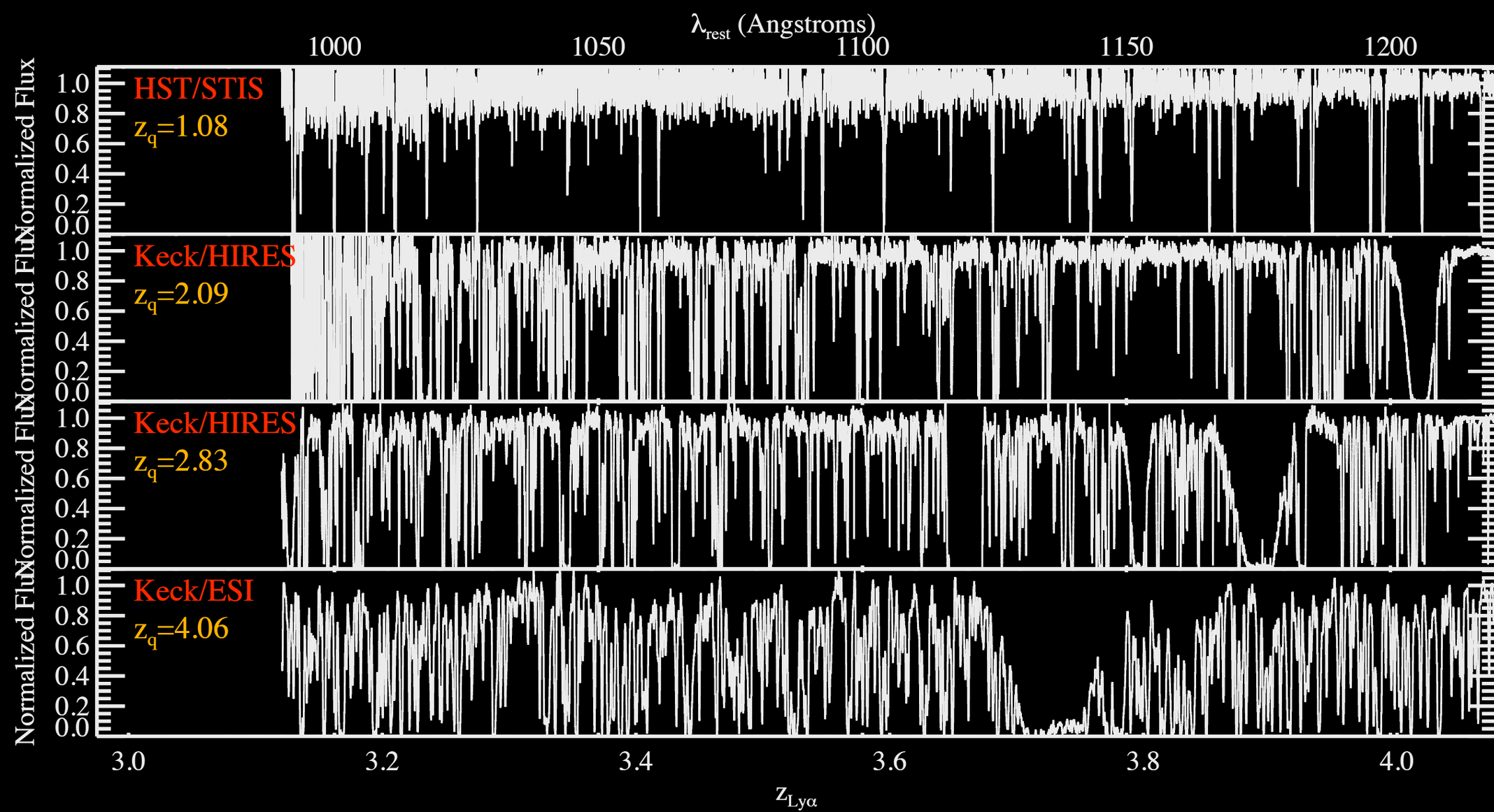

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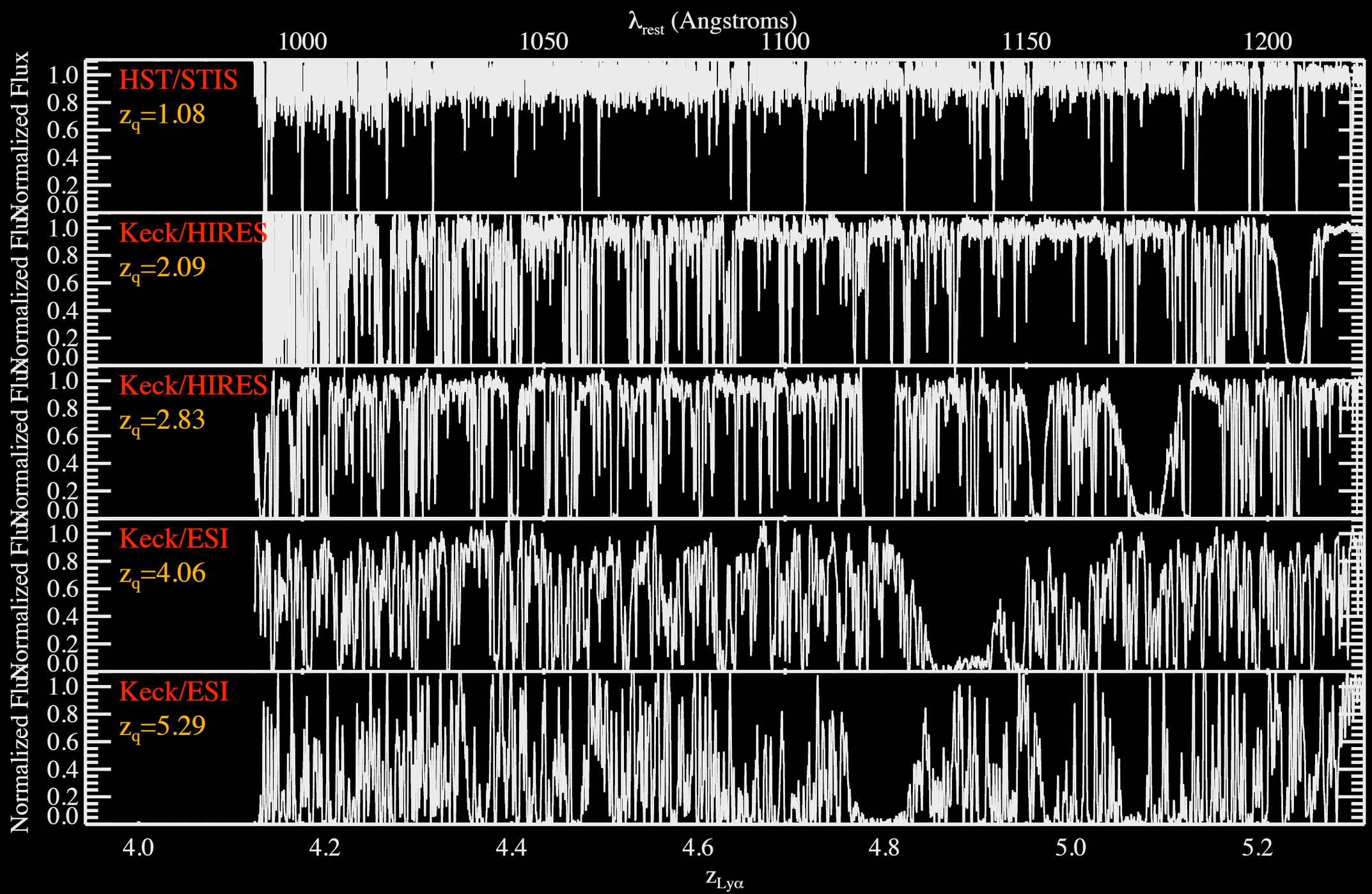

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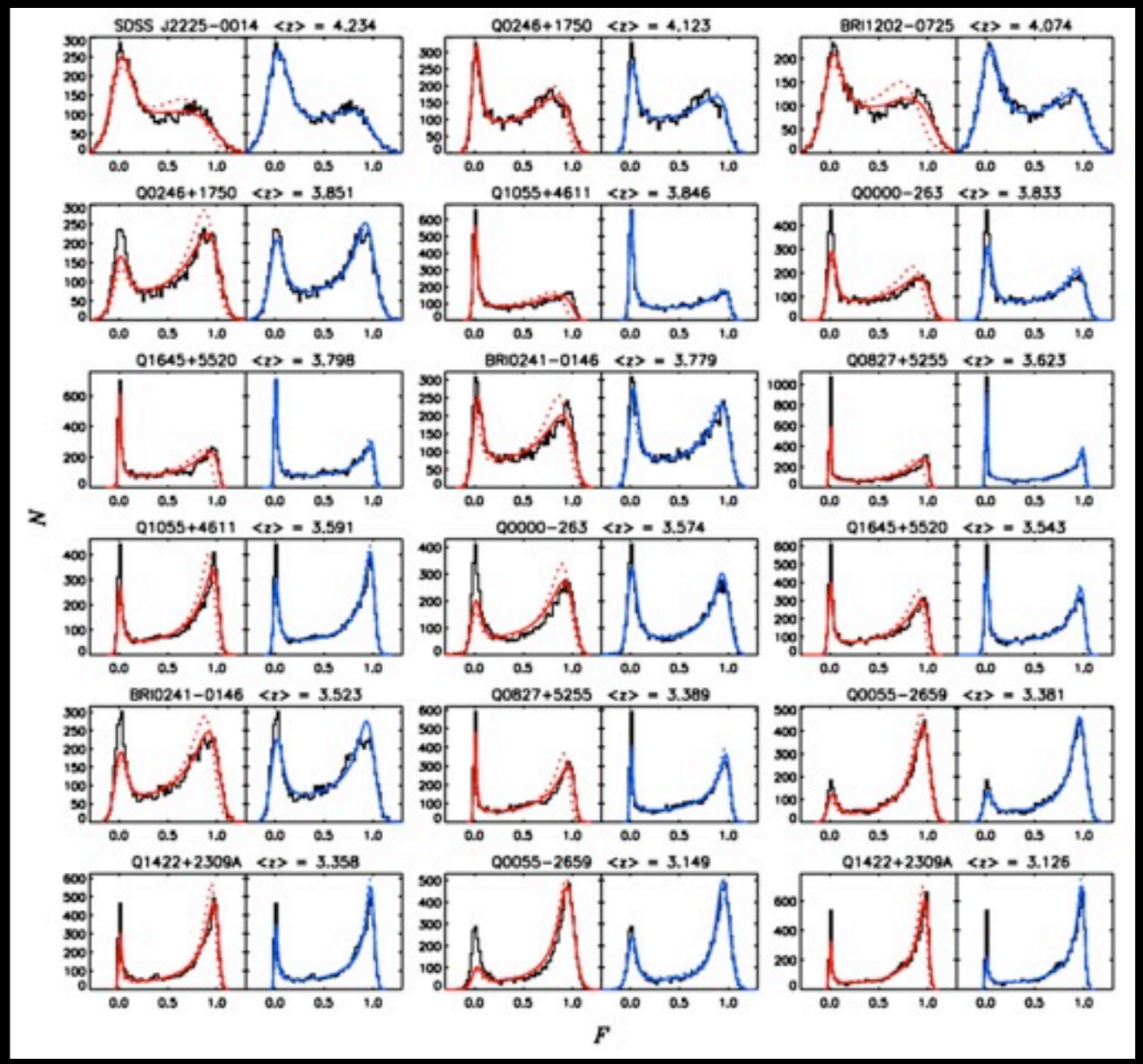
Reionization at z~6?

Becker+07



Reionization at z~6?

Becker+07

- Characterizing $\tau_{Ly\alpha}$
  - High-resolution observations
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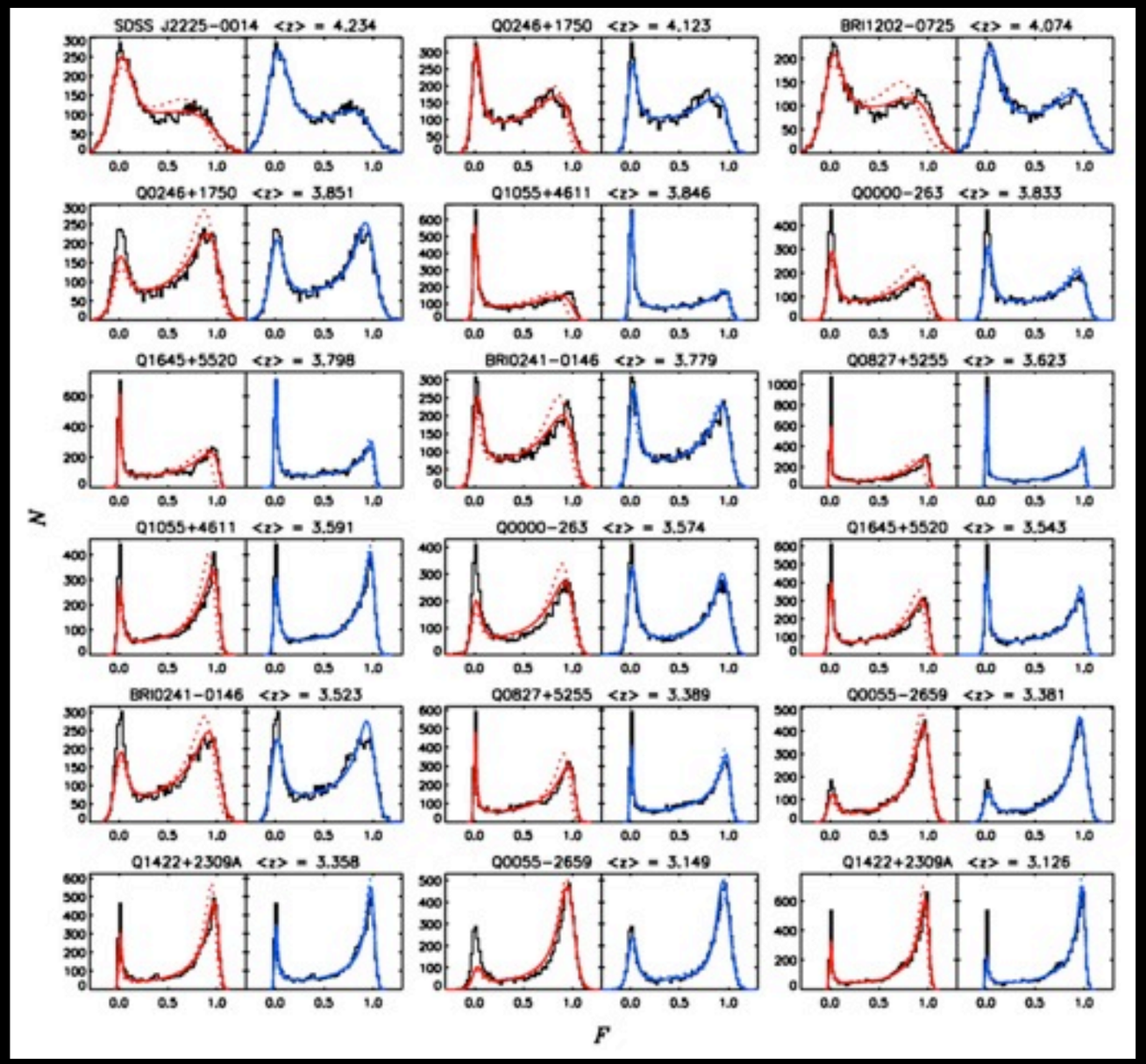
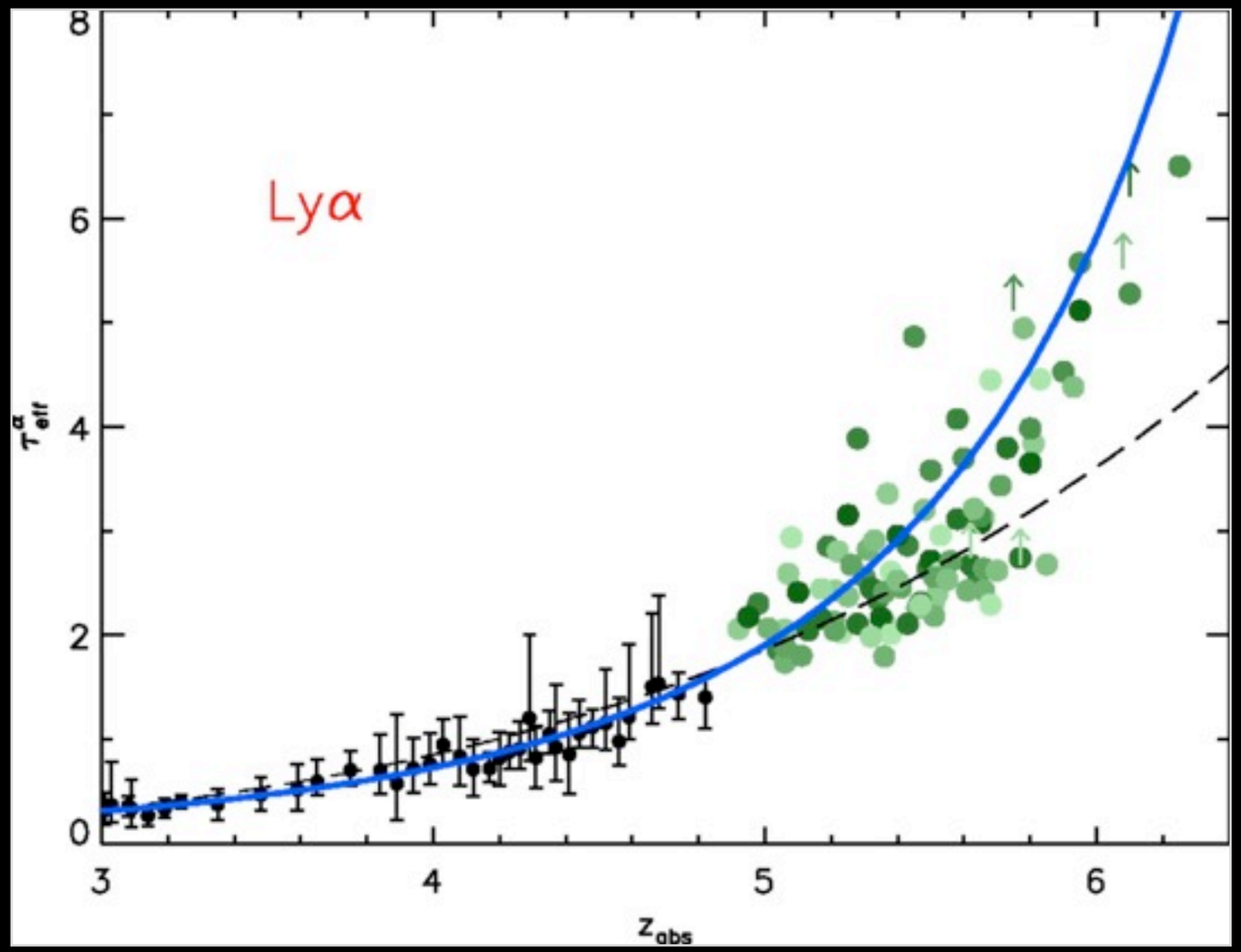


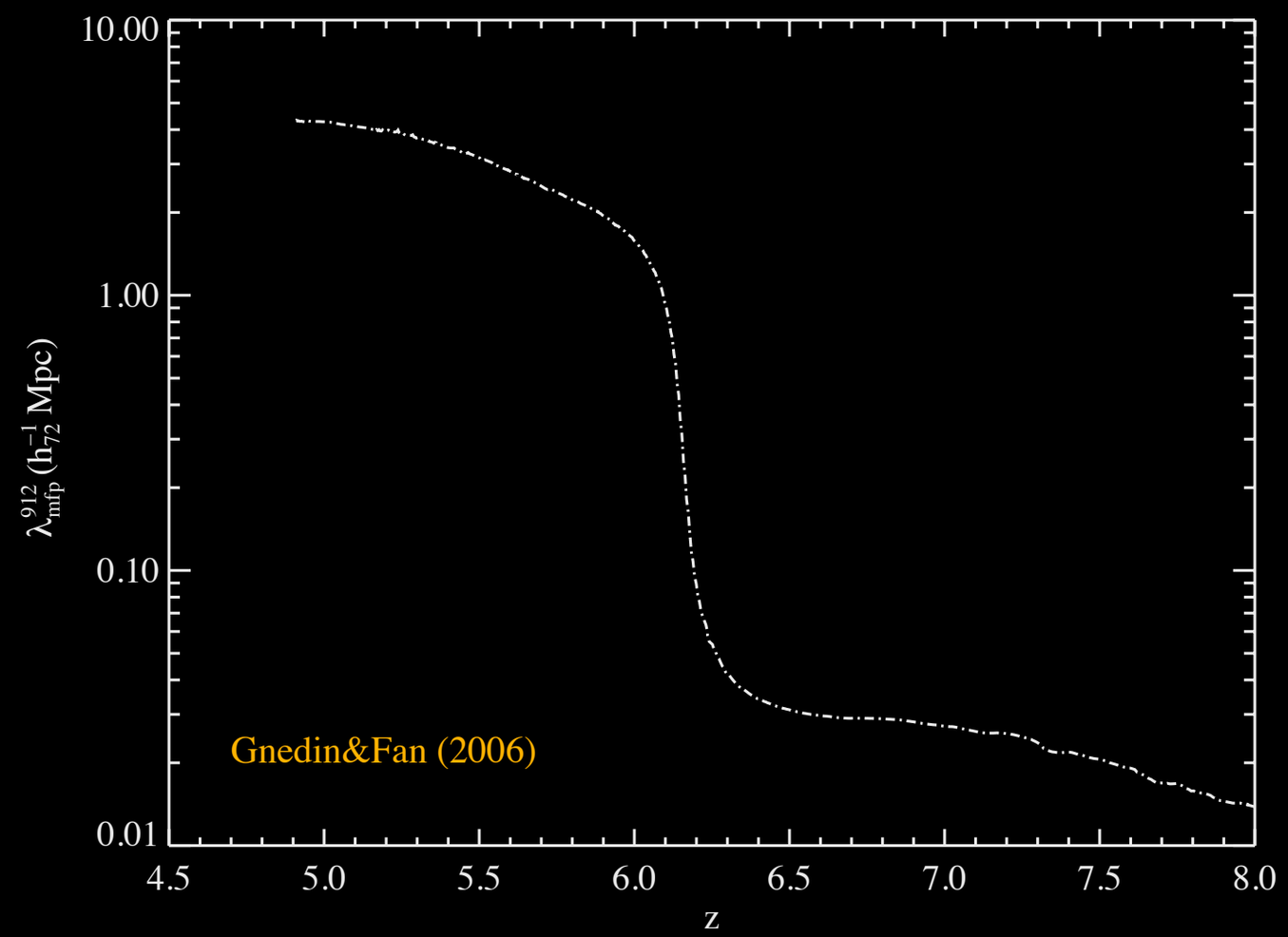
Reionization at z~6?

Becker+07

- Characterizing $\tau_{Ly\alpha}$
  - High-resolution observations
  - Assess the τ distribution
    - Log-normal is preferred
- Extrapolate this functional form to z>6
  - Good 'fit' to the observations
  - No requirement for a 'phase transition' indicating reionization

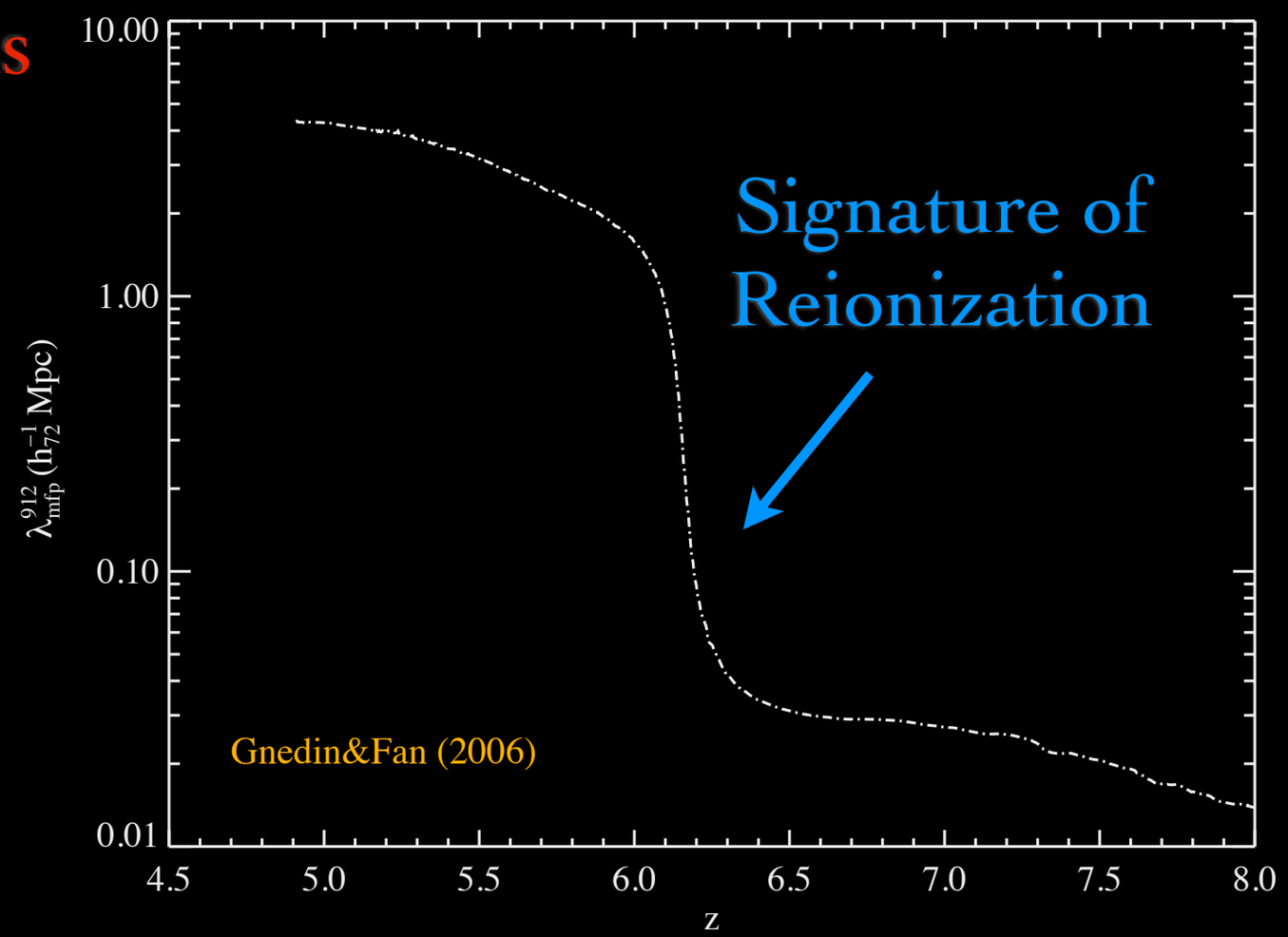


Defining Reionization



Defining Reionization

- Reionization is the complete absorption of ionizing photons
  - Mean free path (λ_{mfp}) must go to zero



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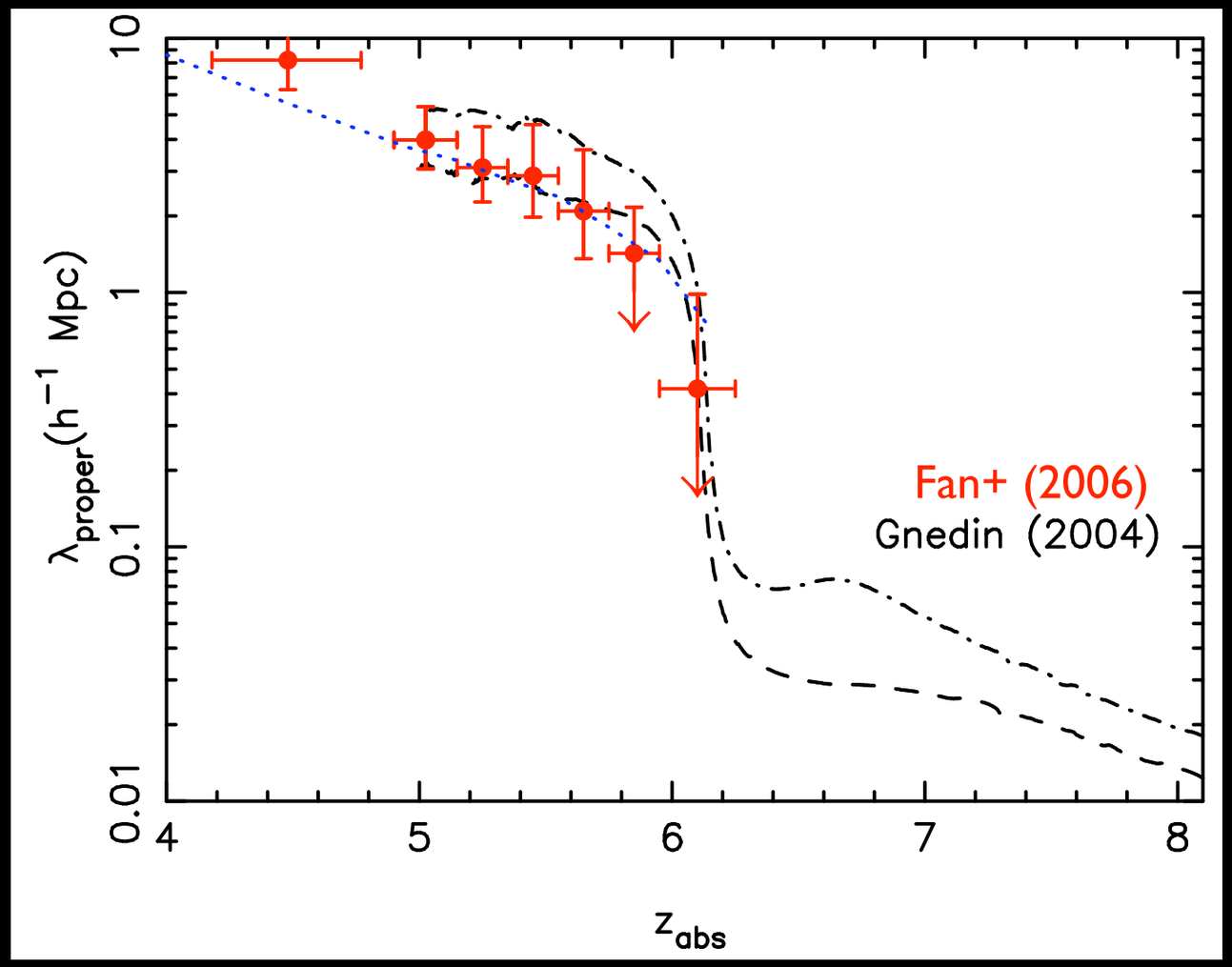

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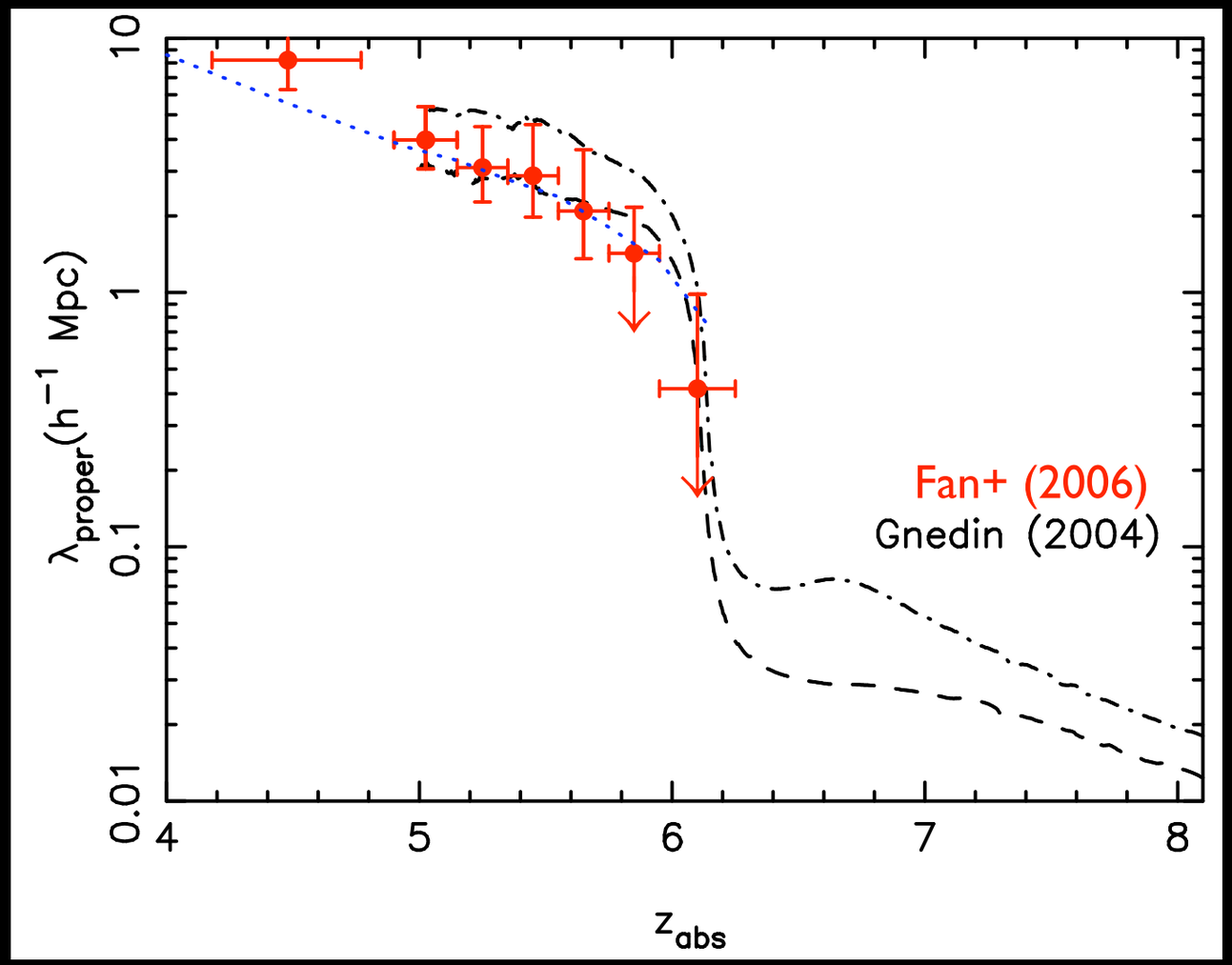
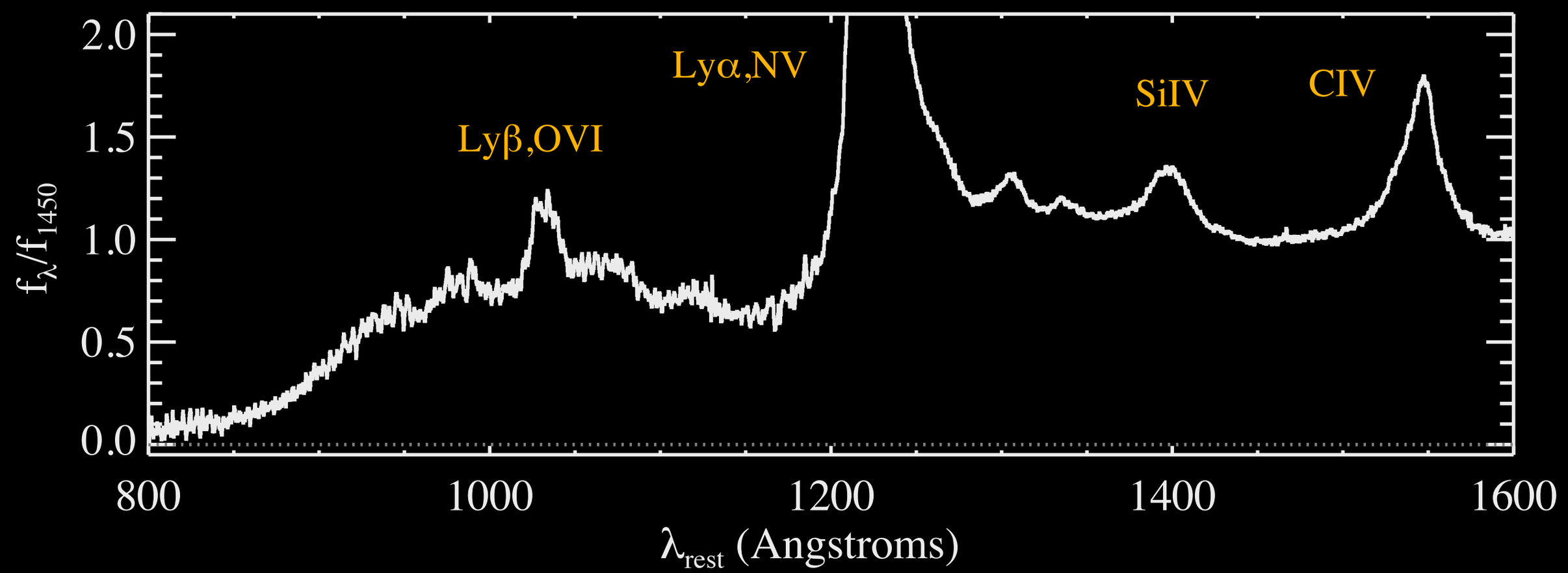


Maybe it is better to start at z<6...

State of the IGM at z~4



- IGM conditions
  - Highly ionized
  - T ~ 10^4 K
  - Partially (at least) enriched with metals
- Radiation field
  - Extragalactic UV Background (EUVB)
  - Sources
    - Quasars
    - Star-forming galaxies

Ionization Field (Rate) at z~4

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  - Combined UV radiation field from quasars+galaxies
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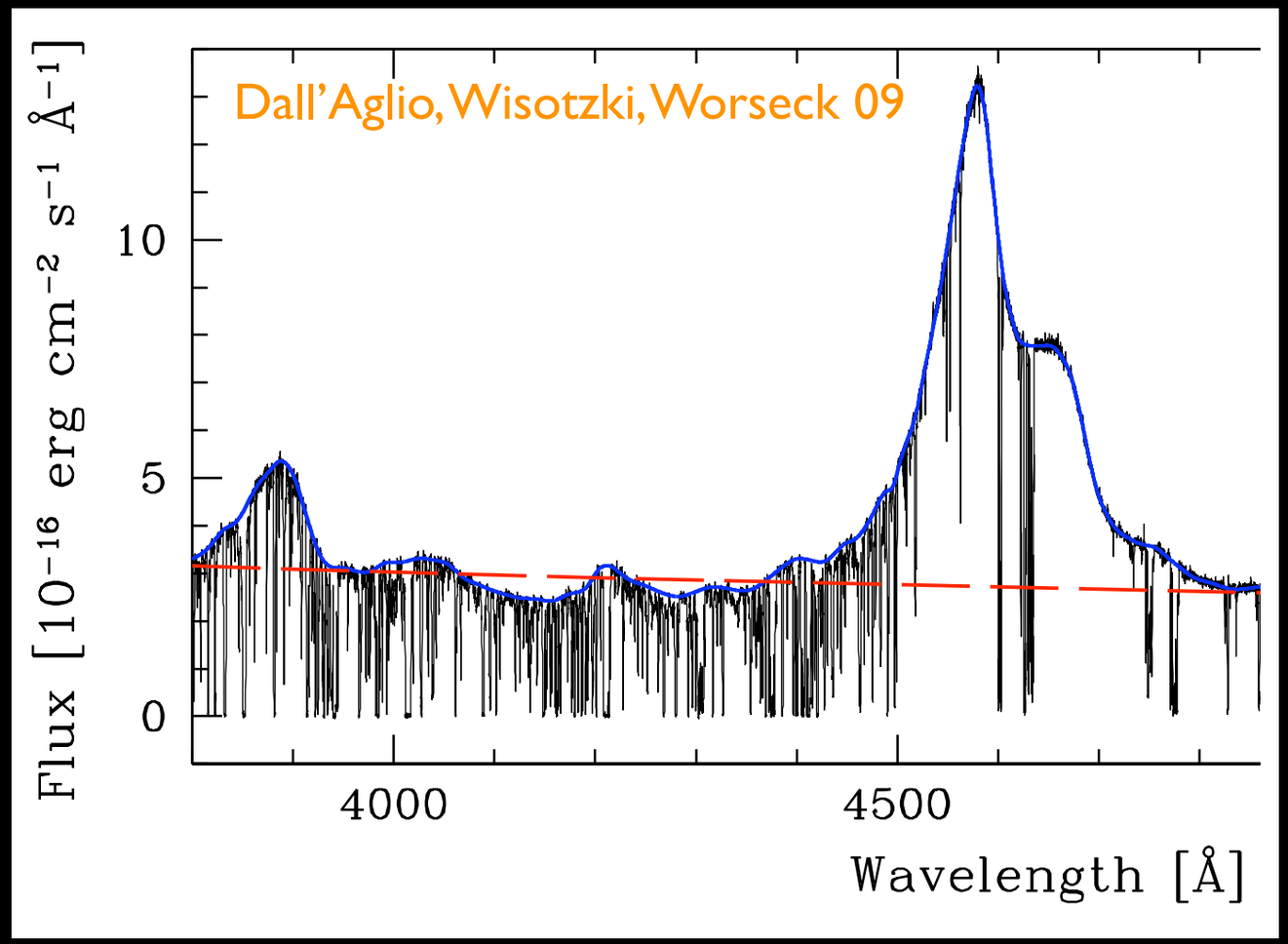

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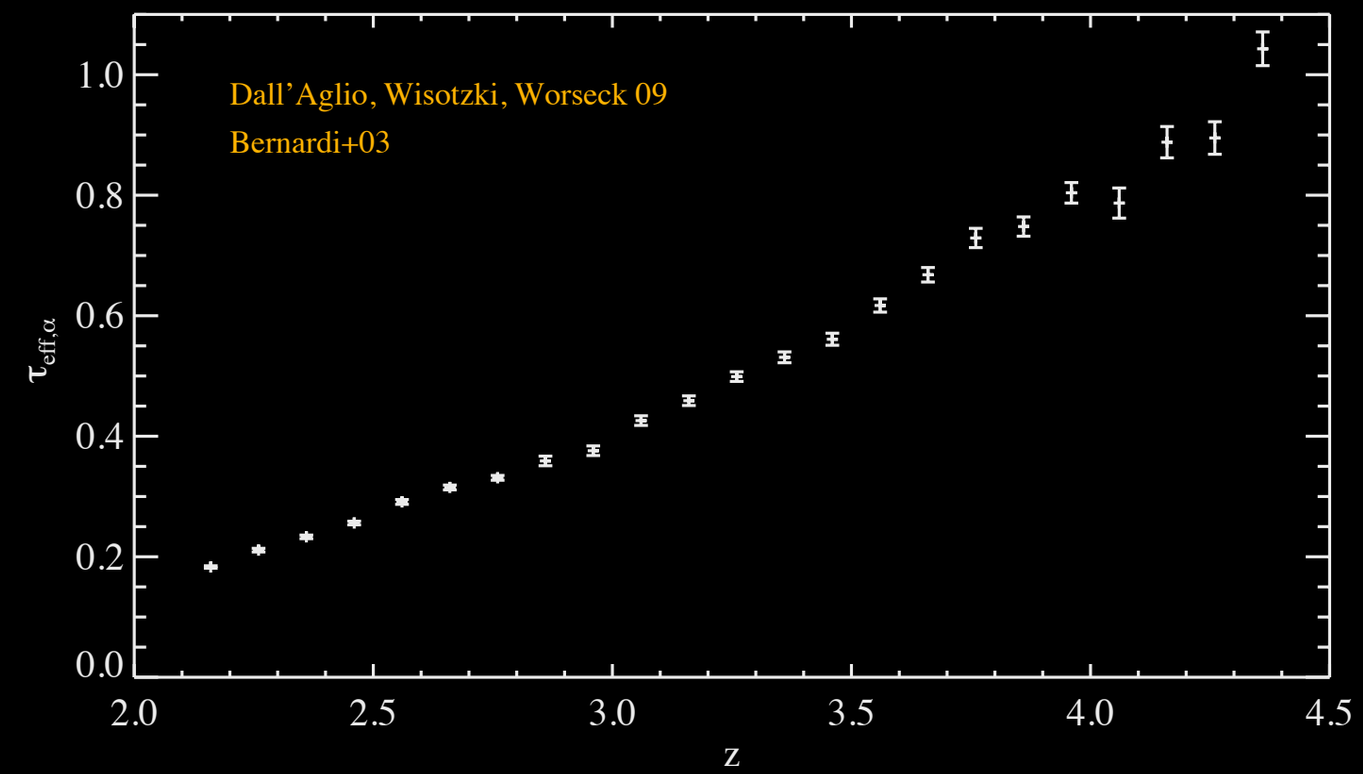
  - Compare to $\tau_{Ly\alpha}$



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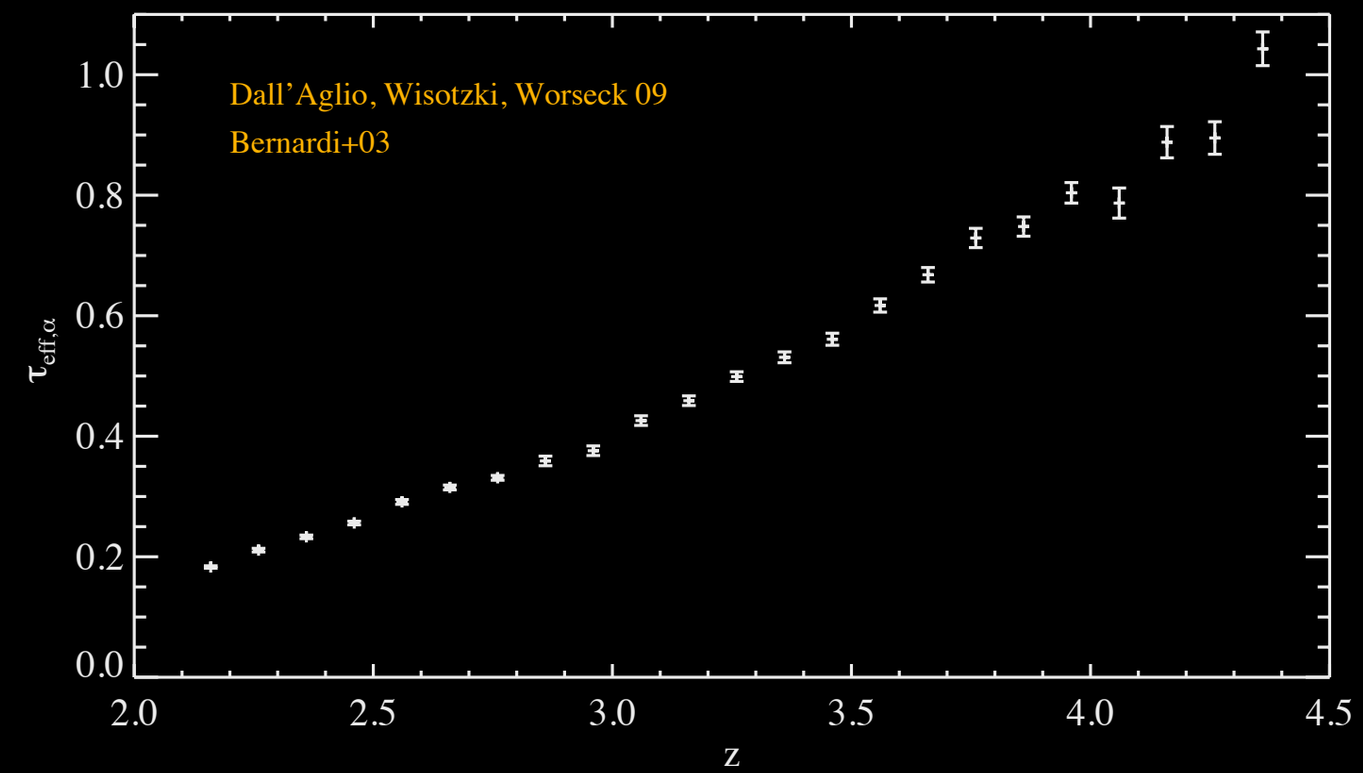
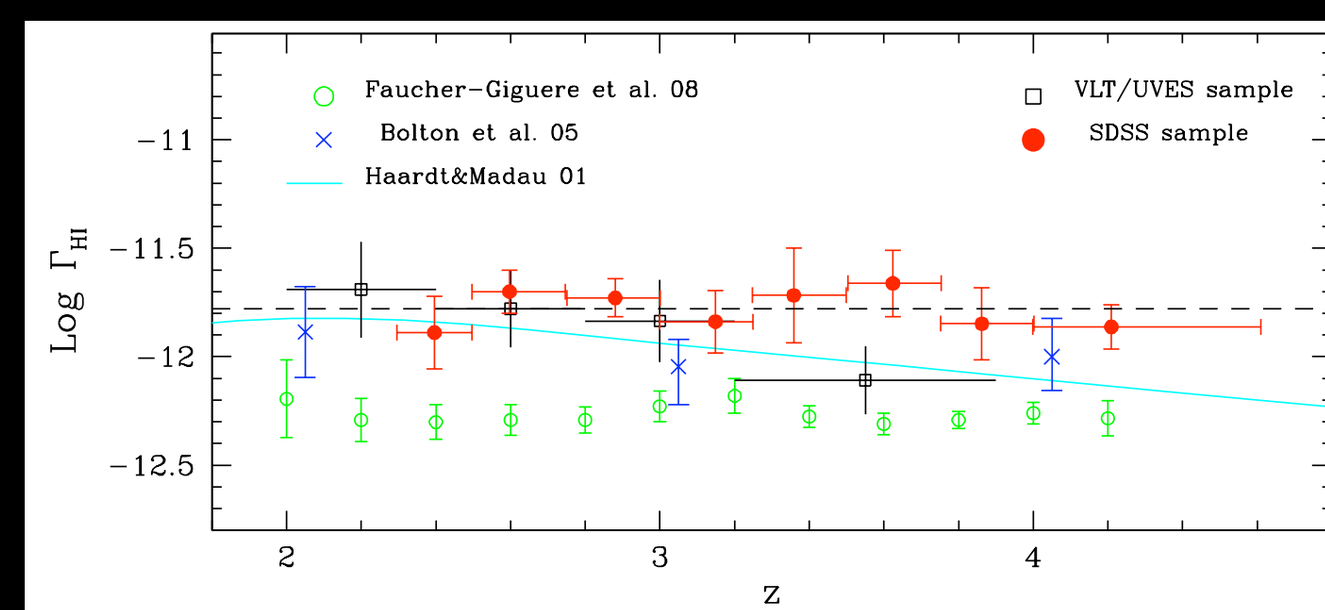
- Lyα opacity
  - Simulate Lyα forest
    - Inputs: Ω_b+cosmology+T
  - Compare to $\tau_{Ly\alpha}$
- Answer: $\Gamma_{912} \sim 10^{-12}\ s^{-1}$
  - Roughly constant with z?
  - Dispersion of ~5 in normalization



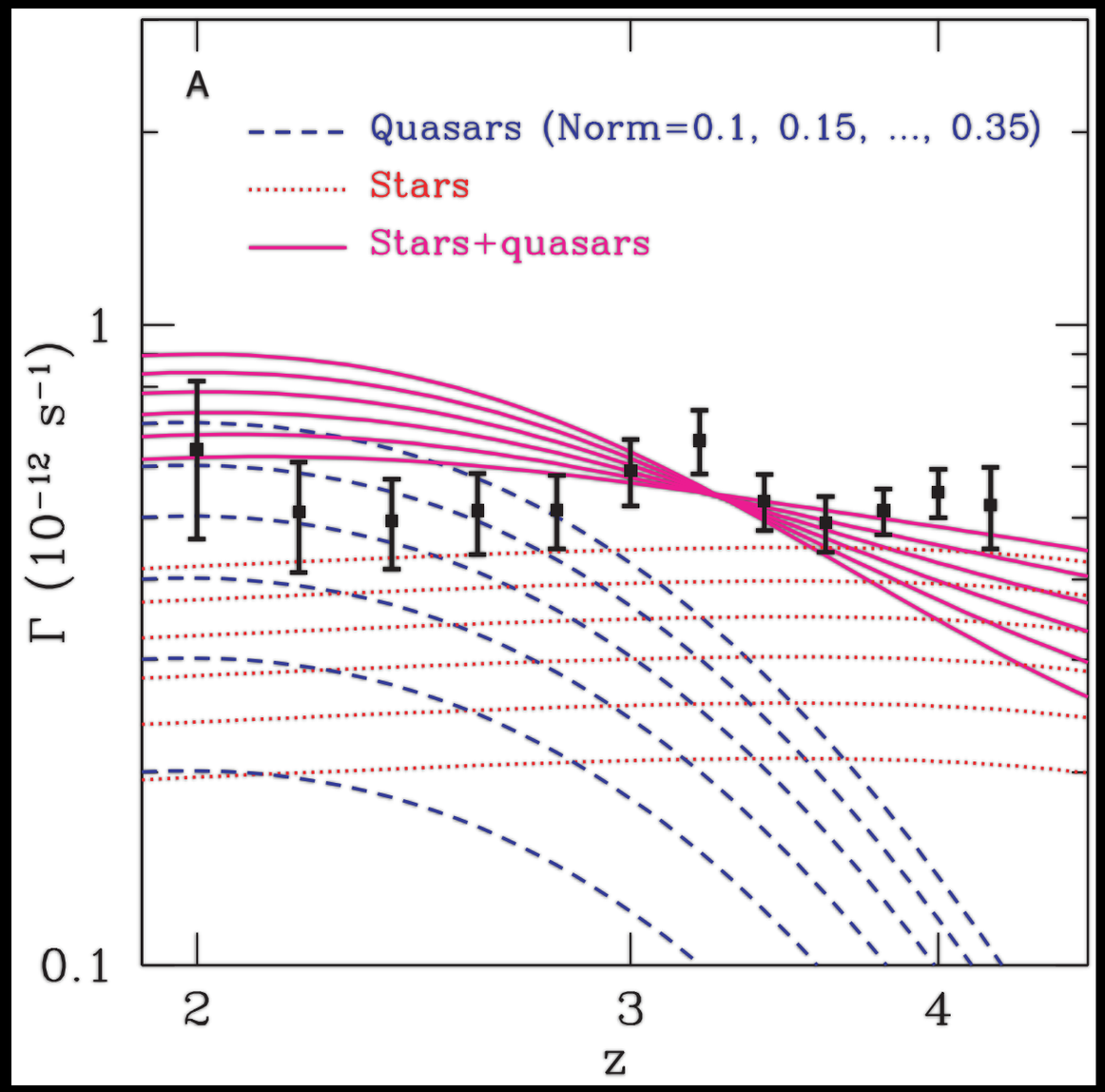


Can Quasars Ionize the IGM at z~4?

- **Observation**
  - Ionization rate (~10^{-12} s^{-1})
  - Luminosity function of quasars
    - Bright-end, primarily, at z>3
    - Estimate of the quasar emissivity ε_q
  - Quasar SED (α_{HI})
- **Missing piece: λ_{mfp}**
  - Mean free path

$$\Gamma_q \approx \frac{\sigma_{\rm HI}\lambda_{\rm mfp}\epsilon_q}{h(\alpha_{\rm HI}+3)}$$

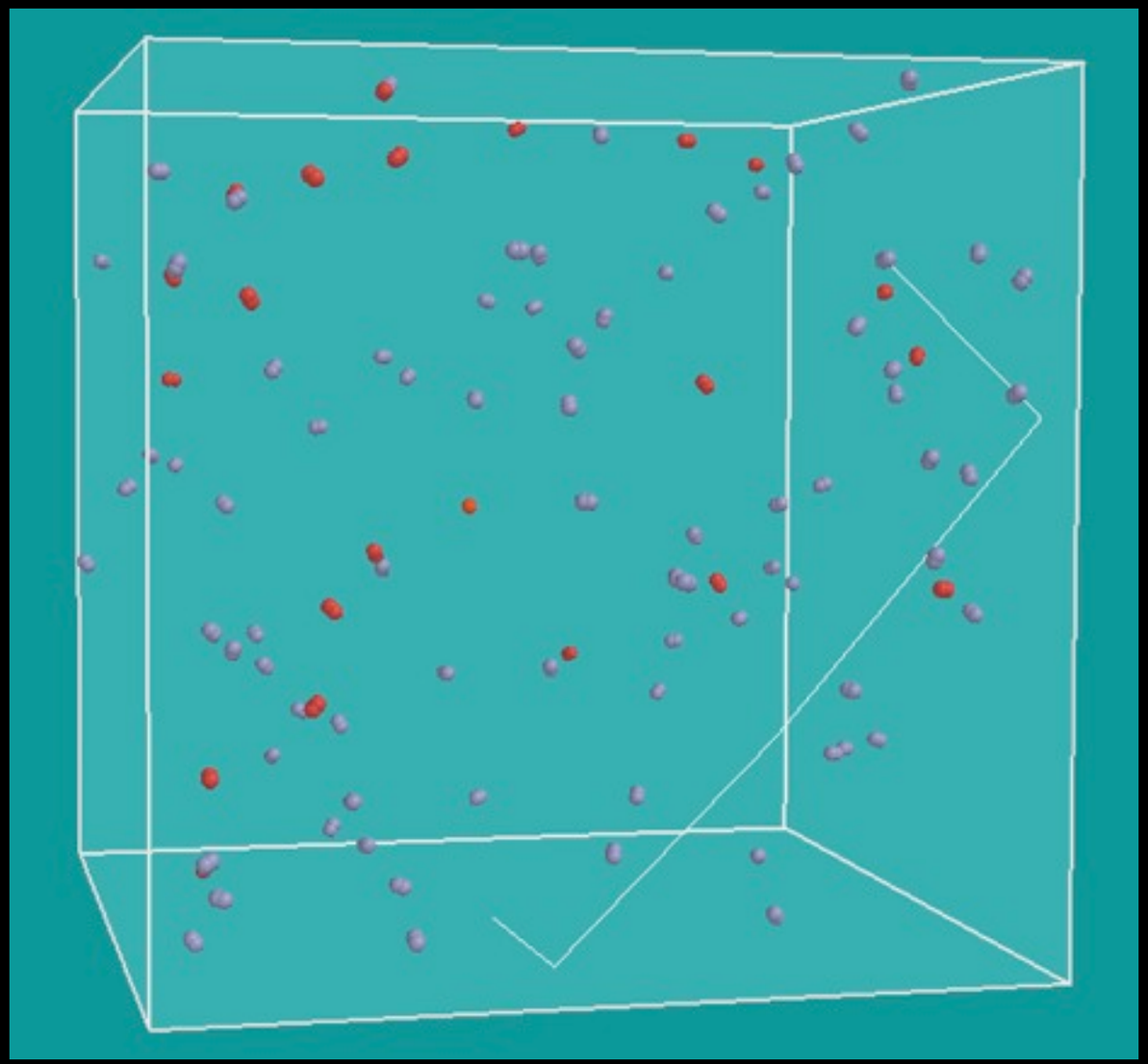
- **Best guess**
  - Quasars are sub-dominant at z>4
  - Highly uncertain conclusion...



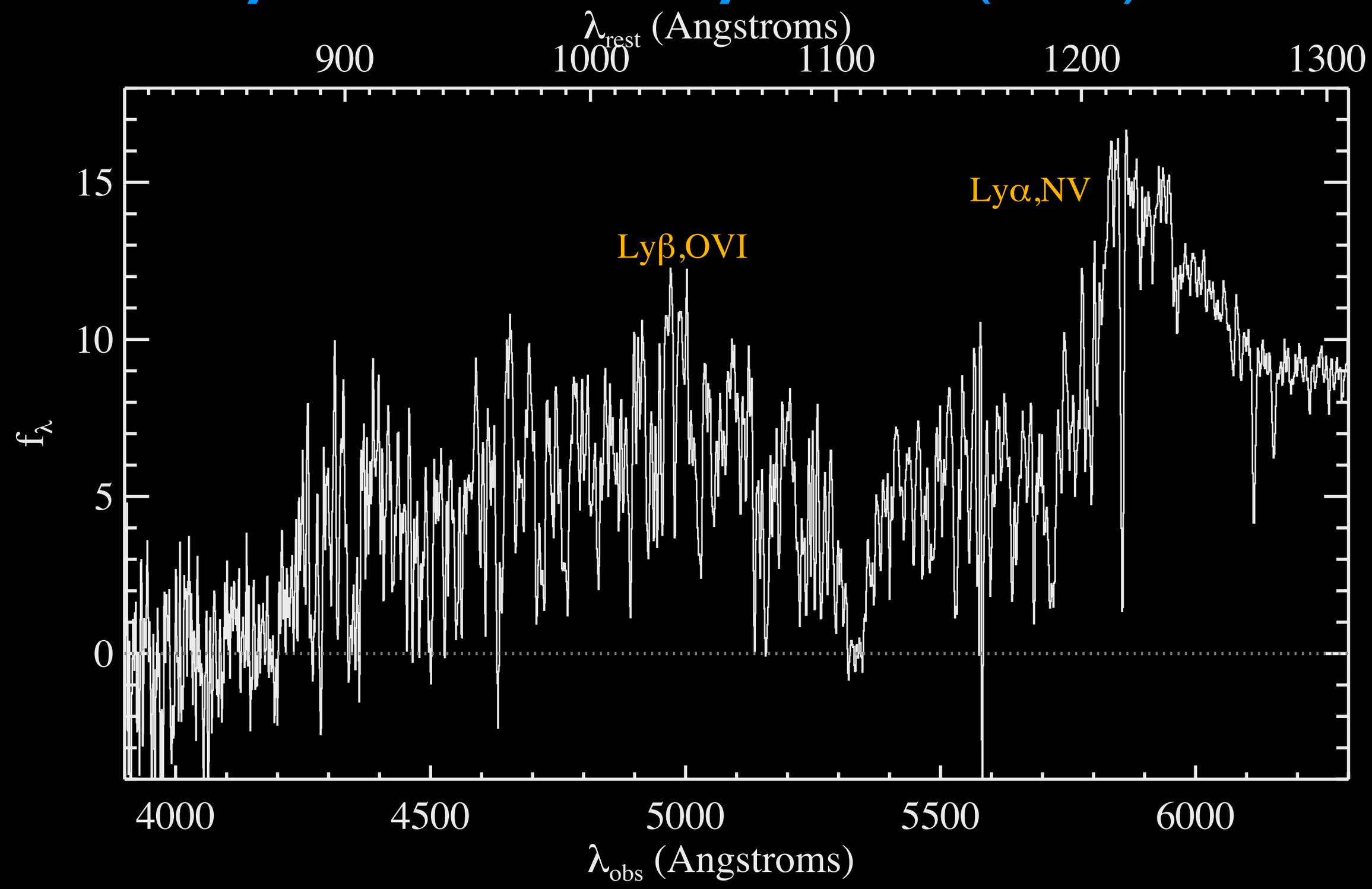
Faucher-Giguerre+09
Miralda-Escude 03
Meisksin & White 04
Dall'Algio, Wisotzki, Worseck 09

Mean Free Path (λ_{mfp}): Definition

- Definition
  - Average distance that a packet of ionizing photons travels before experiencing an e^{-1} attenuation
  - Proper distance (Mpc)
- Sources of Opacity
  - Galaxies
    - Damped Lyα systems
  - IGM
    - Lyα forest
    - Lyman limit systems



Lyman Limit System (LLS)



Significant (τ>1) absorption at the Lyman Limit (1Ryd = 912A)

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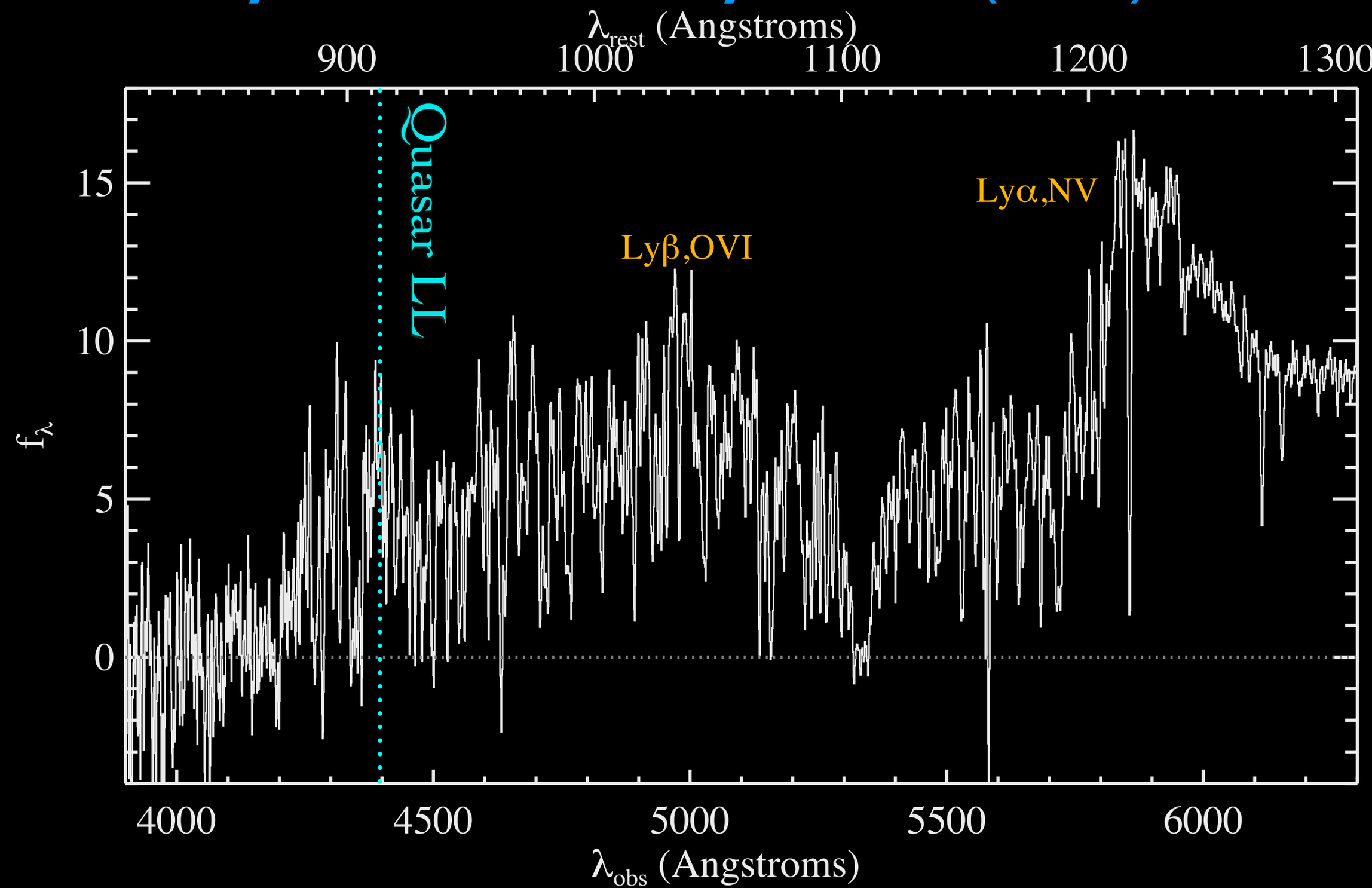

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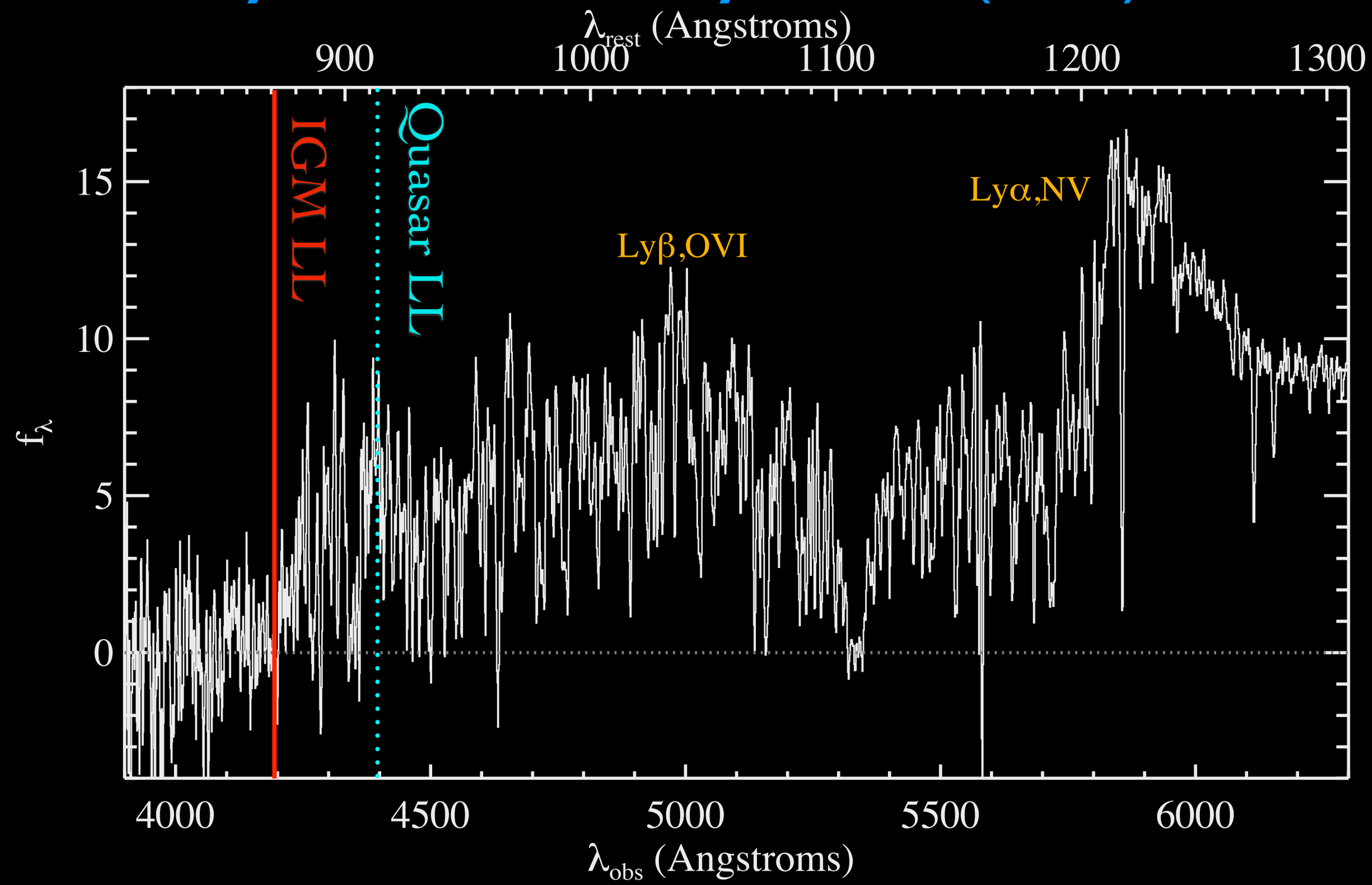

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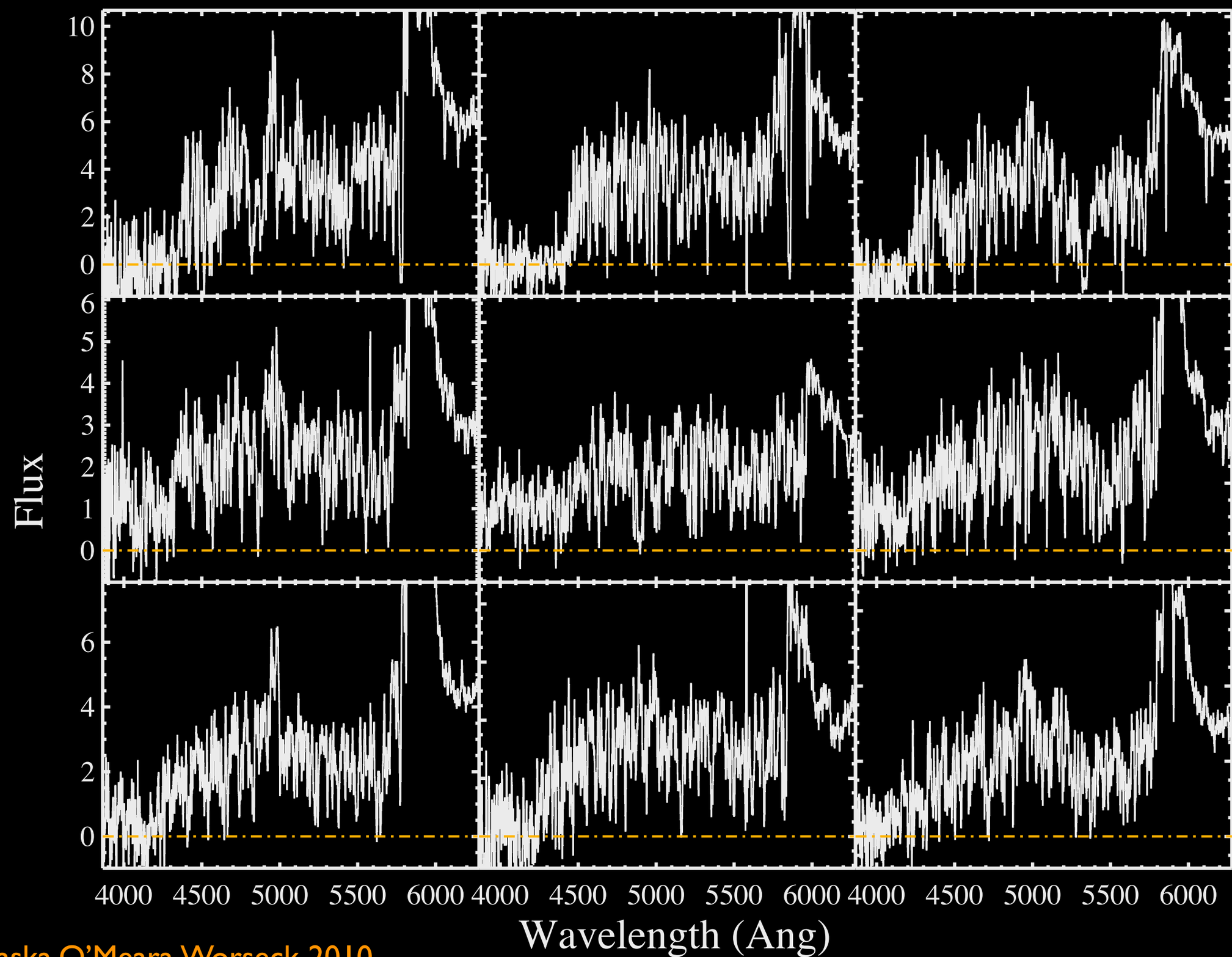
Performing an LLS Survey



Prochaska,O'Meara,Worseck 2010

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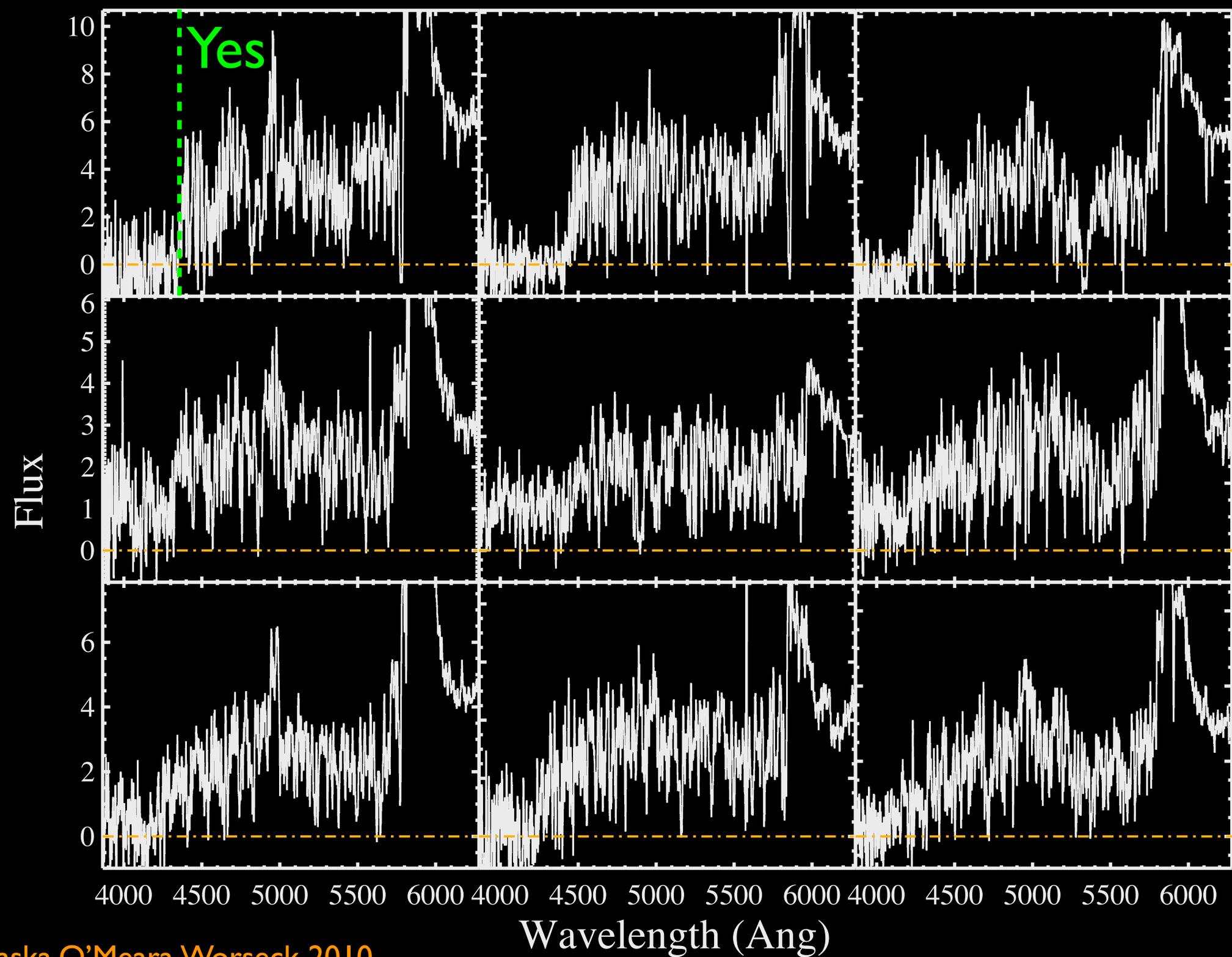

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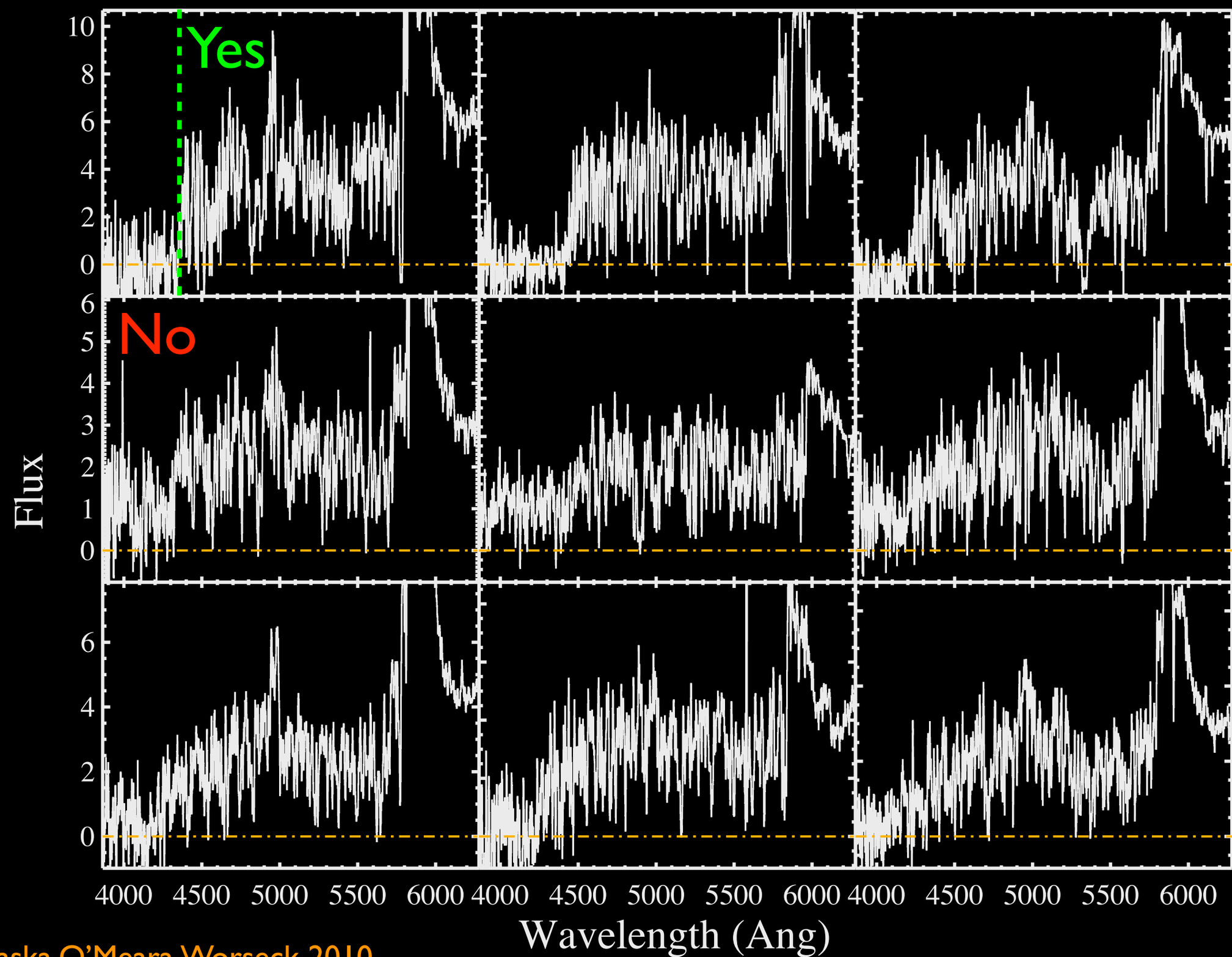

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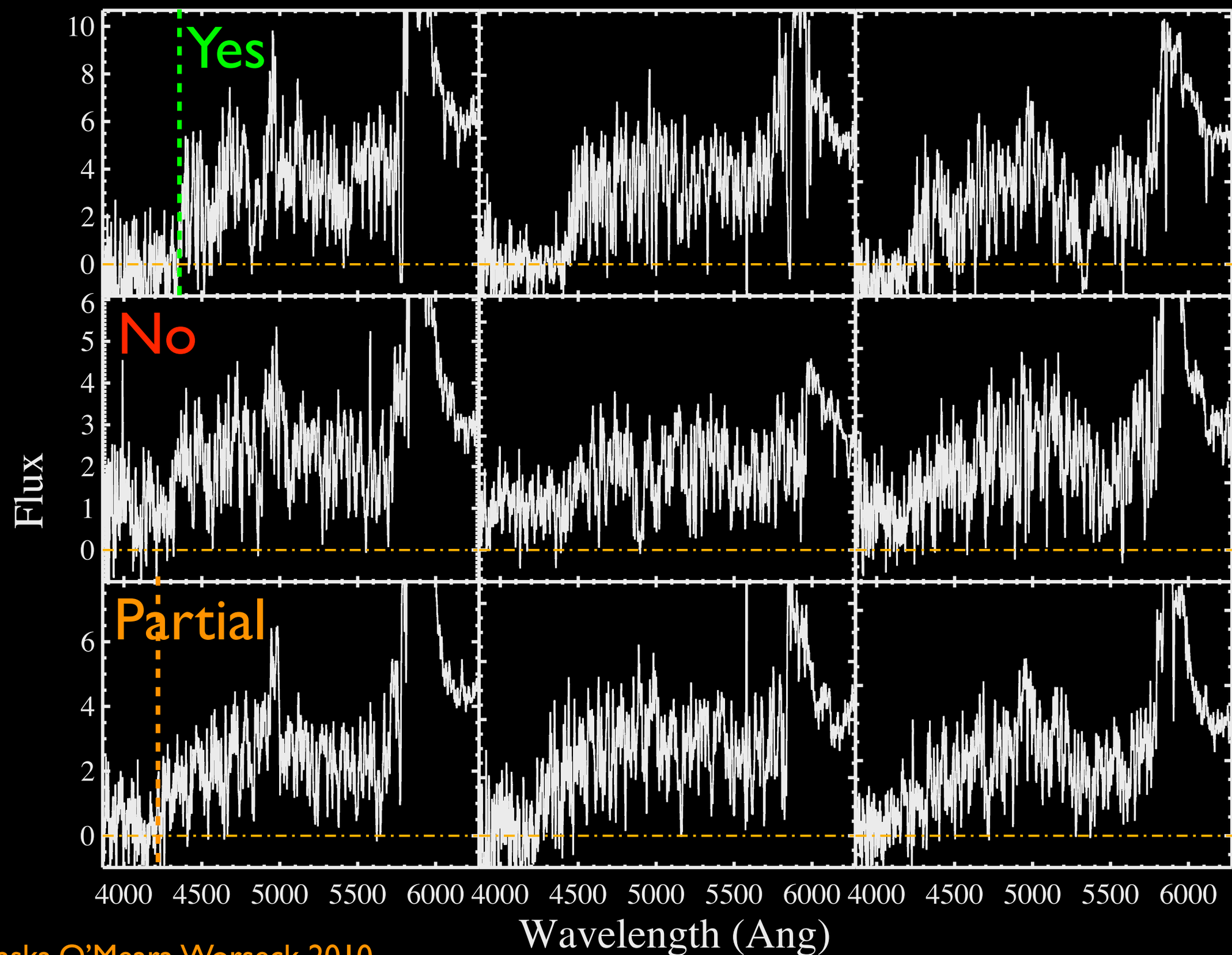

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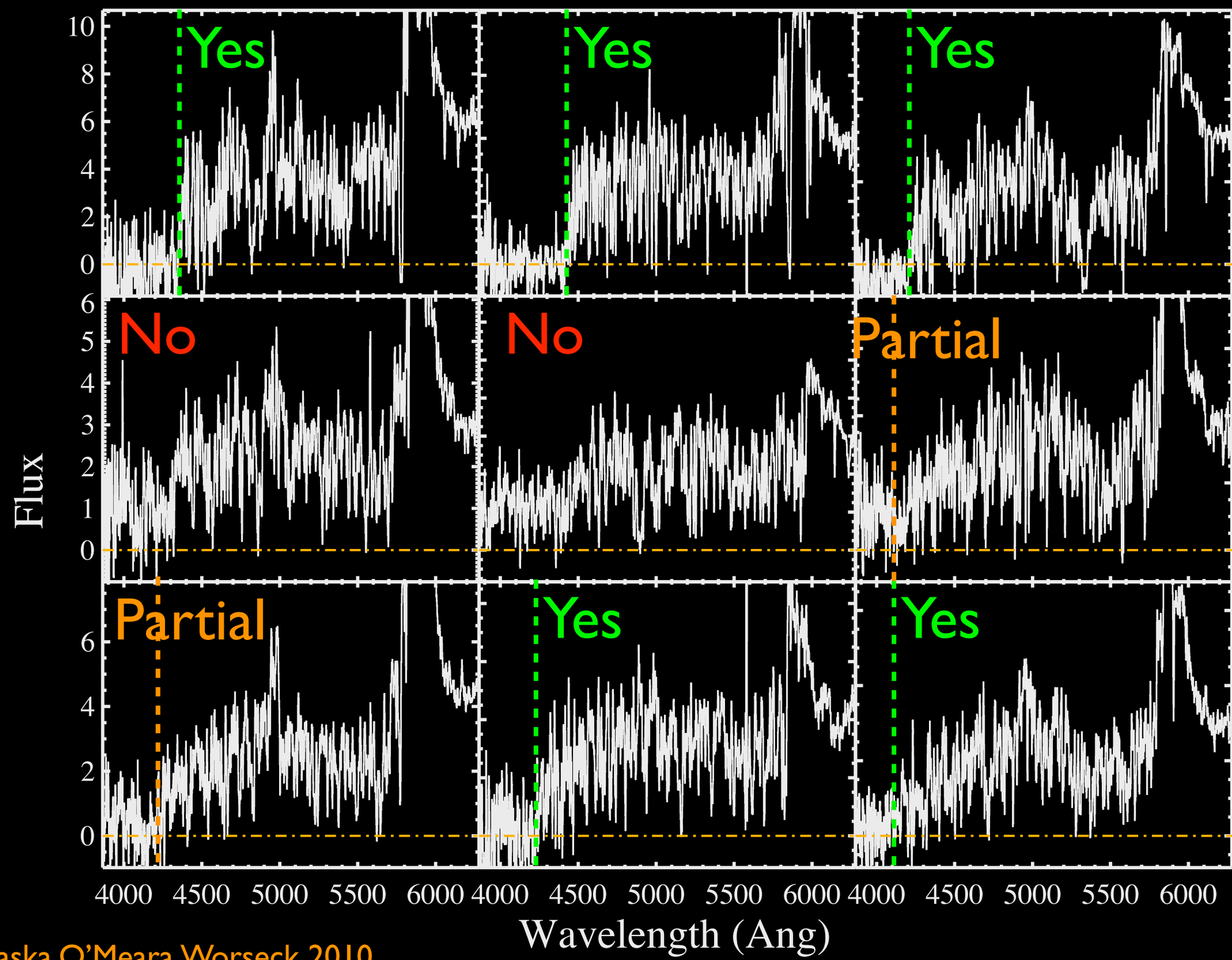
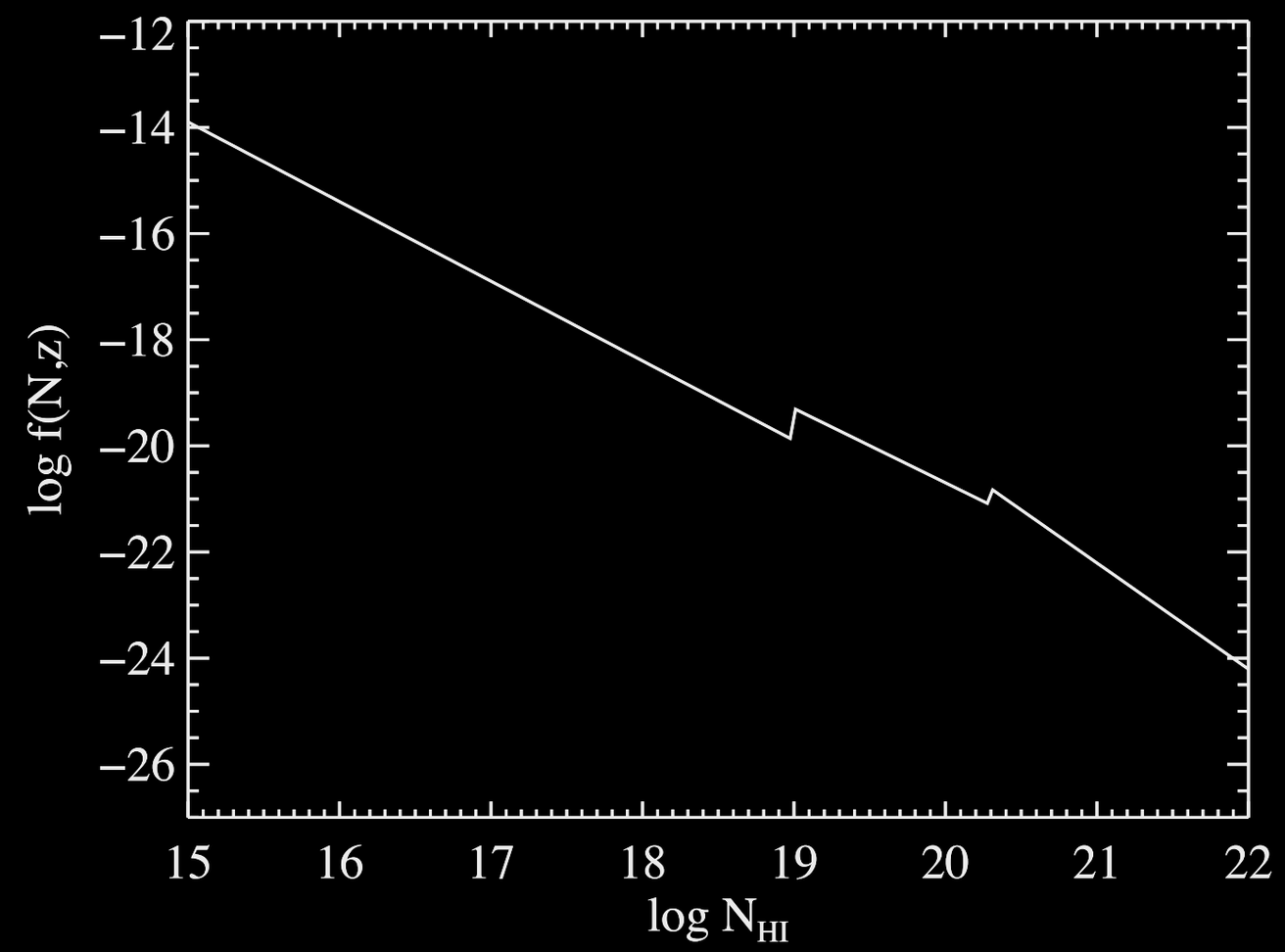


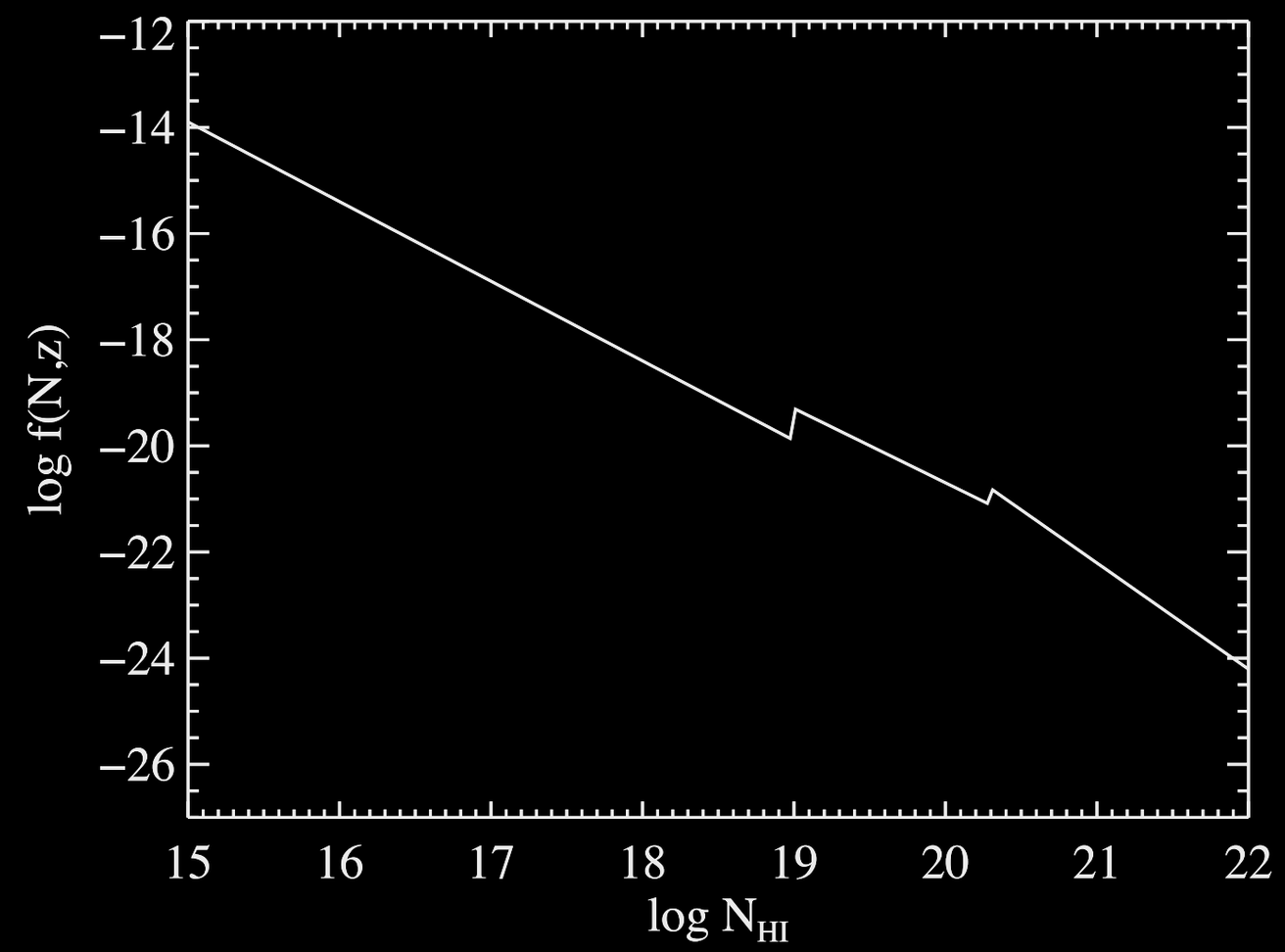
Prochaska, O'Meara, Worseck 2010

λ_{mfp}: The Traditional Approach



λ_{mfp}: The Traditional Approach

- $f(N_{HI})$
  - Frequency distribution of N_{HI} values for IGM 'absorbers'
    - Analogous to a luminosity function
  - Observations: Simple counting



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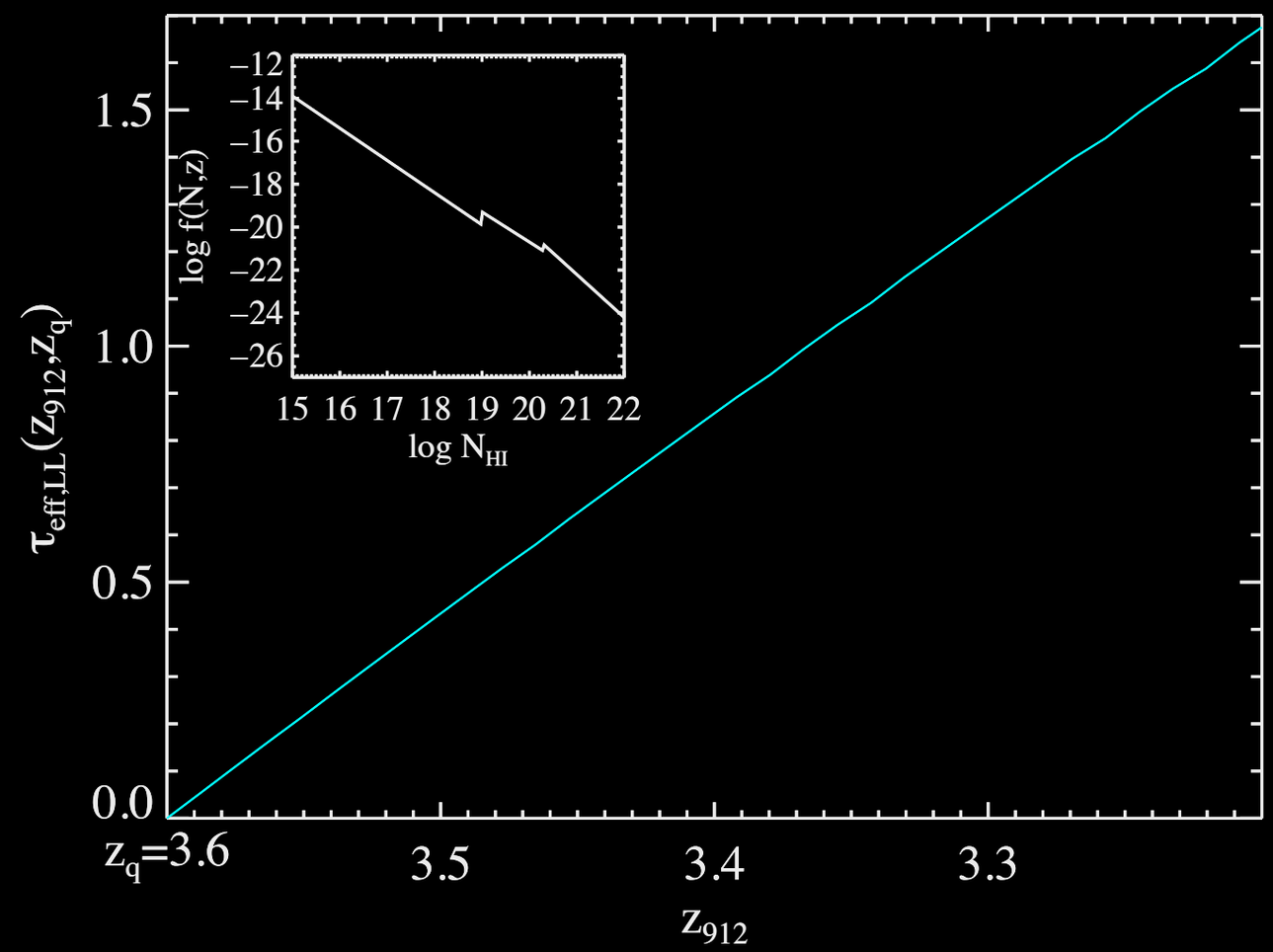
    - From the quasar (z_q) to a lower redshift



$$\tau_{\rm eff,LL}(z_{912}, z_q) = \int_{z_{912}}^{z_q} \int_0^{\infty} f(N_{\rm HI}, z')\{1 - \exp[-N_{\rm HI}\sigma_{\rm ph}(z')]\} dN_{\rm HI} dz'$$

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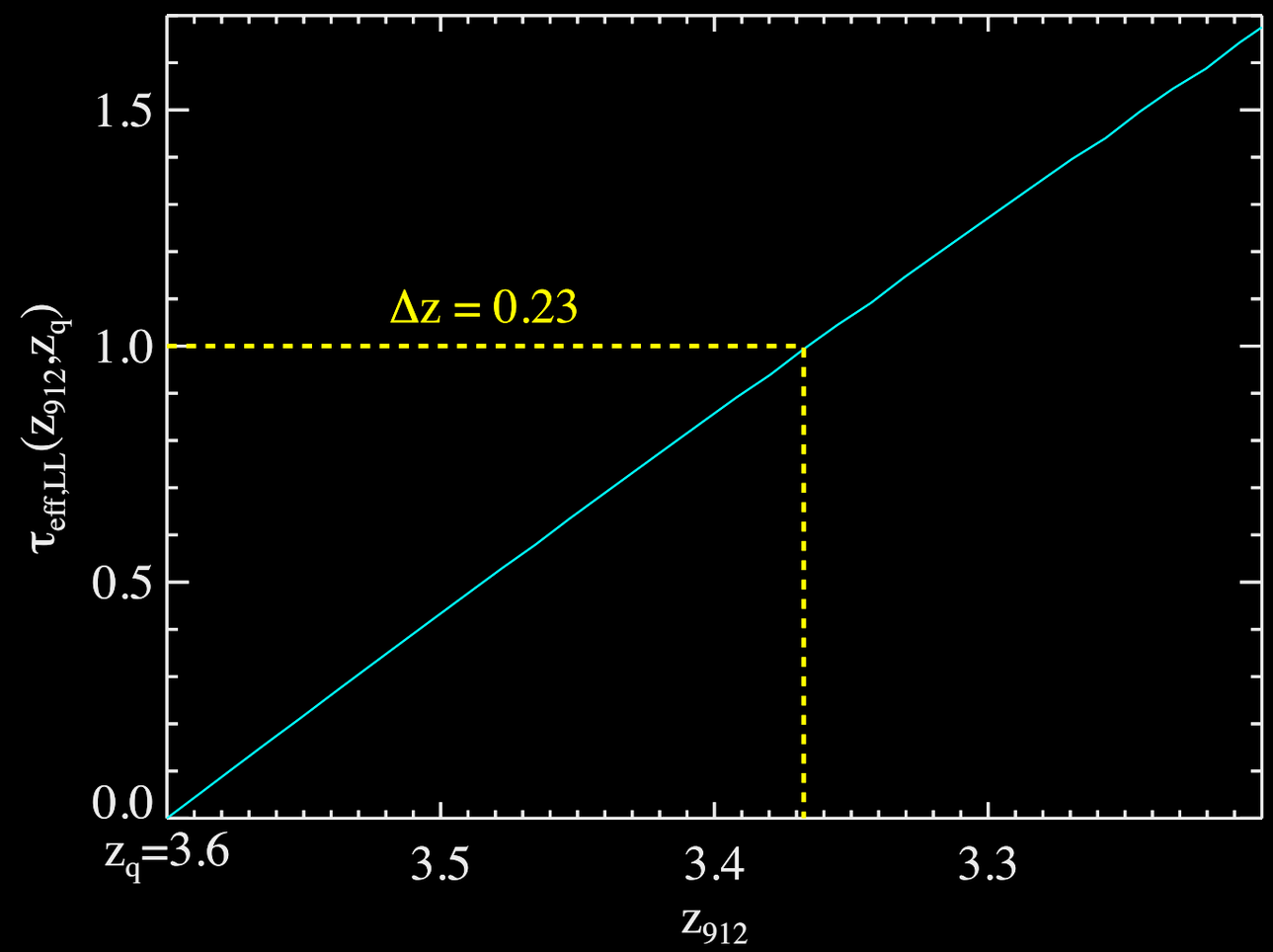

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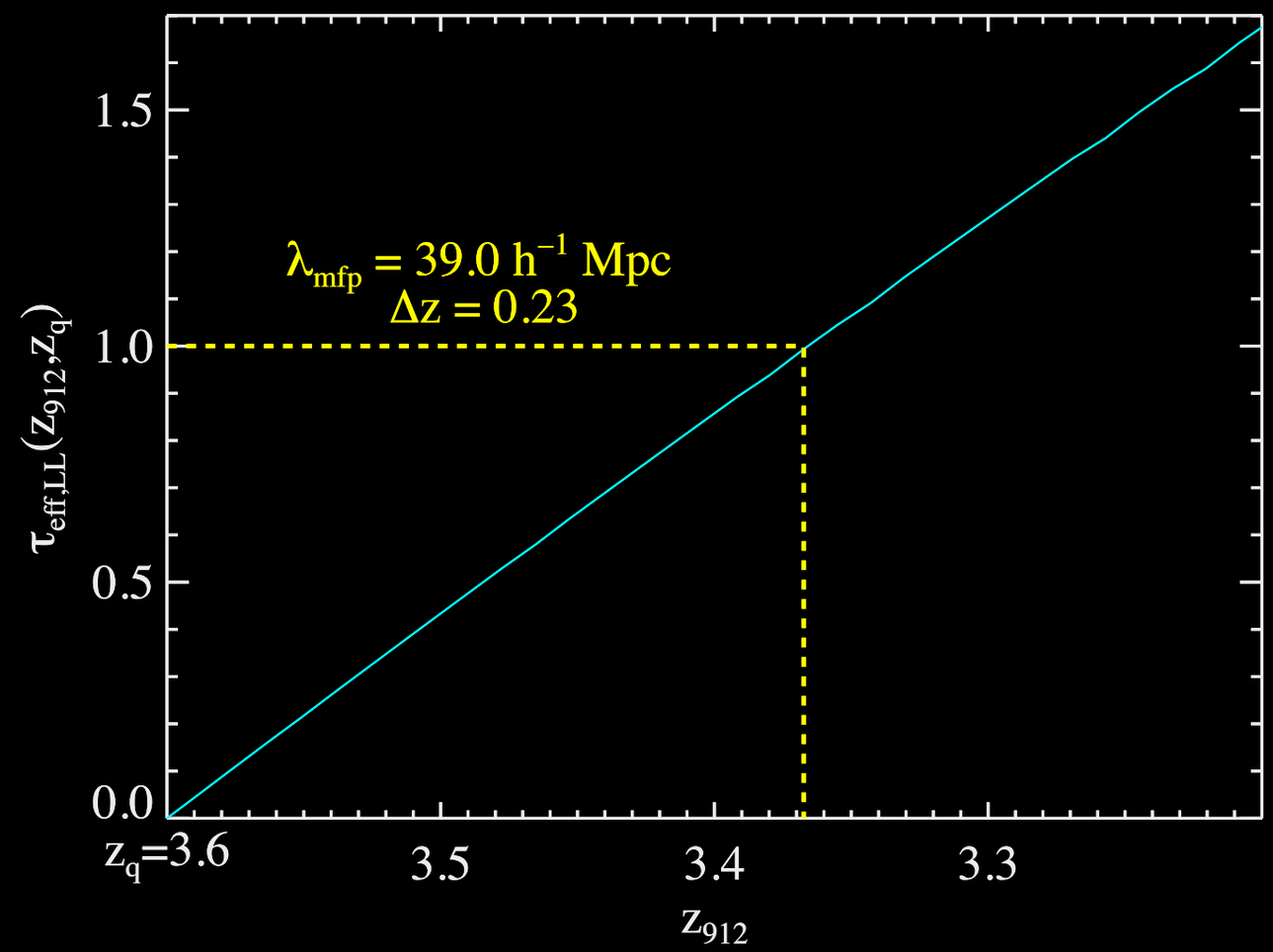

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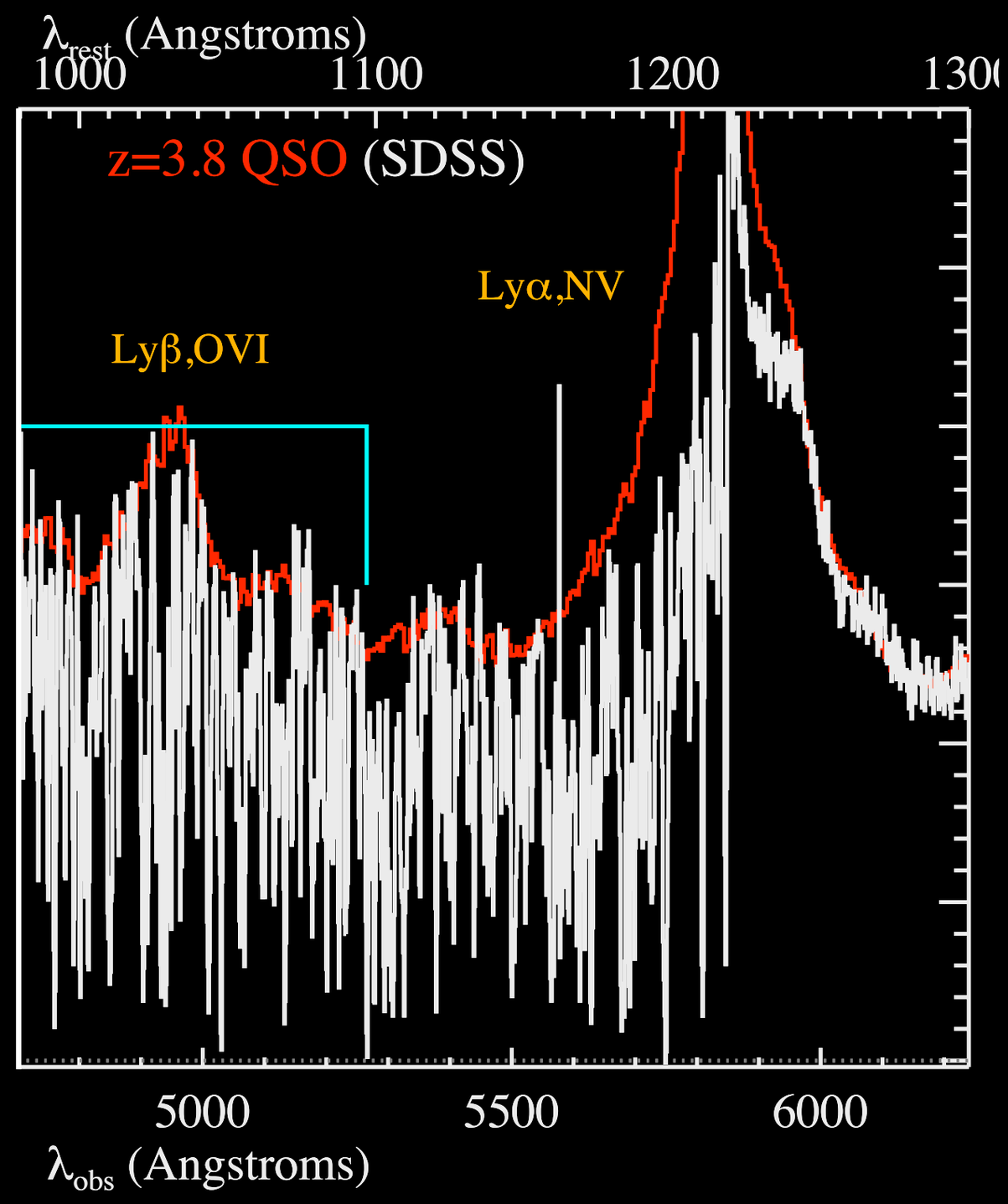
$$\lambda_{\rm mfp} \approx \Delta z \frac{dr}{dz}$$

Evaluating f(N)



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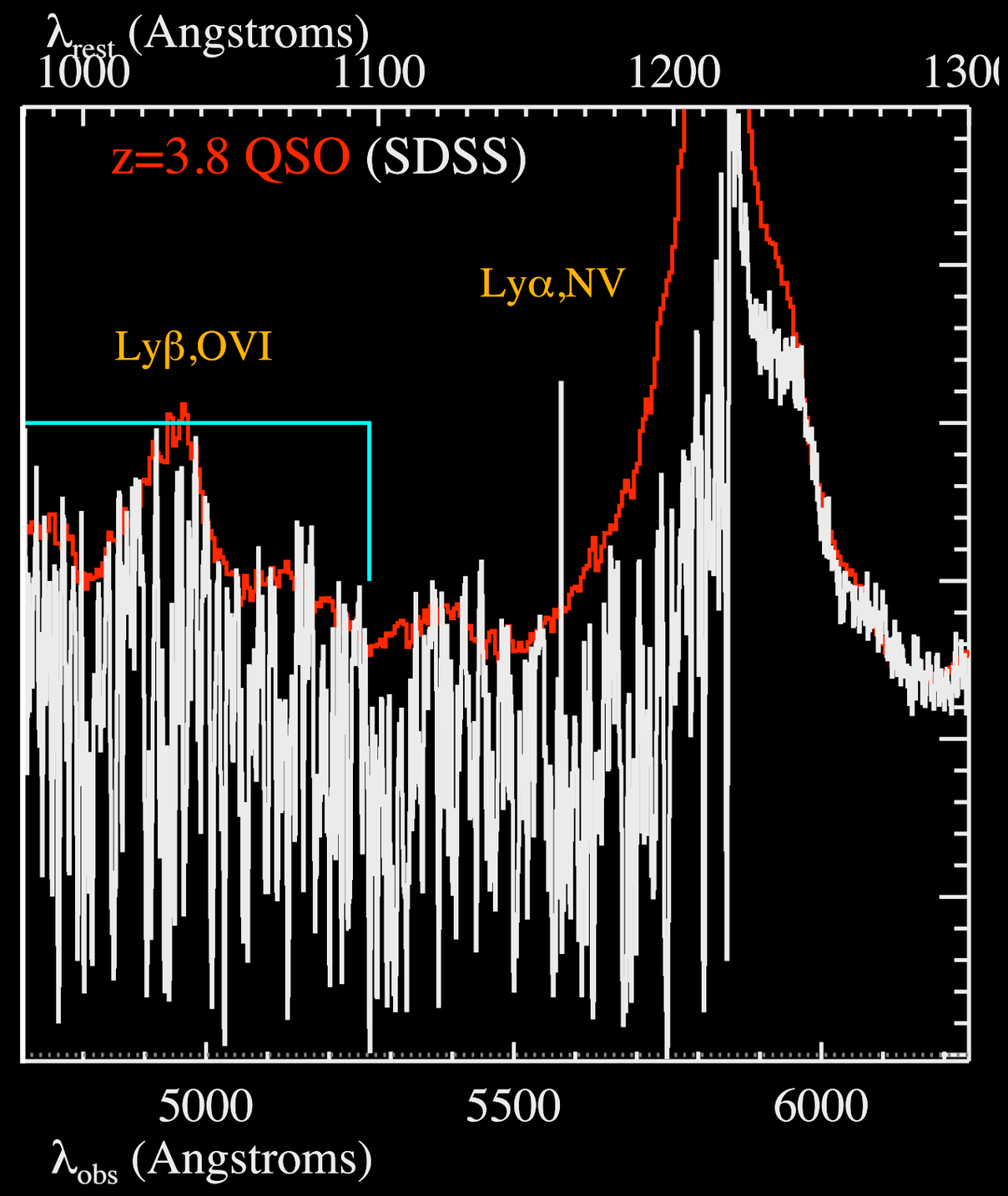

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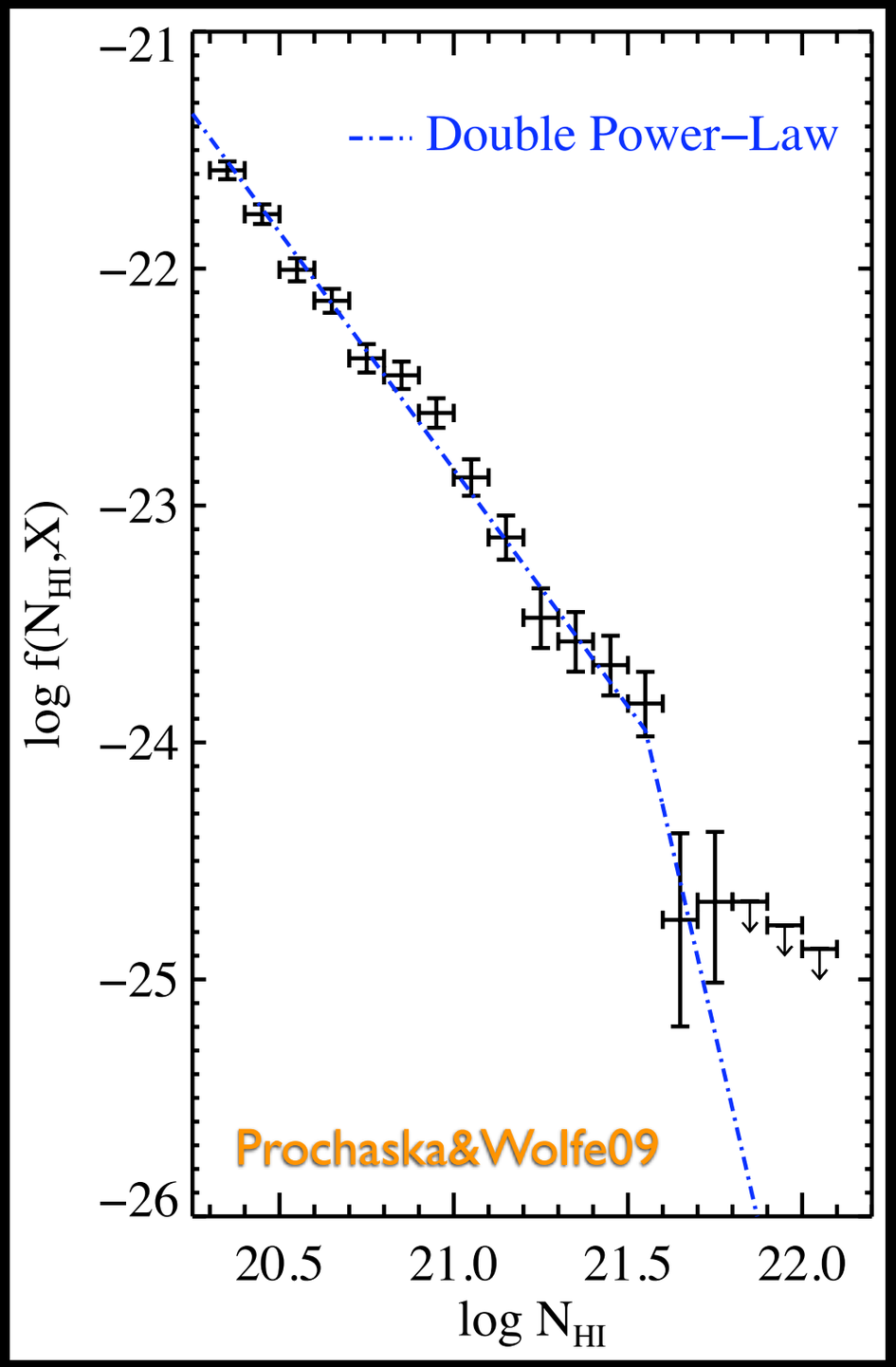

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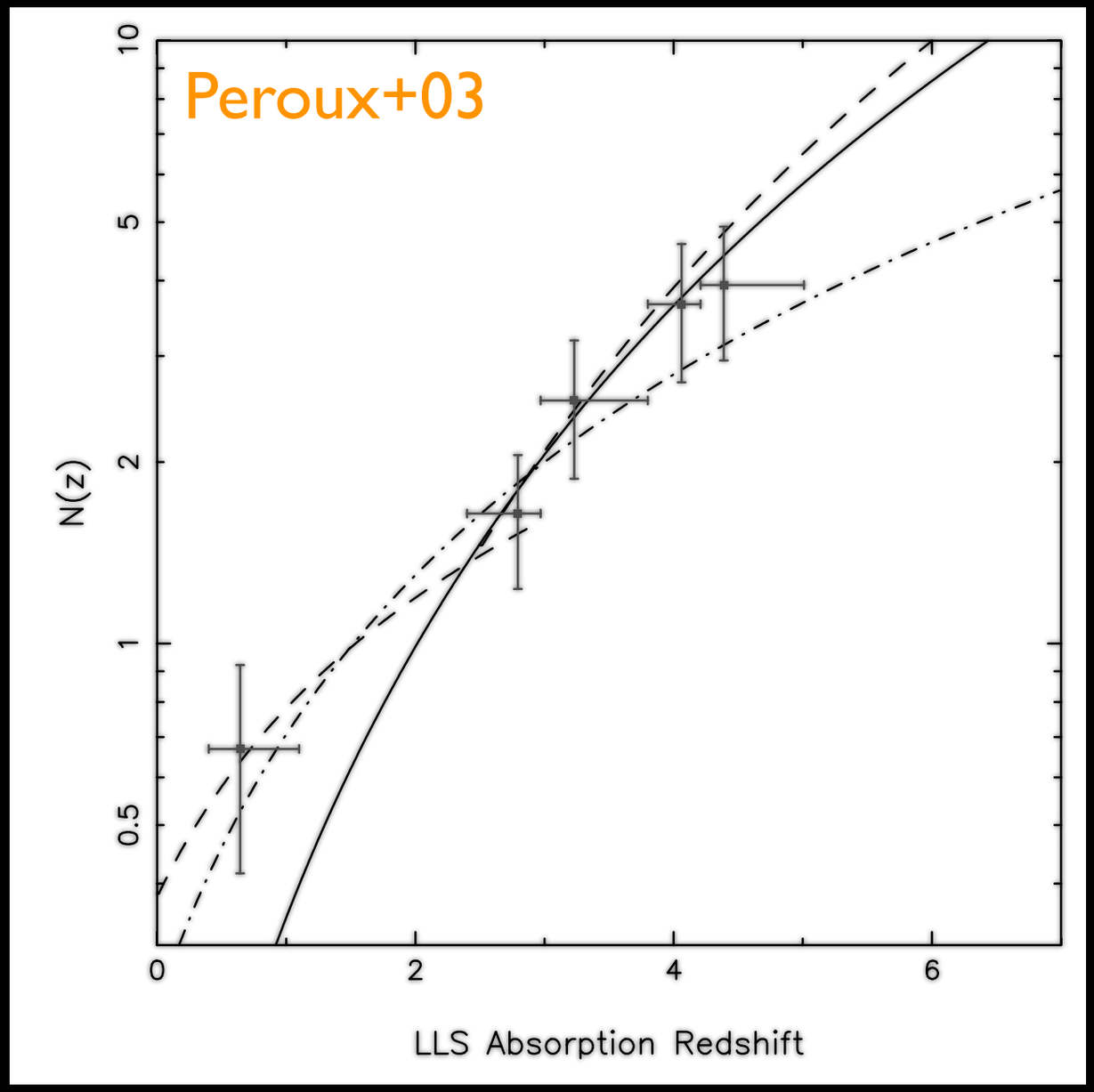

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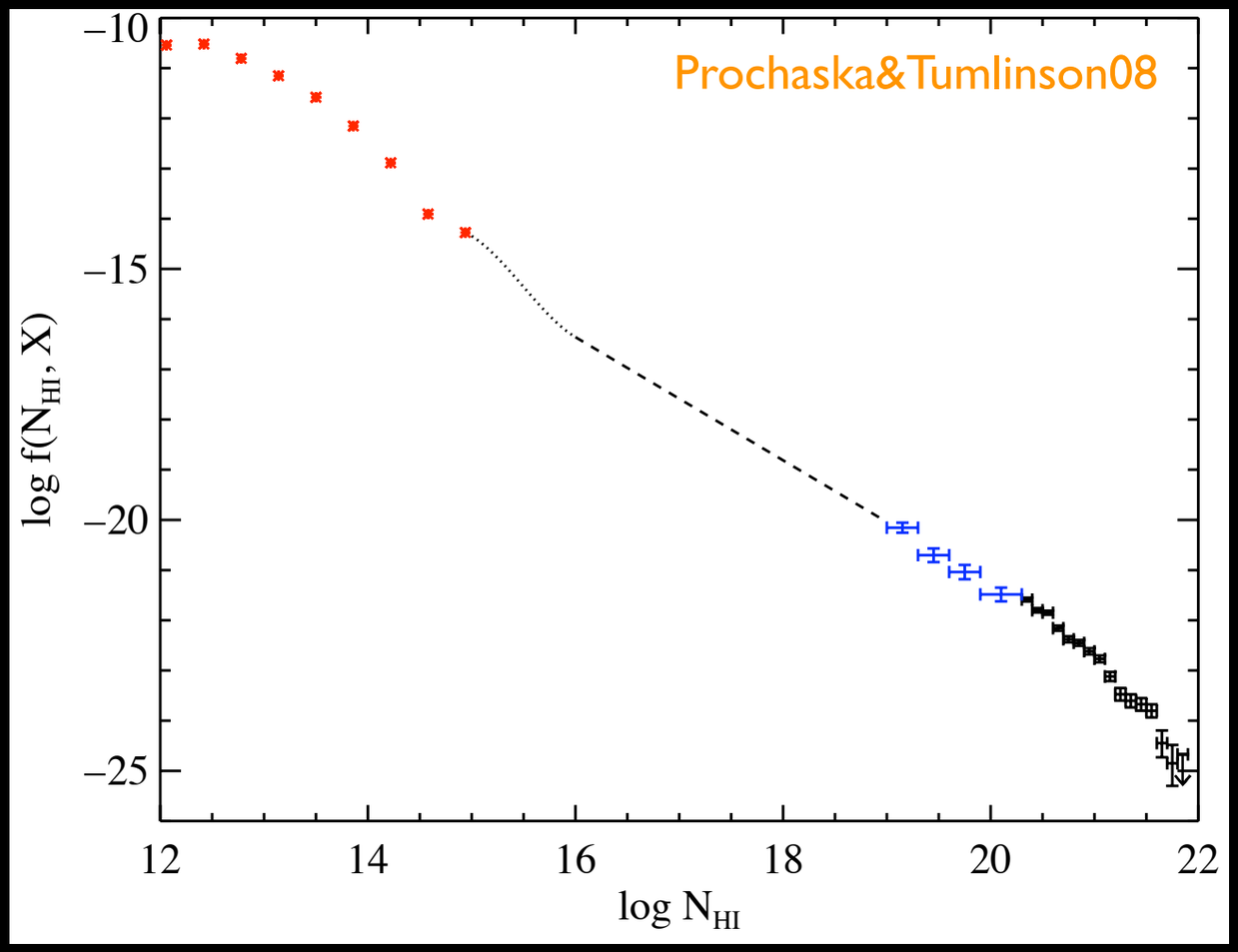
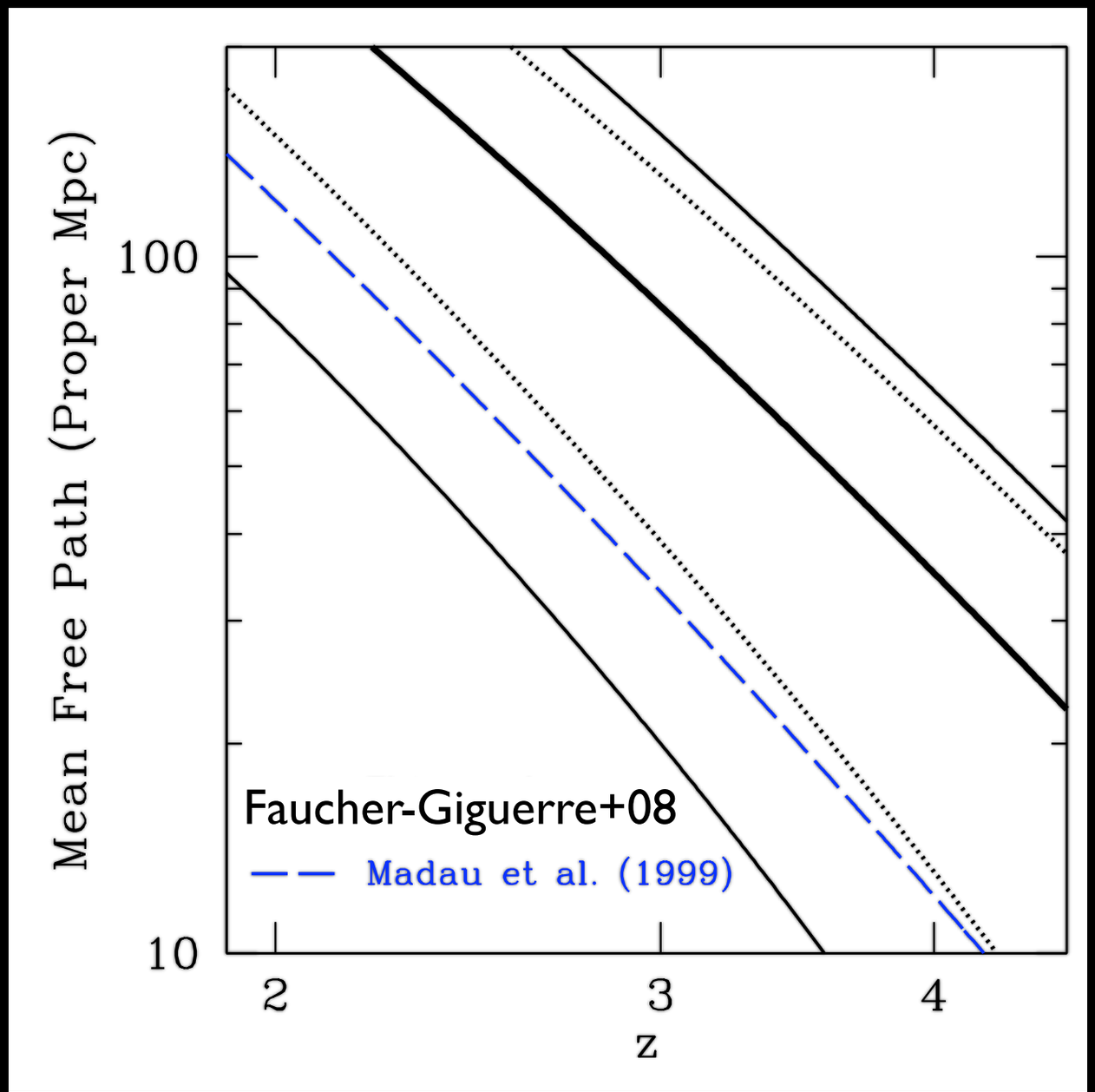
- $15 > \log N_{HI} > 17.5$
  - Almost no constraint!
  - These could easily dominate $\tau_{eff,LL}$



λ_{mfp}: circa 2009.5



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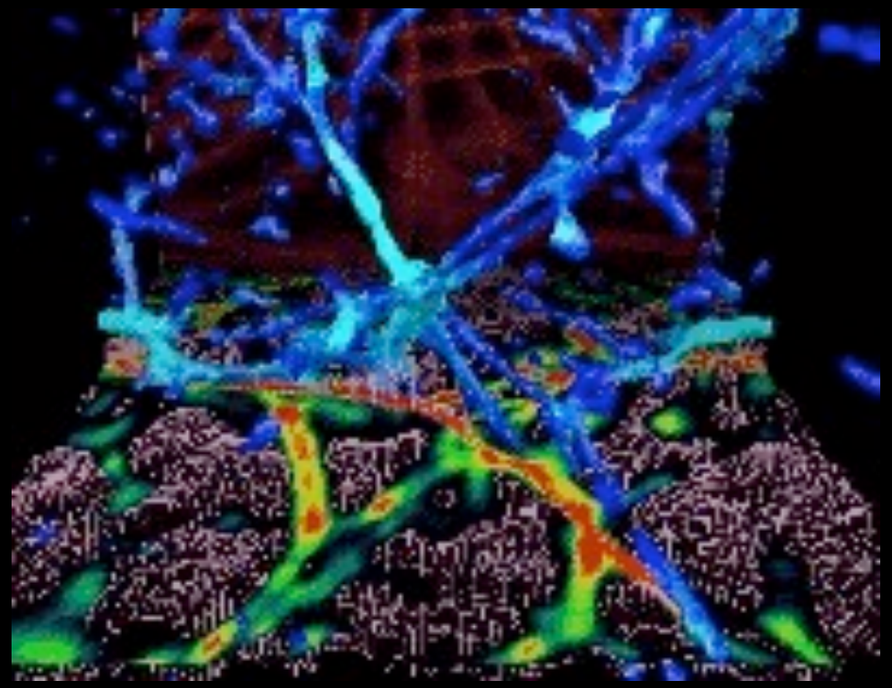

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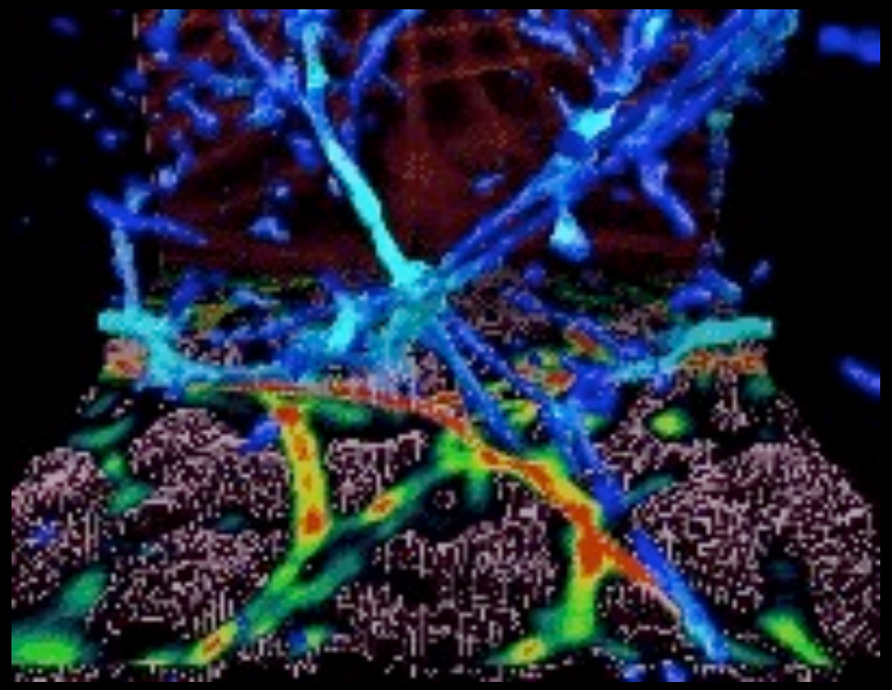

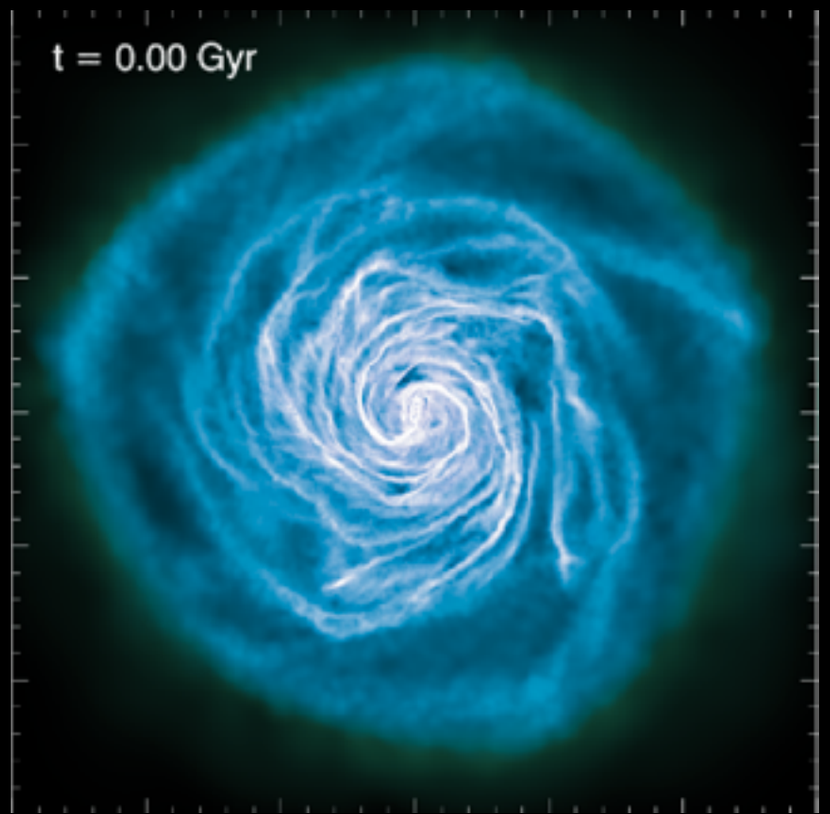

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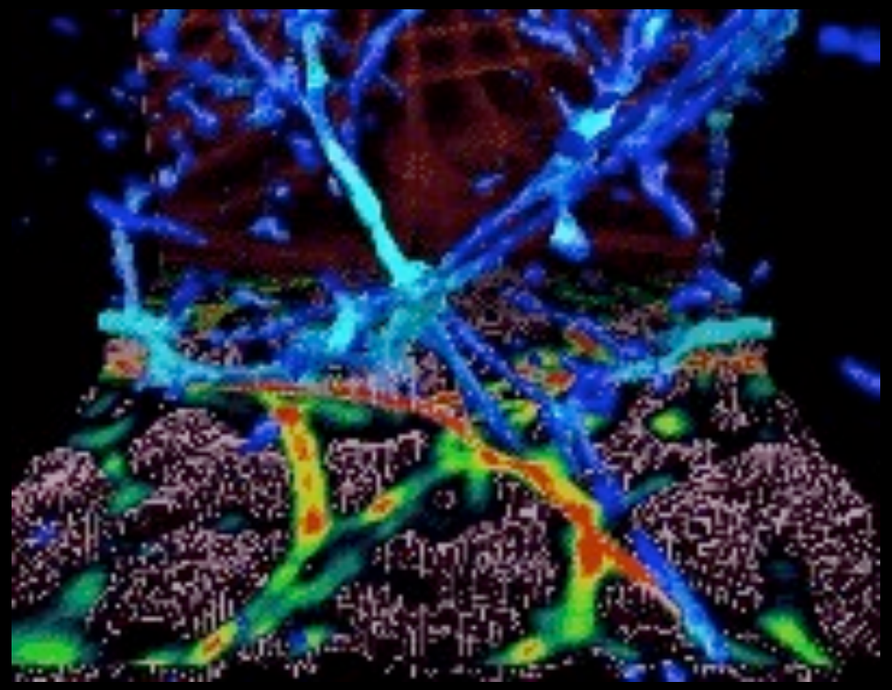

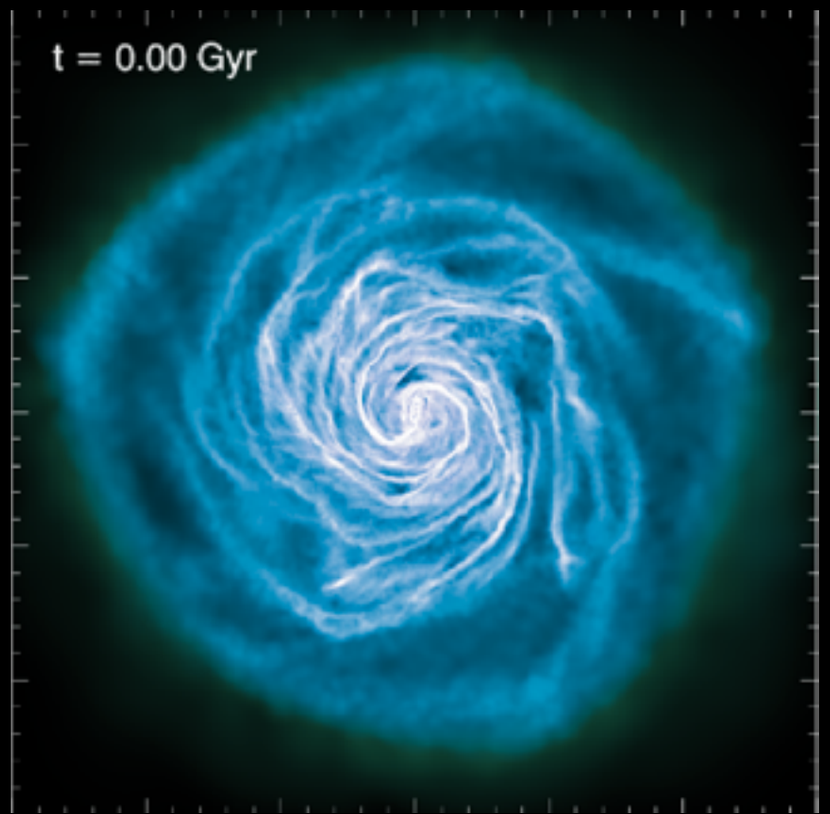

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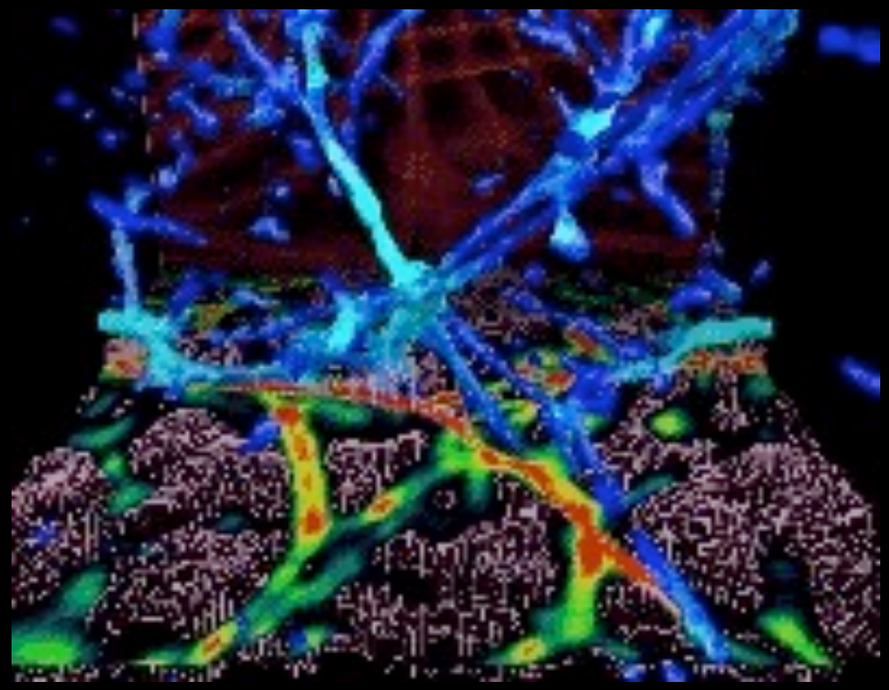
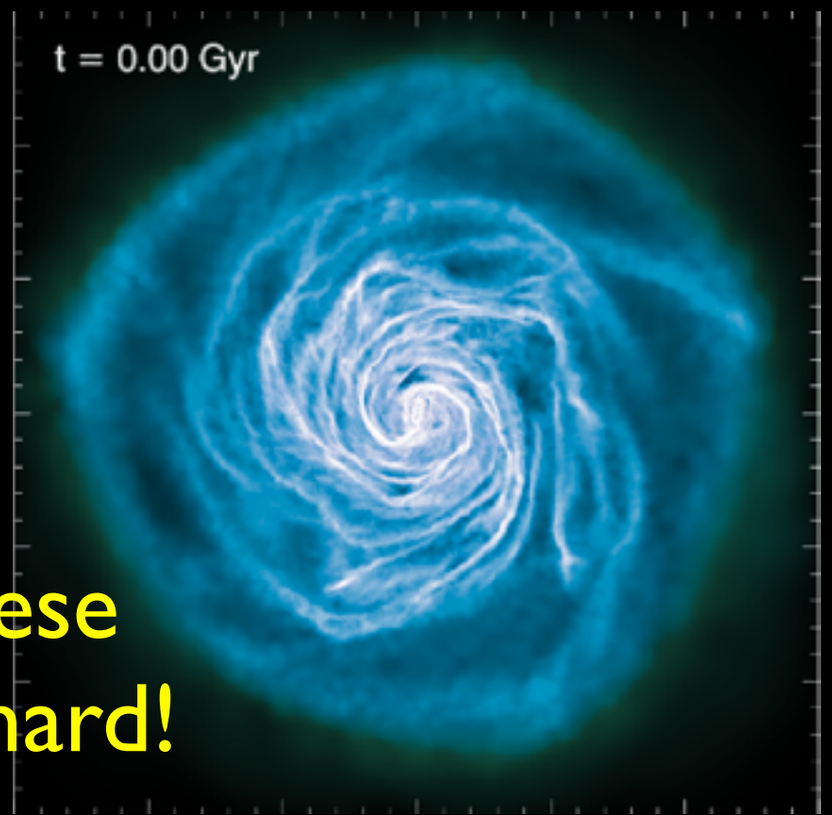




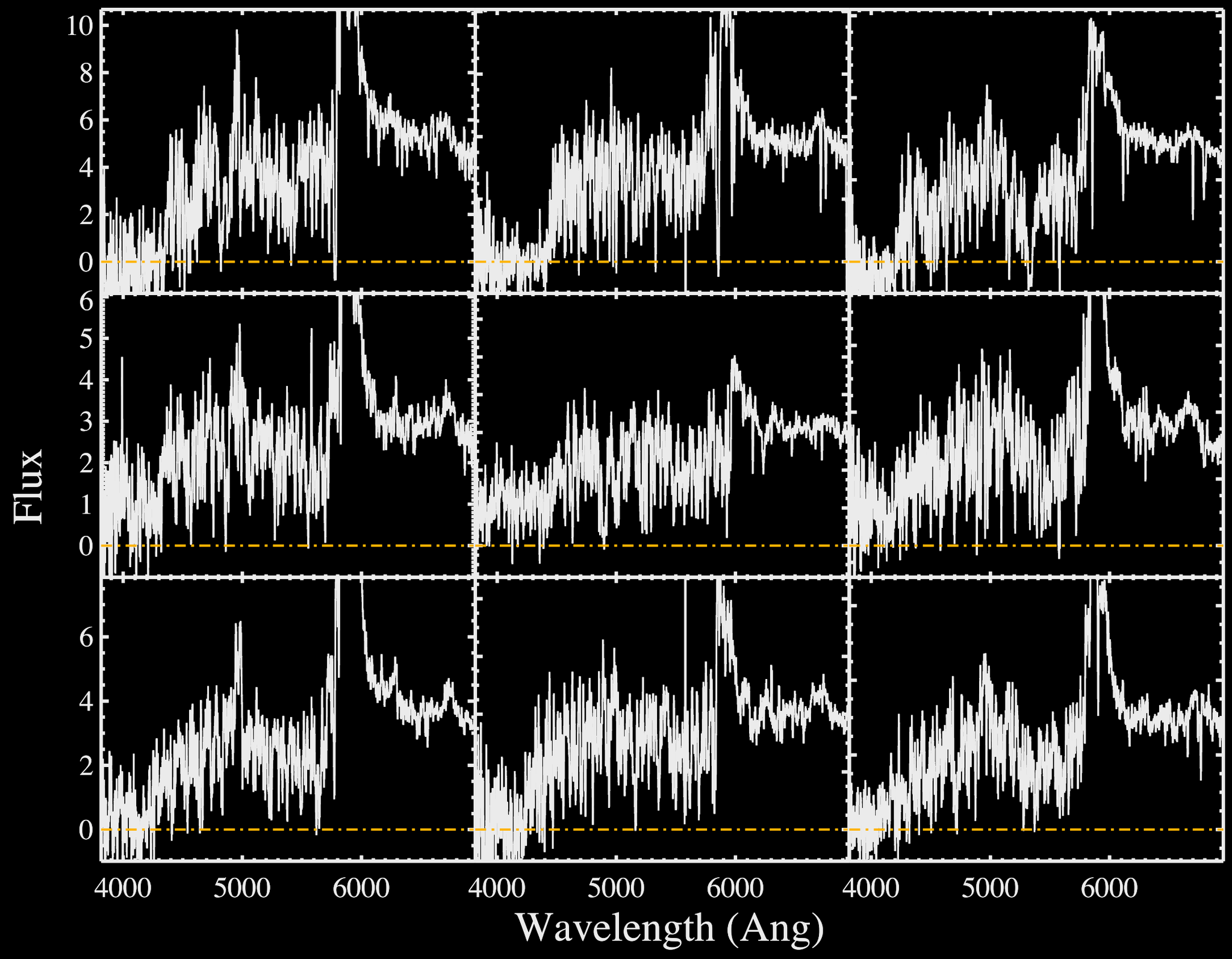
These are hard!

“A New Hope”

Stacked Quasar Spectra

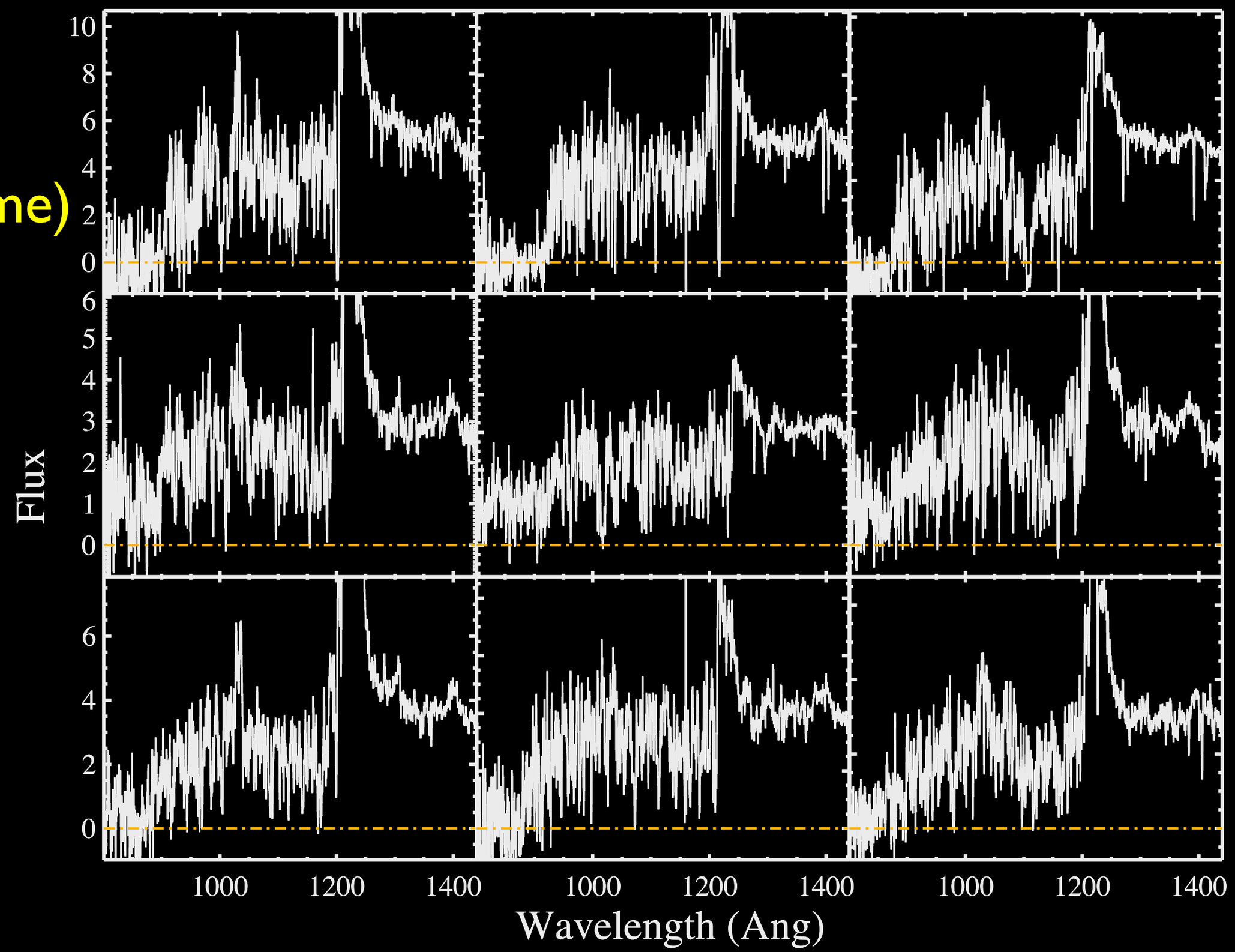
Building a Stacked Quasar Spectrum

'Raw'



Building a Stacked Quasar Spectrum

'Raw'
Shift
(rest frame)

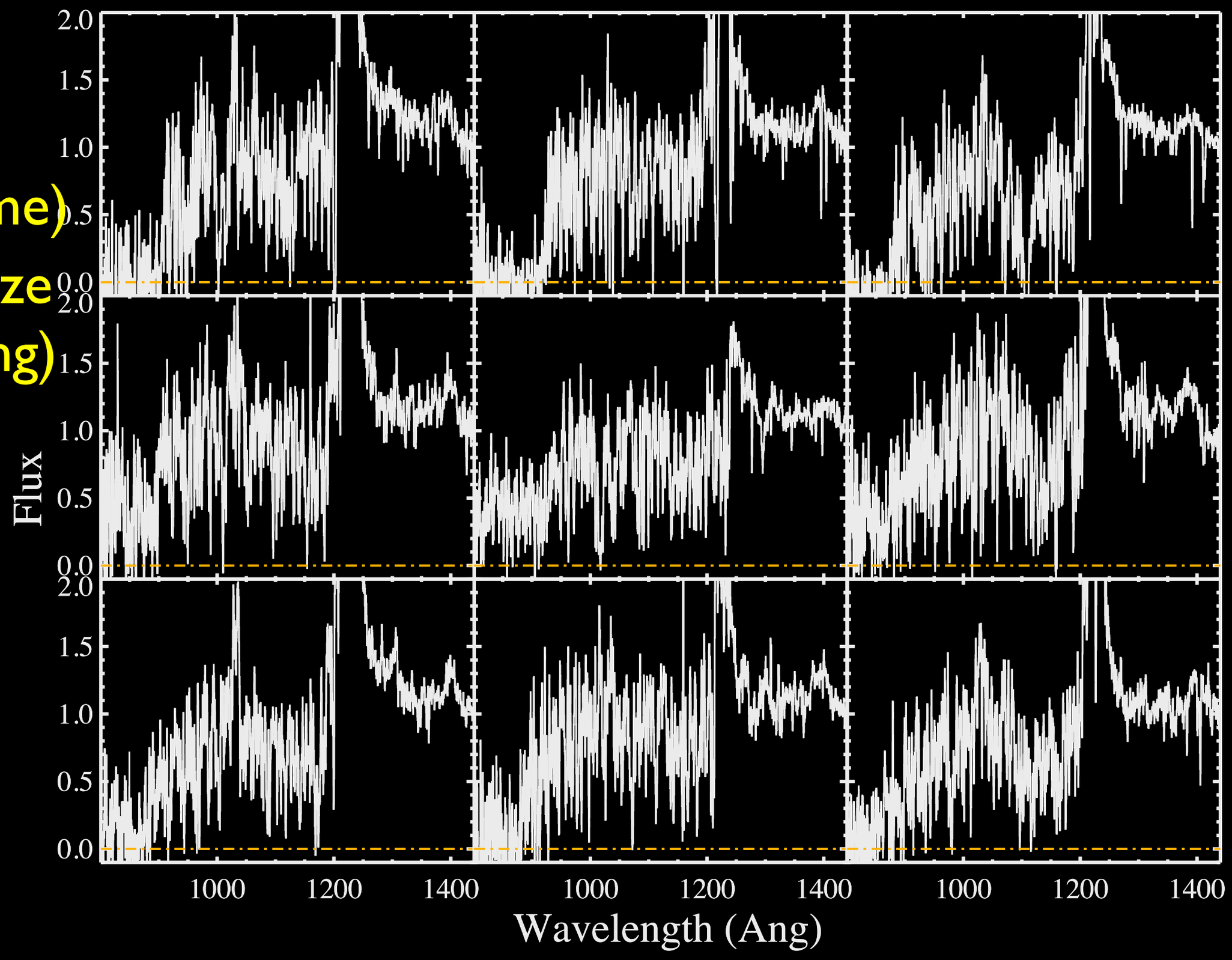


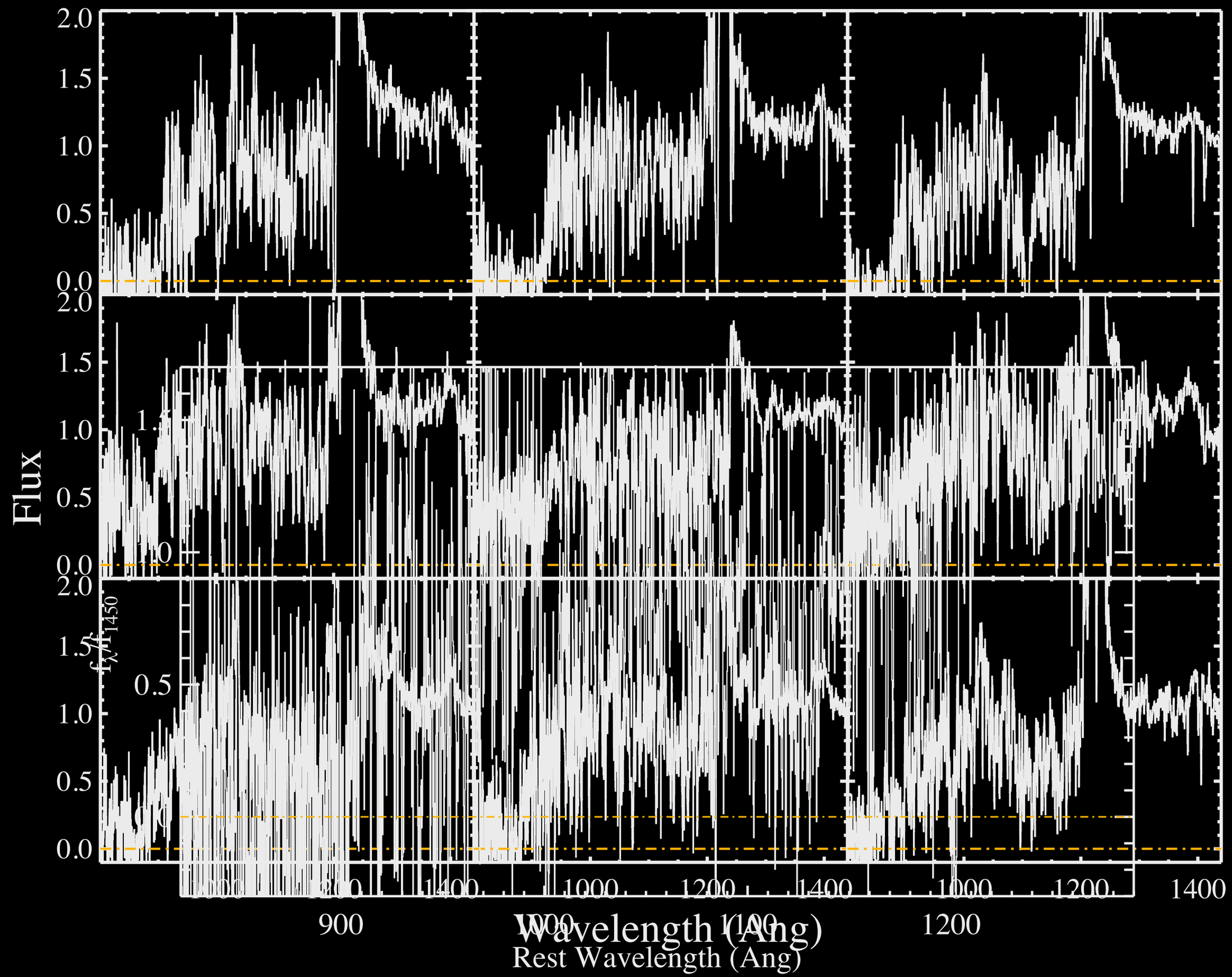
Building a Stacked Quasar Spectrum

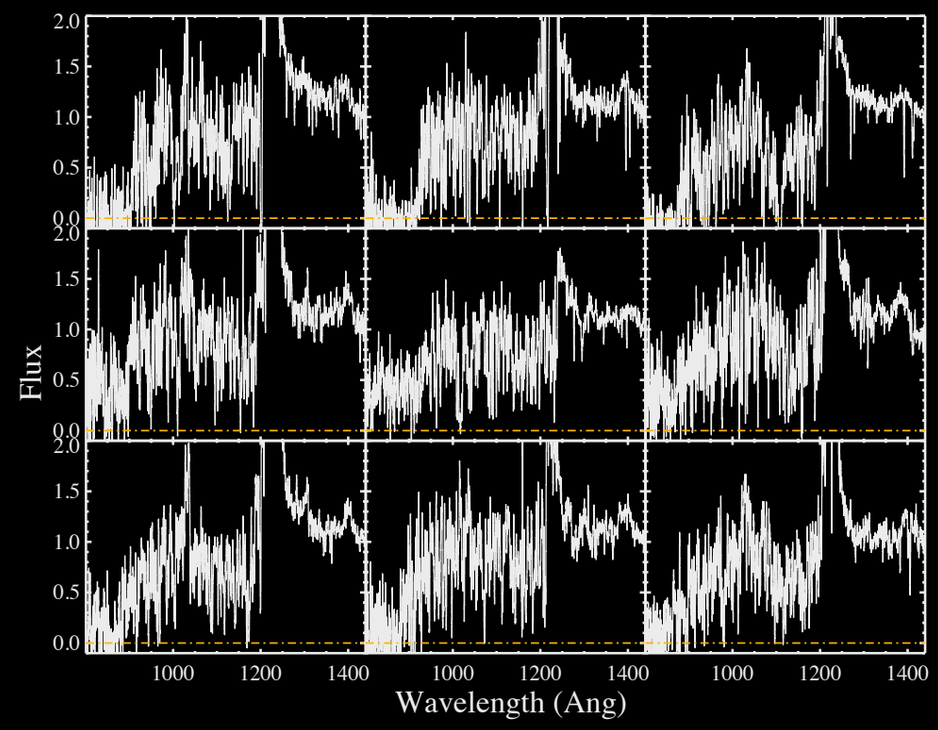
'Raw'

Shift (rest frame)

Normalize (1450 Ang)

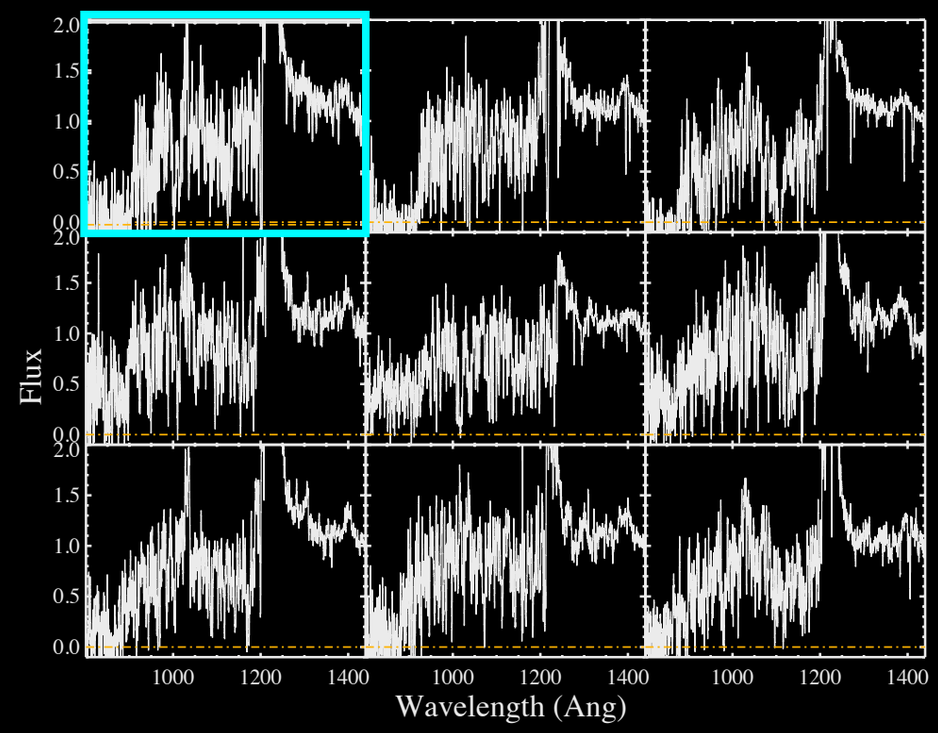



Flux
Wavelength (Ang)
Rest Wavelength (Ang)



Stacking the Quasars

- Restrict to S/N>4 at 1450
- Narrow range of z_{qso} per stack



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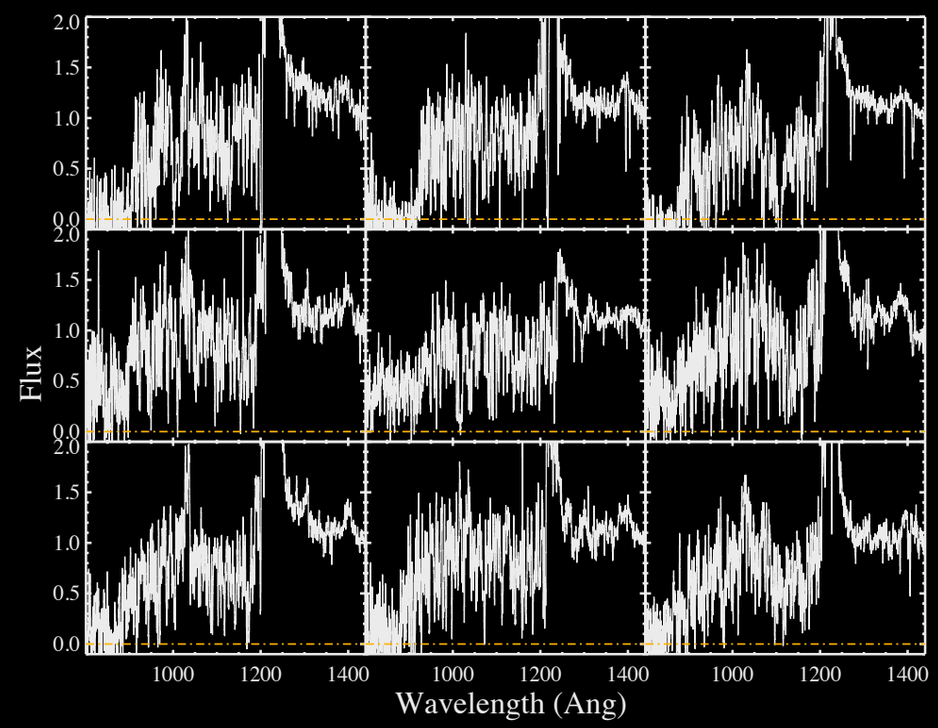

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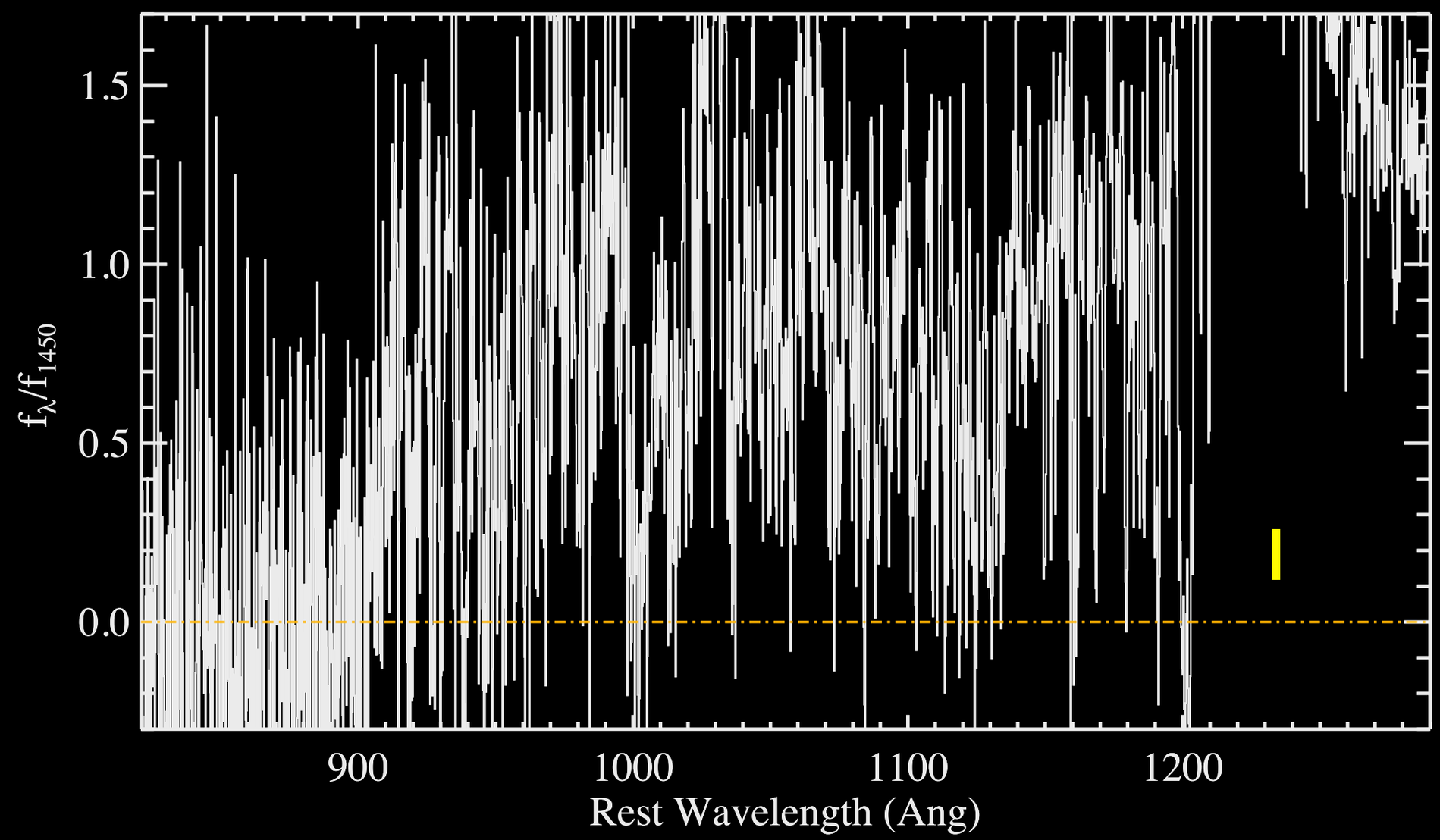

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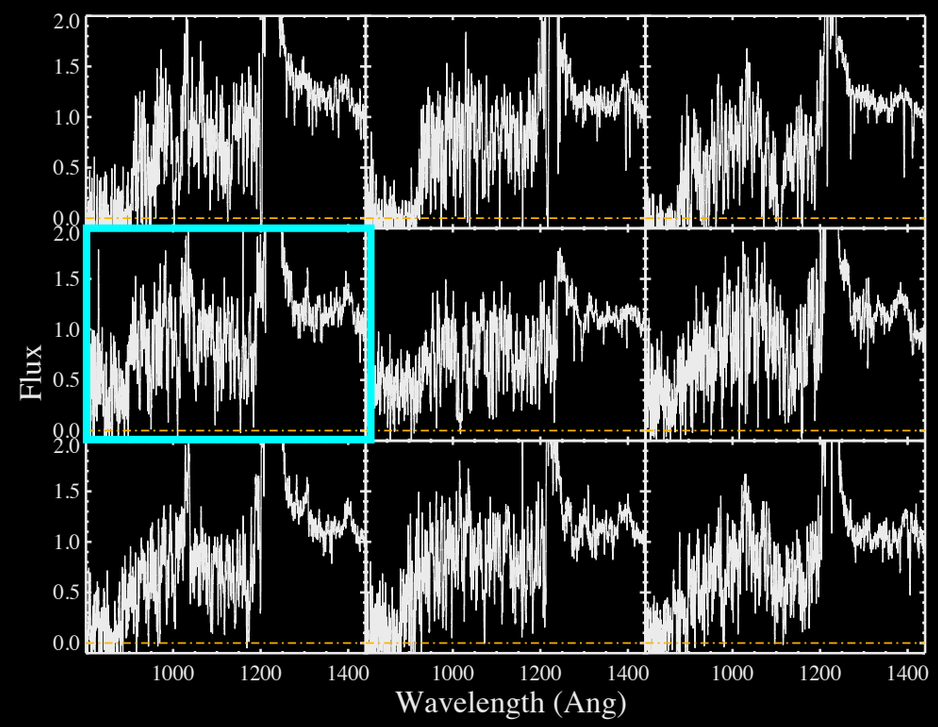

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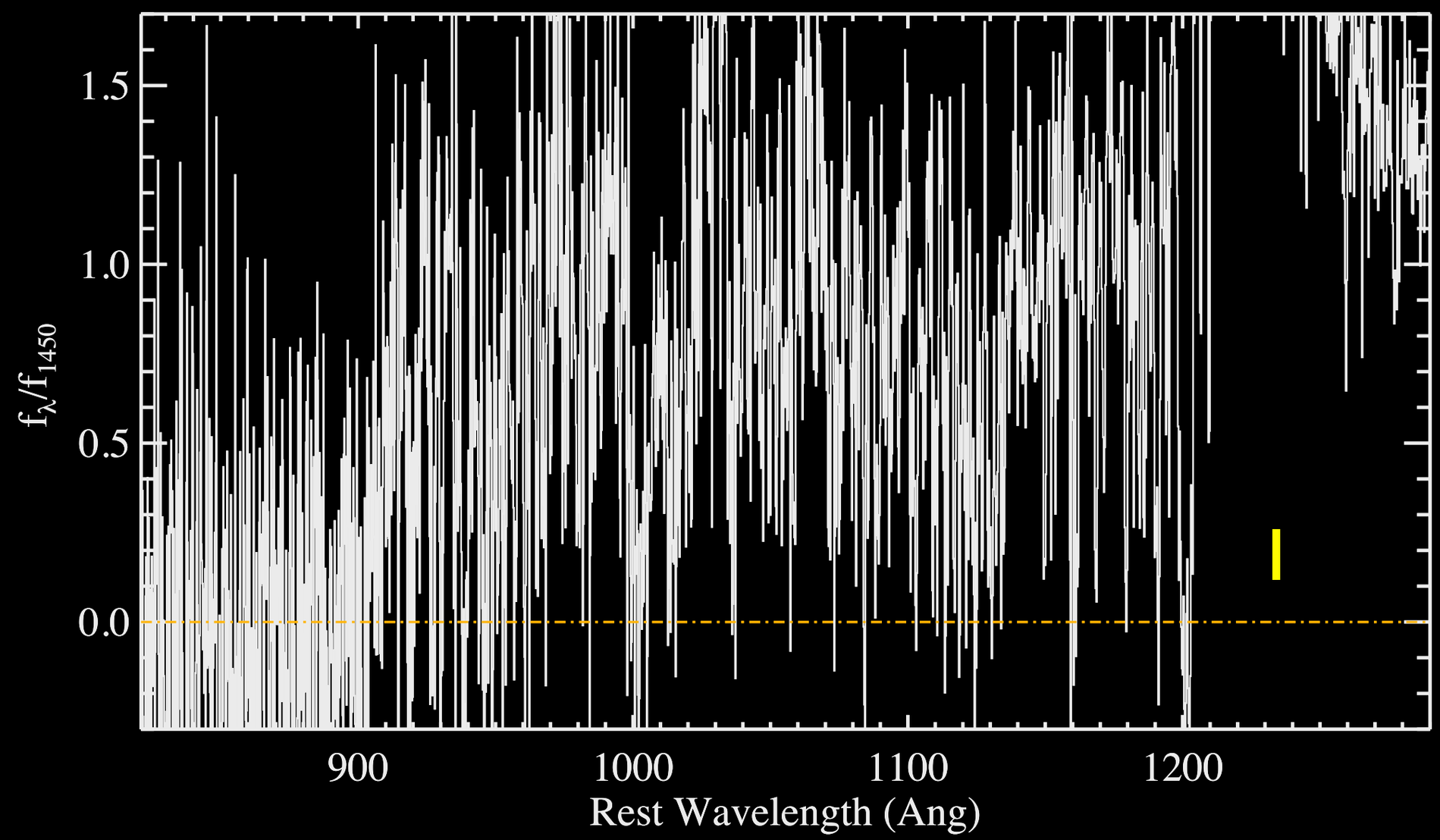

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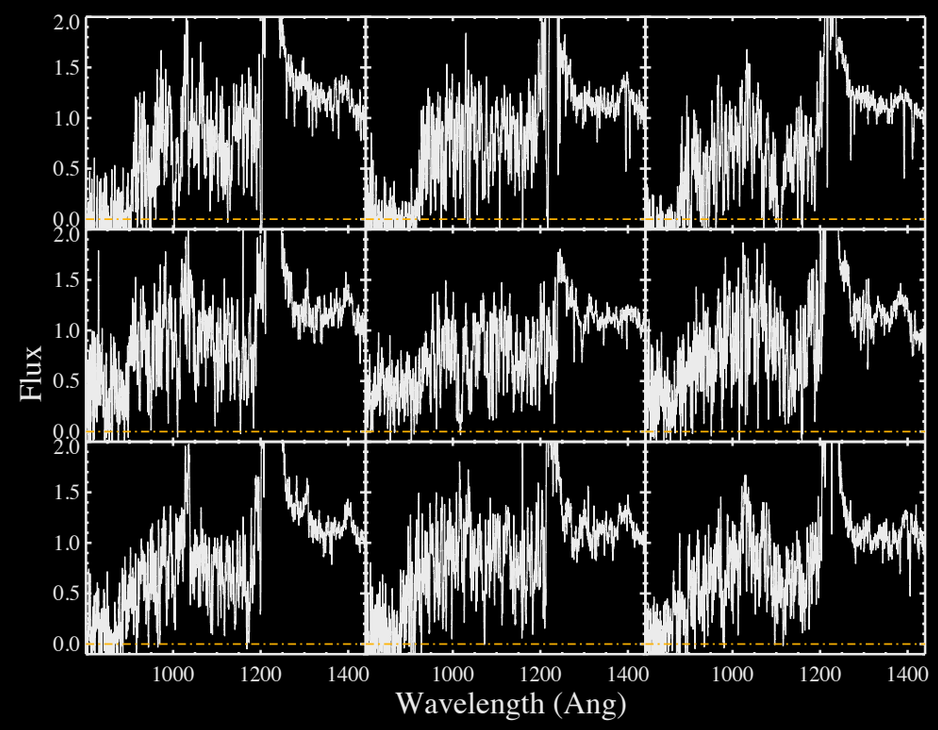

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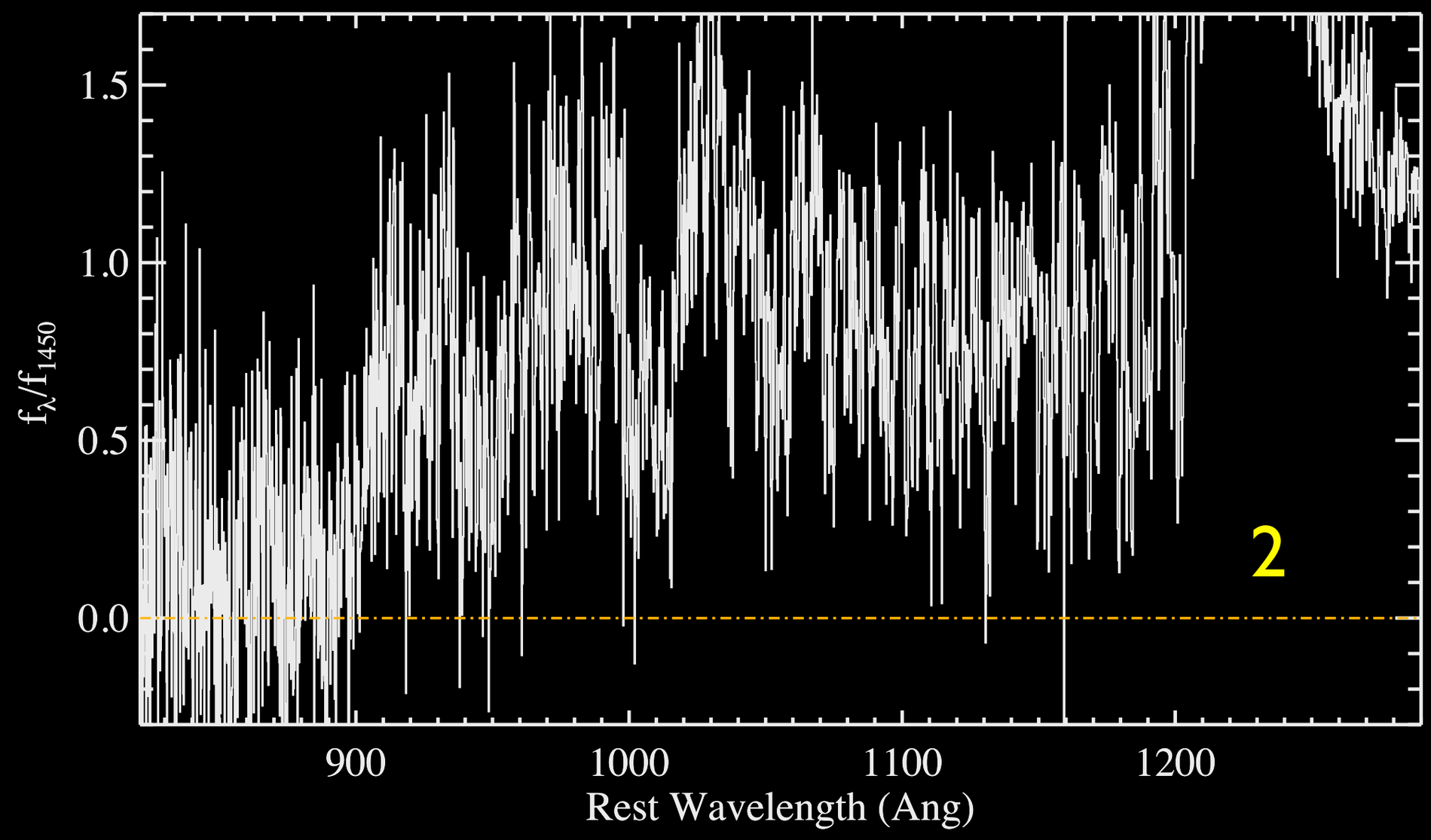

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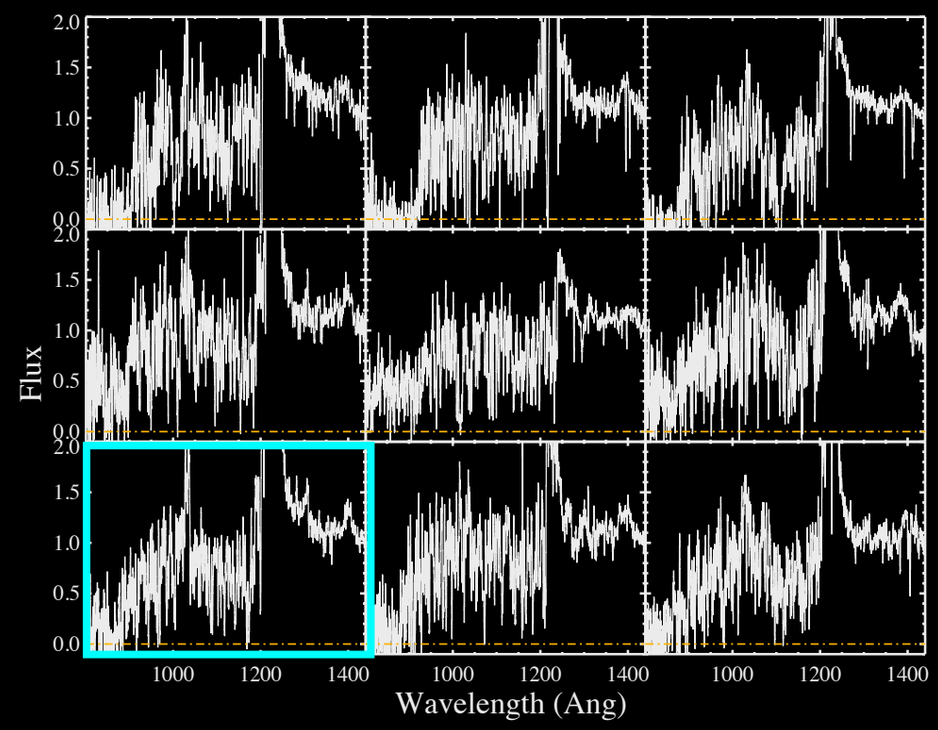

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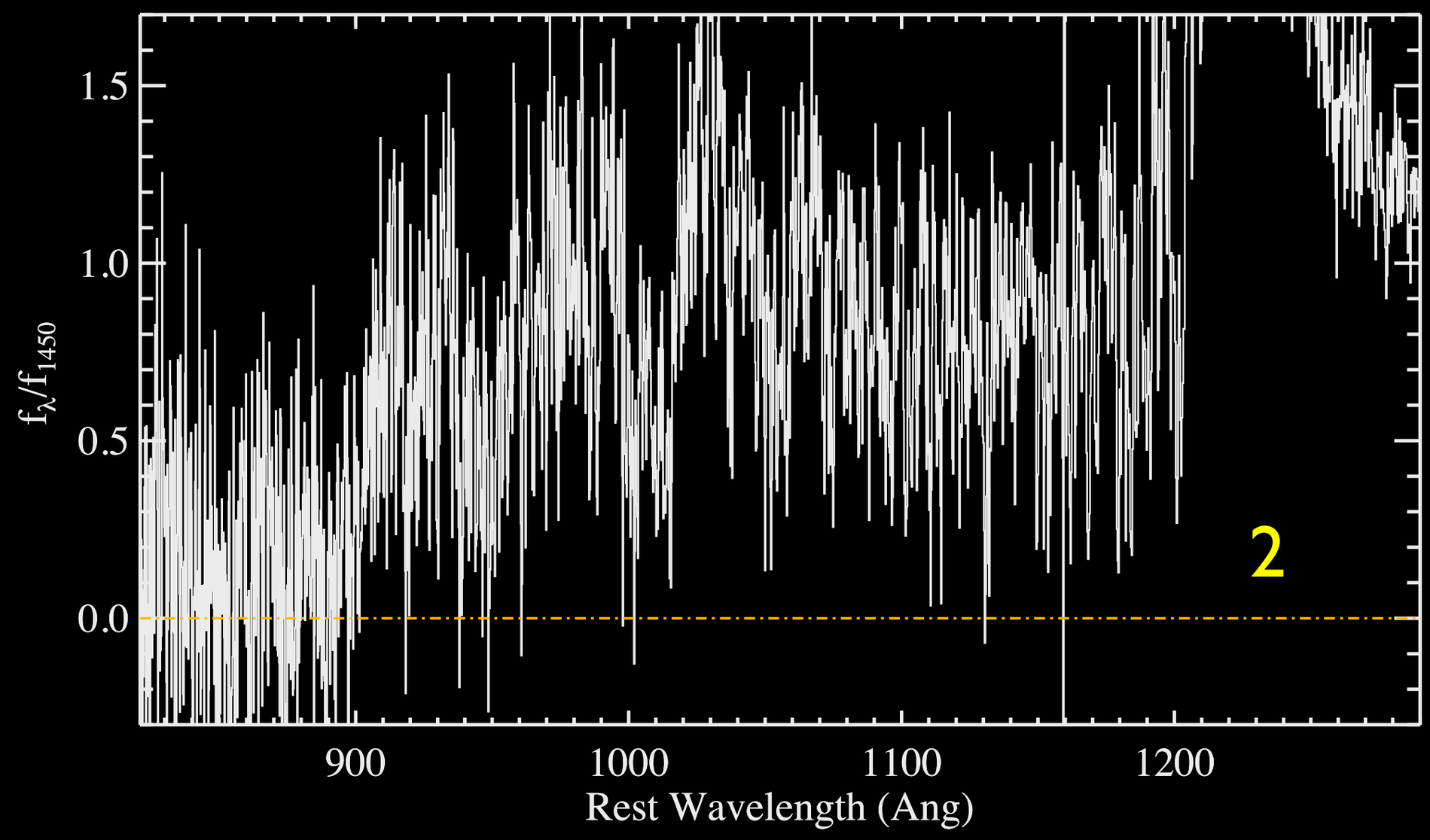
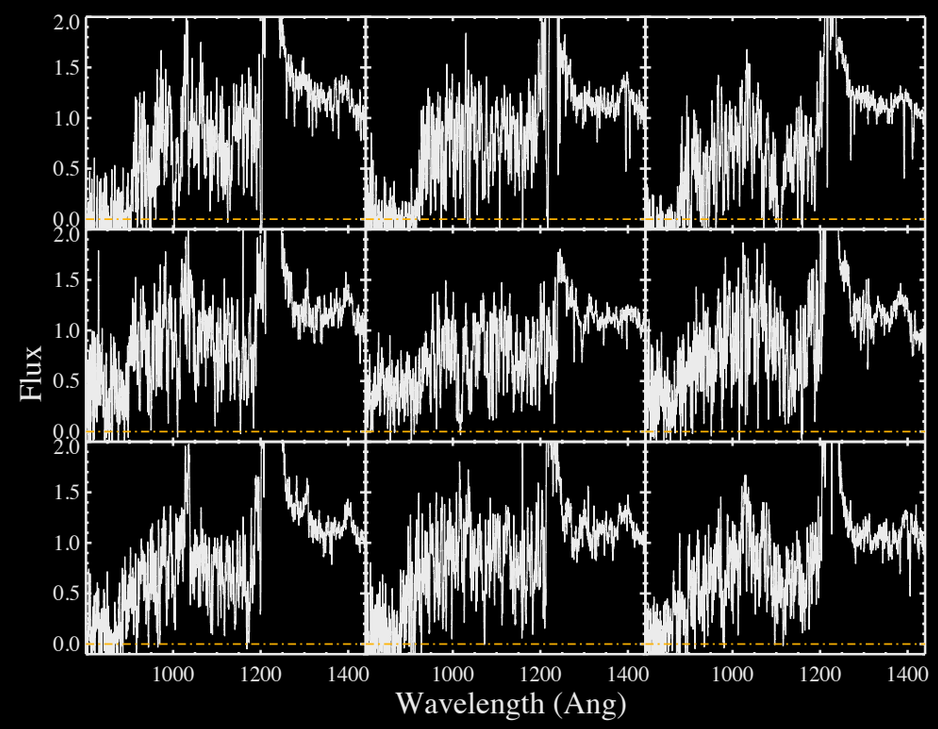
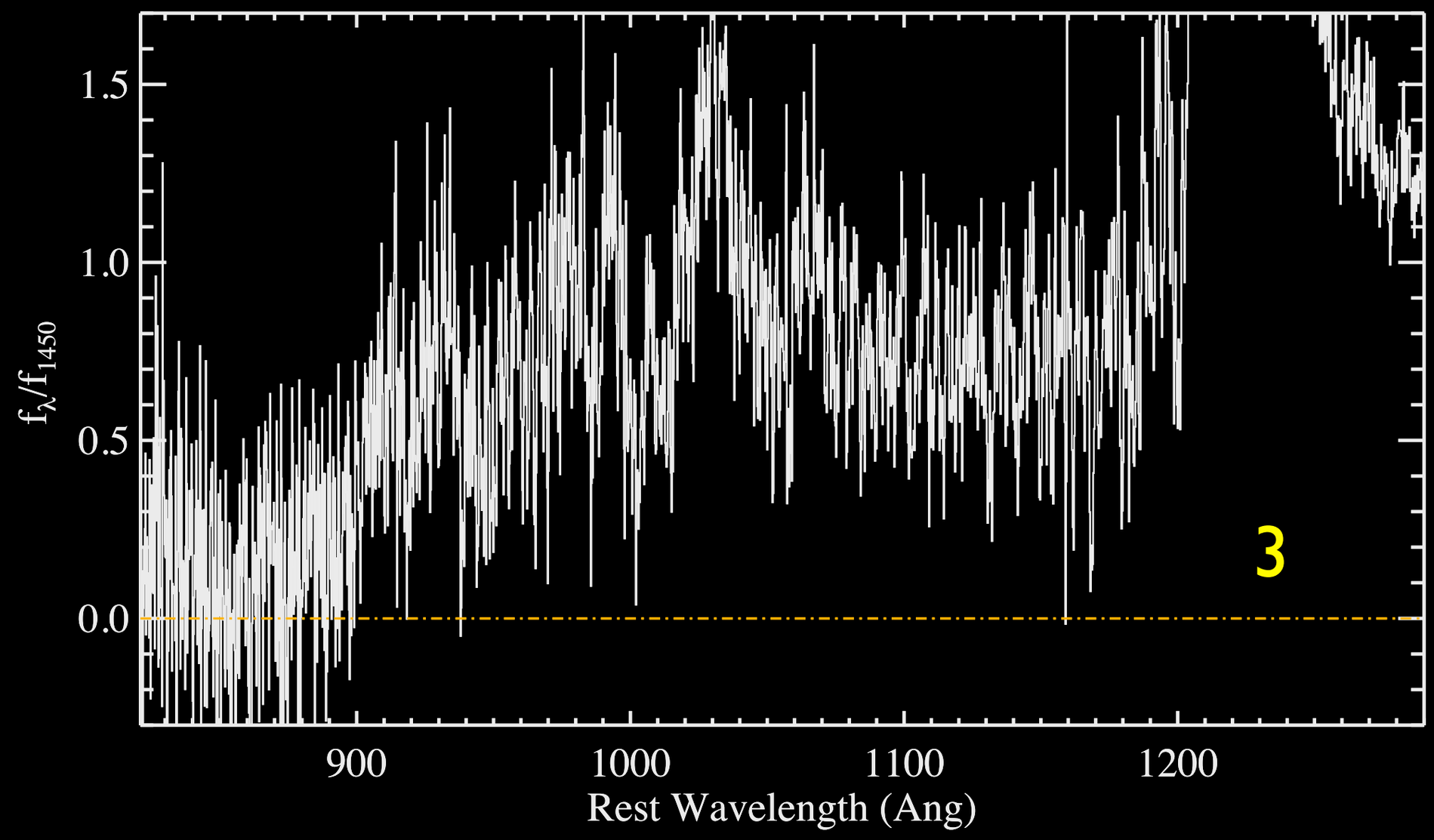
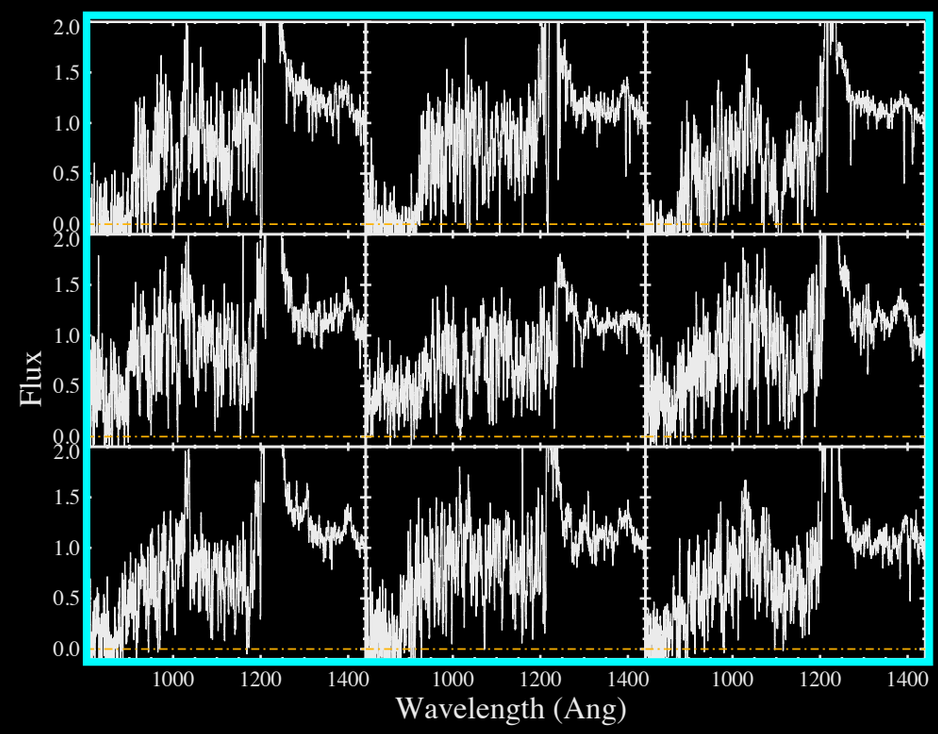


Stacking the Quasars



- Restrict to S/N>4 at 1450
- Narrow range of z_{qso} per stack
- Straight average (no weighting)





Stacking the Quasars

- Restrict to S/N>4 at 1450
- Narrow range of z_{qso} per stack
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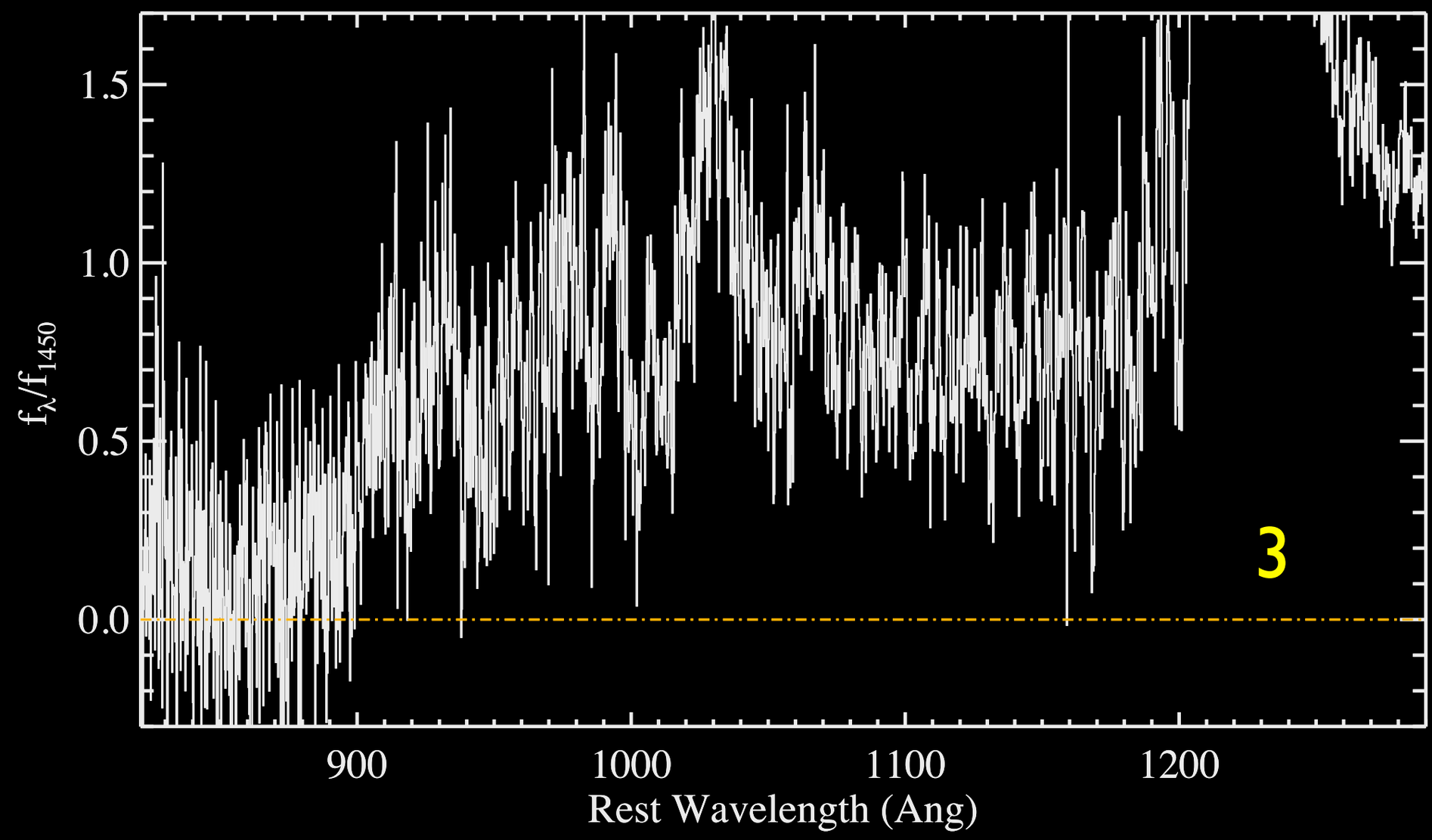
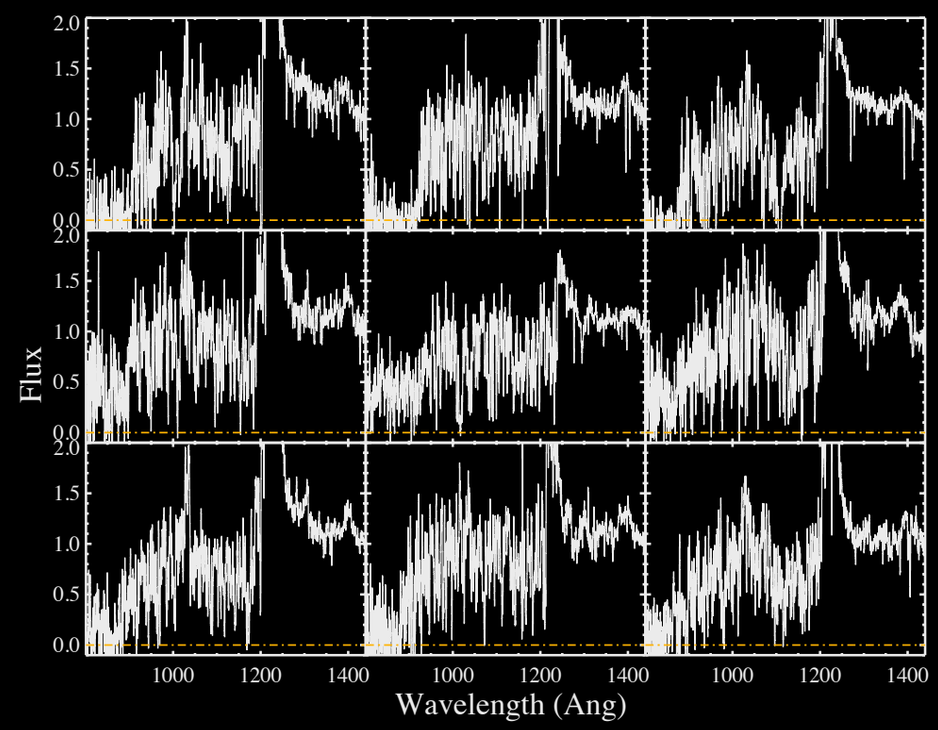


Stacking the Quasars



- Restrict to S/N>4 at 1450
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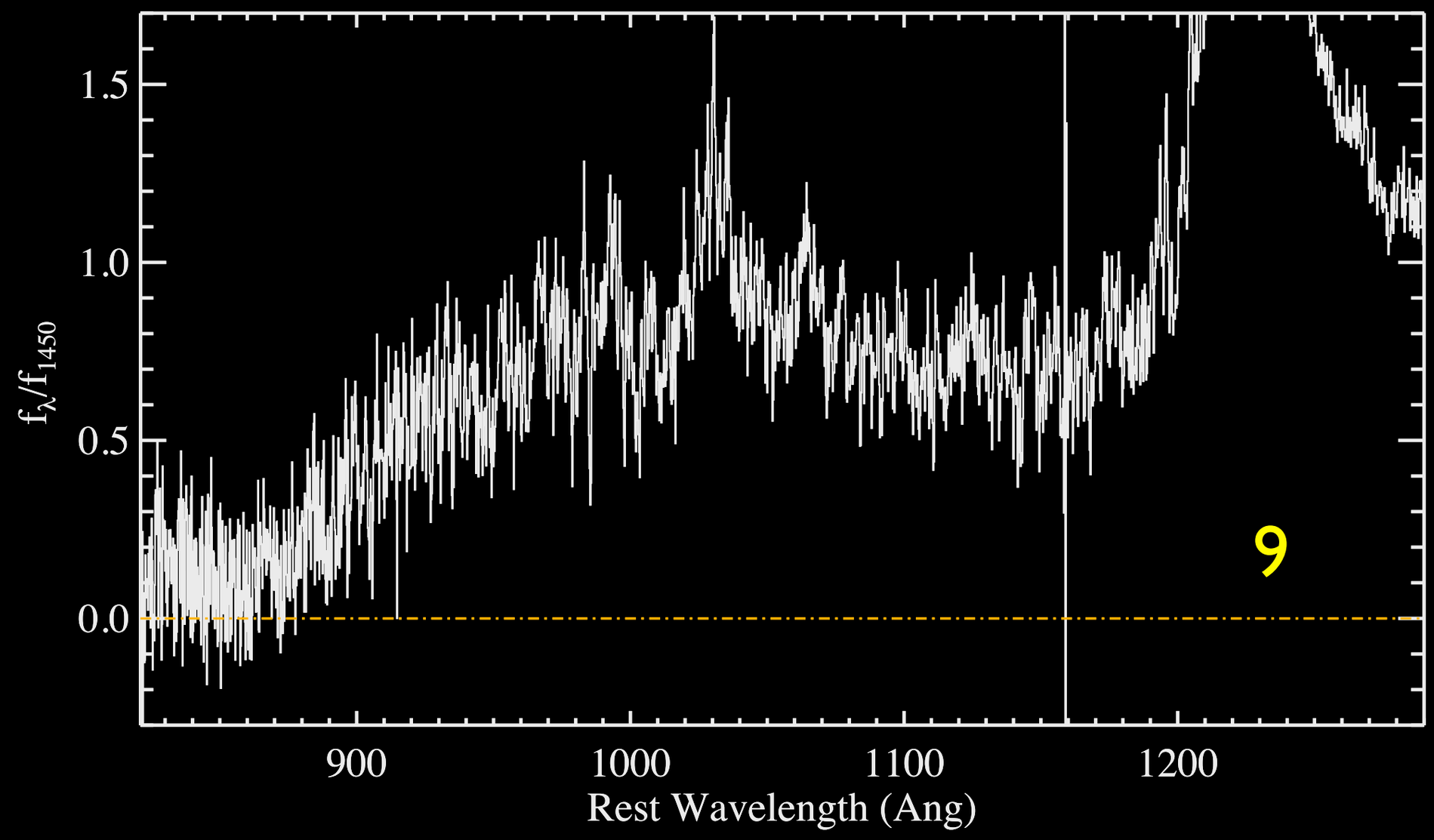
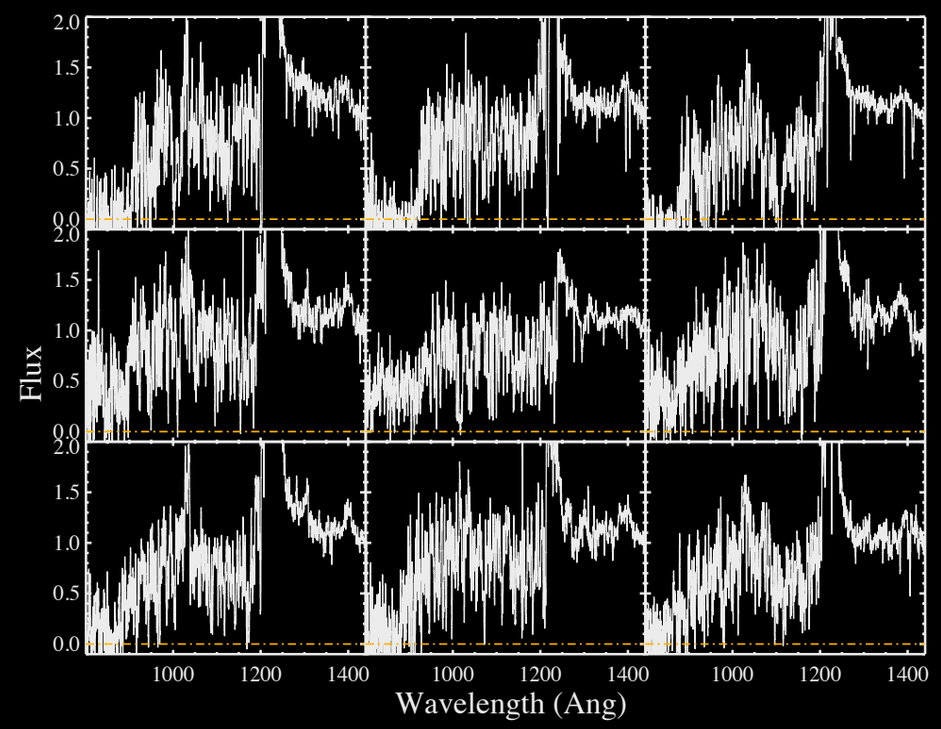
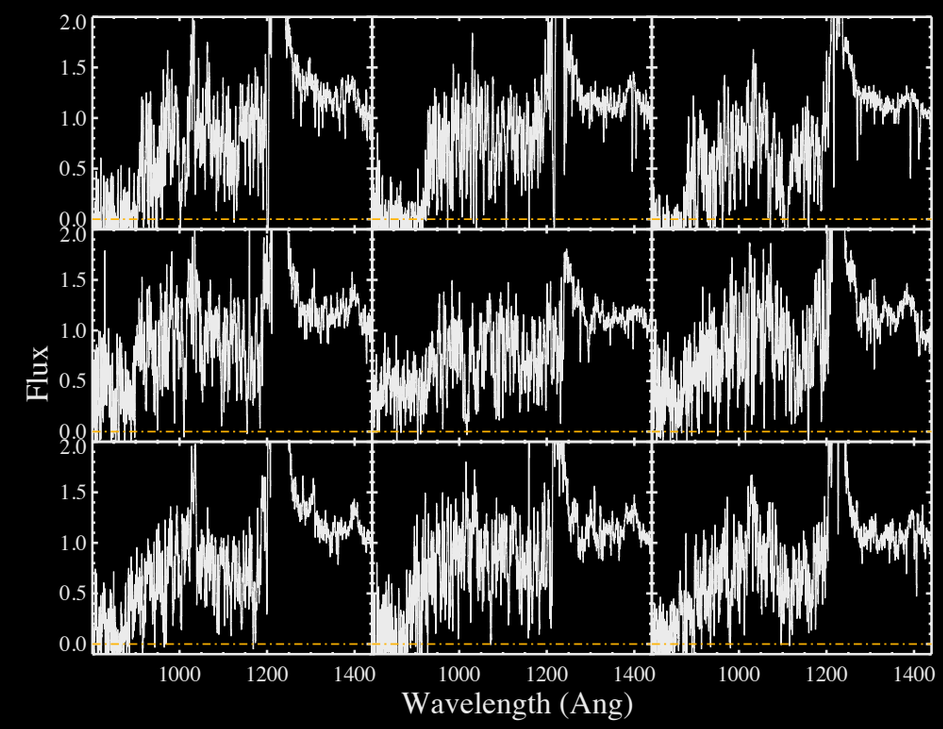
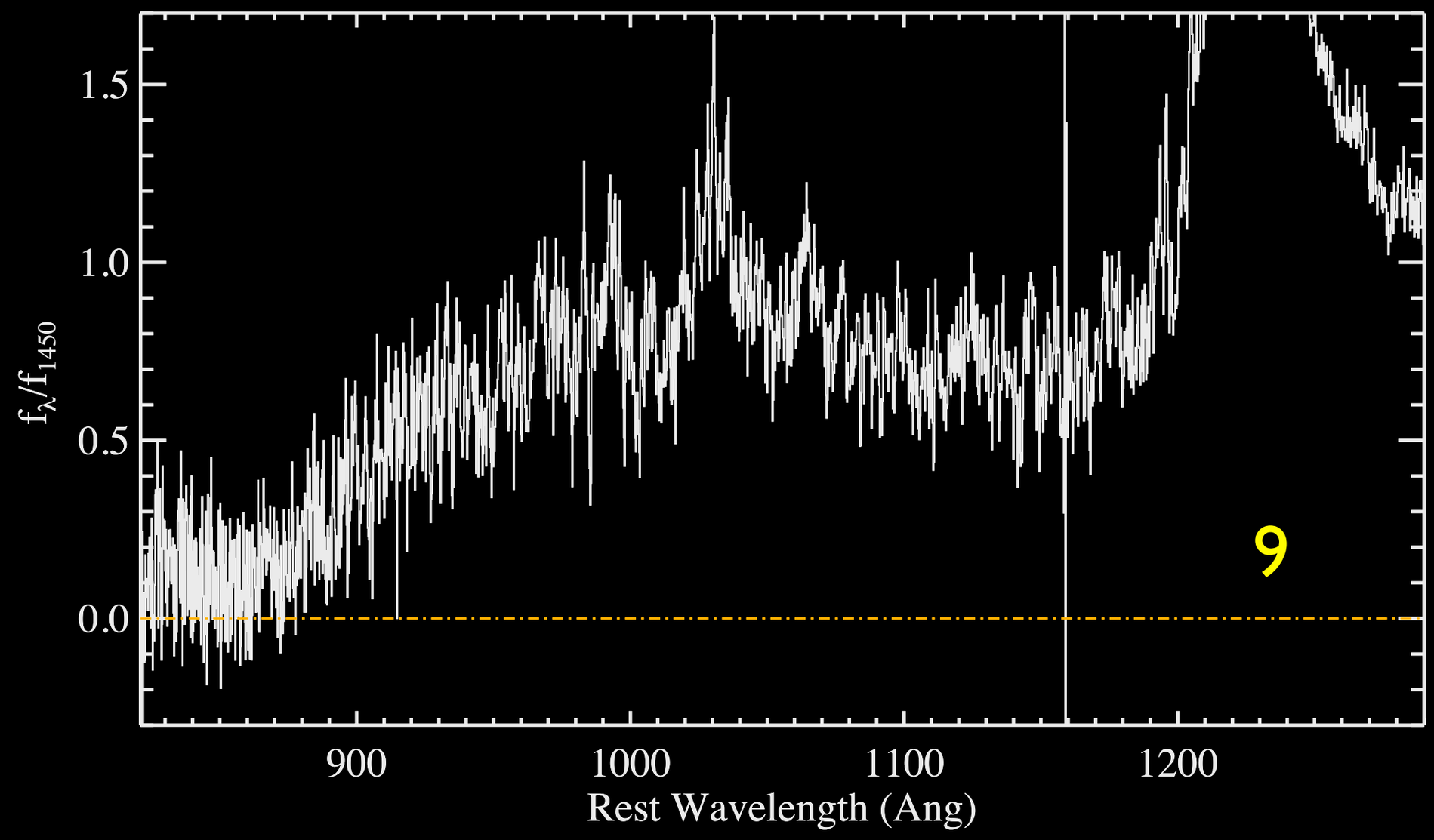
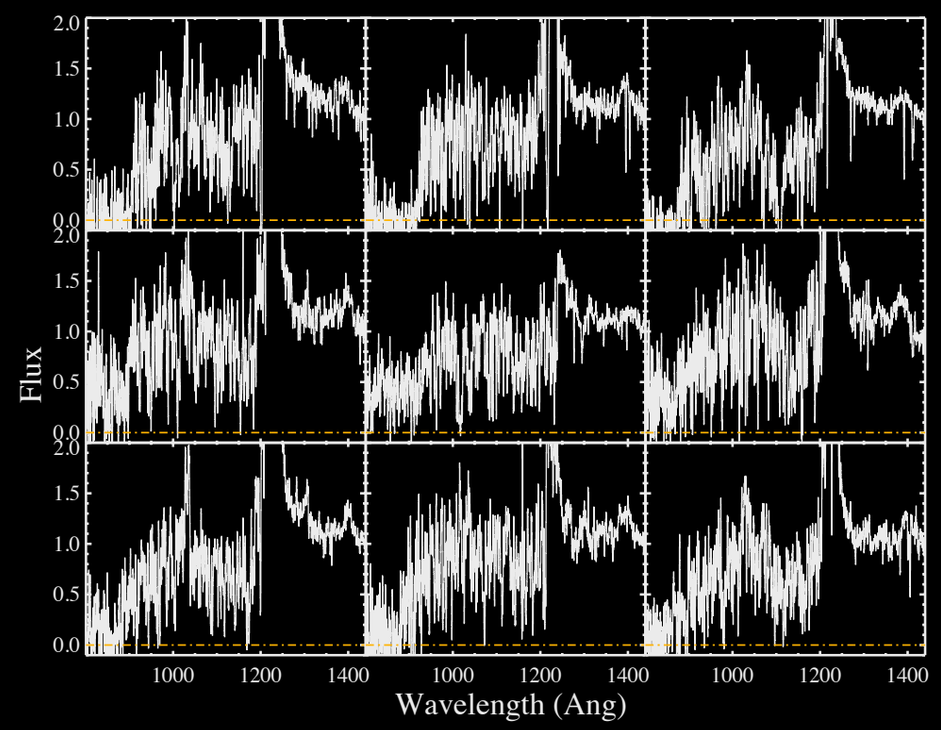
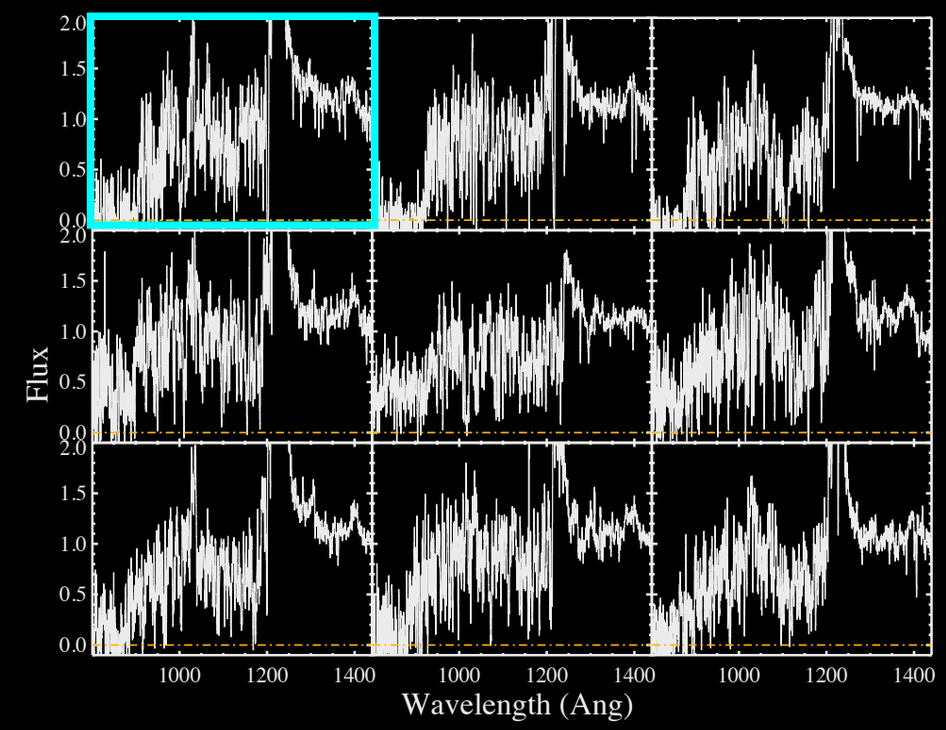


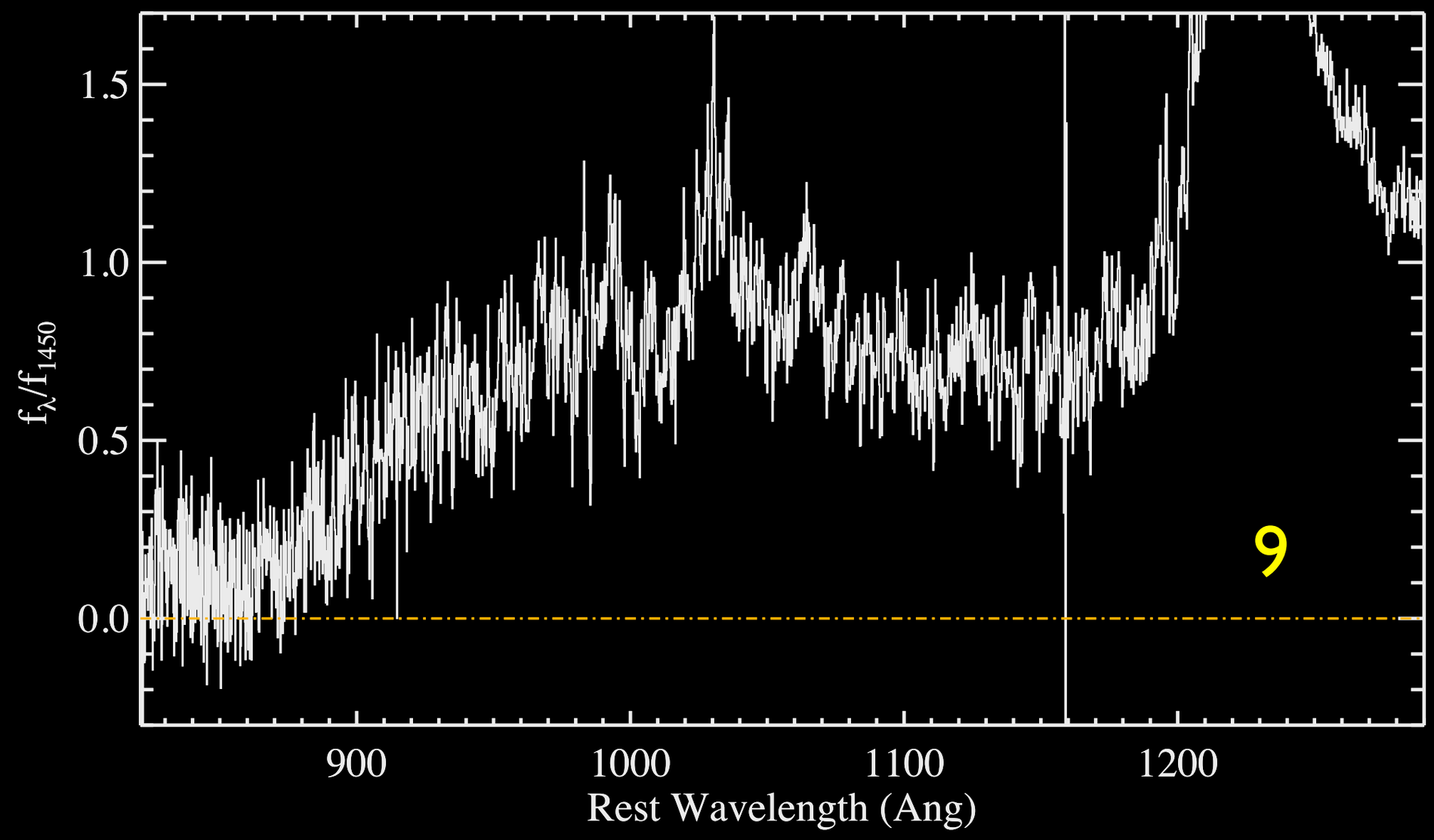

Flux
Wavelength (Ang)

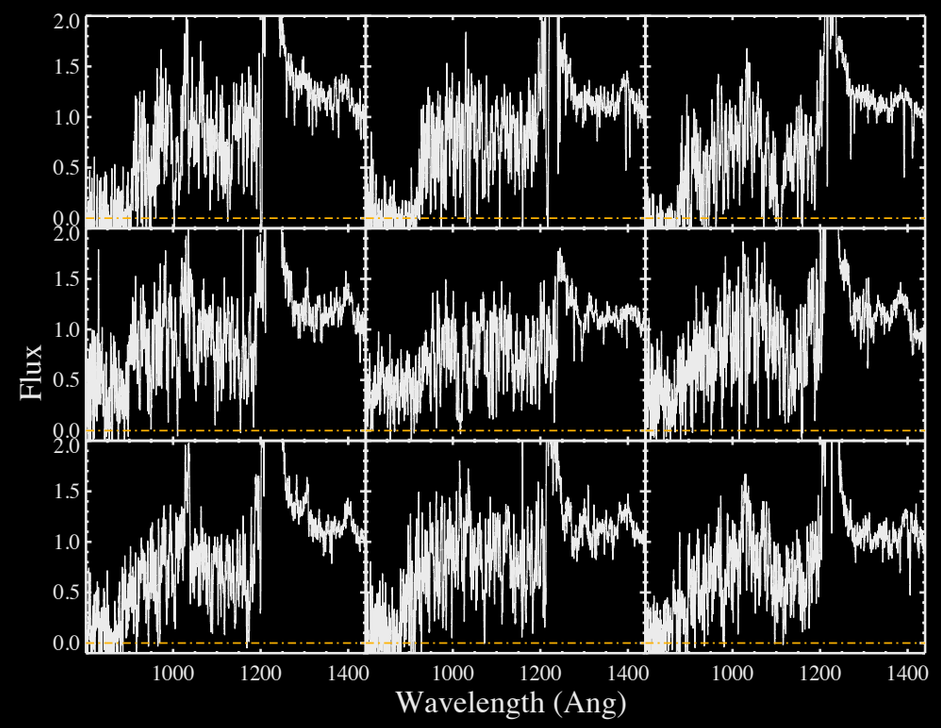

Flux
Wavelength (Ang)

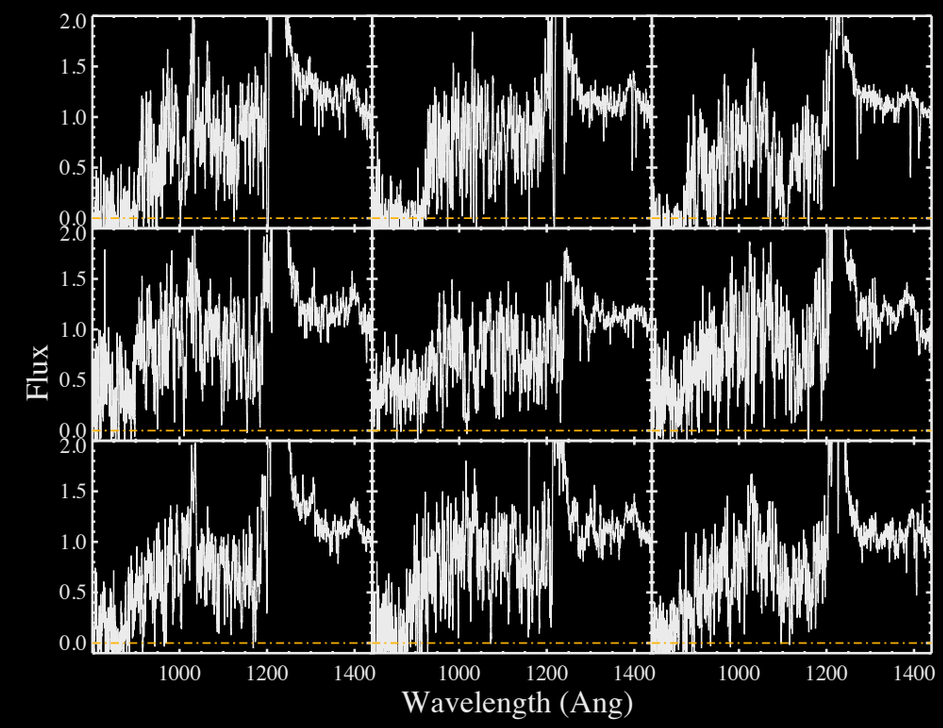

f_λ/f_{1450}
Rest Wavelength (Ang)
9

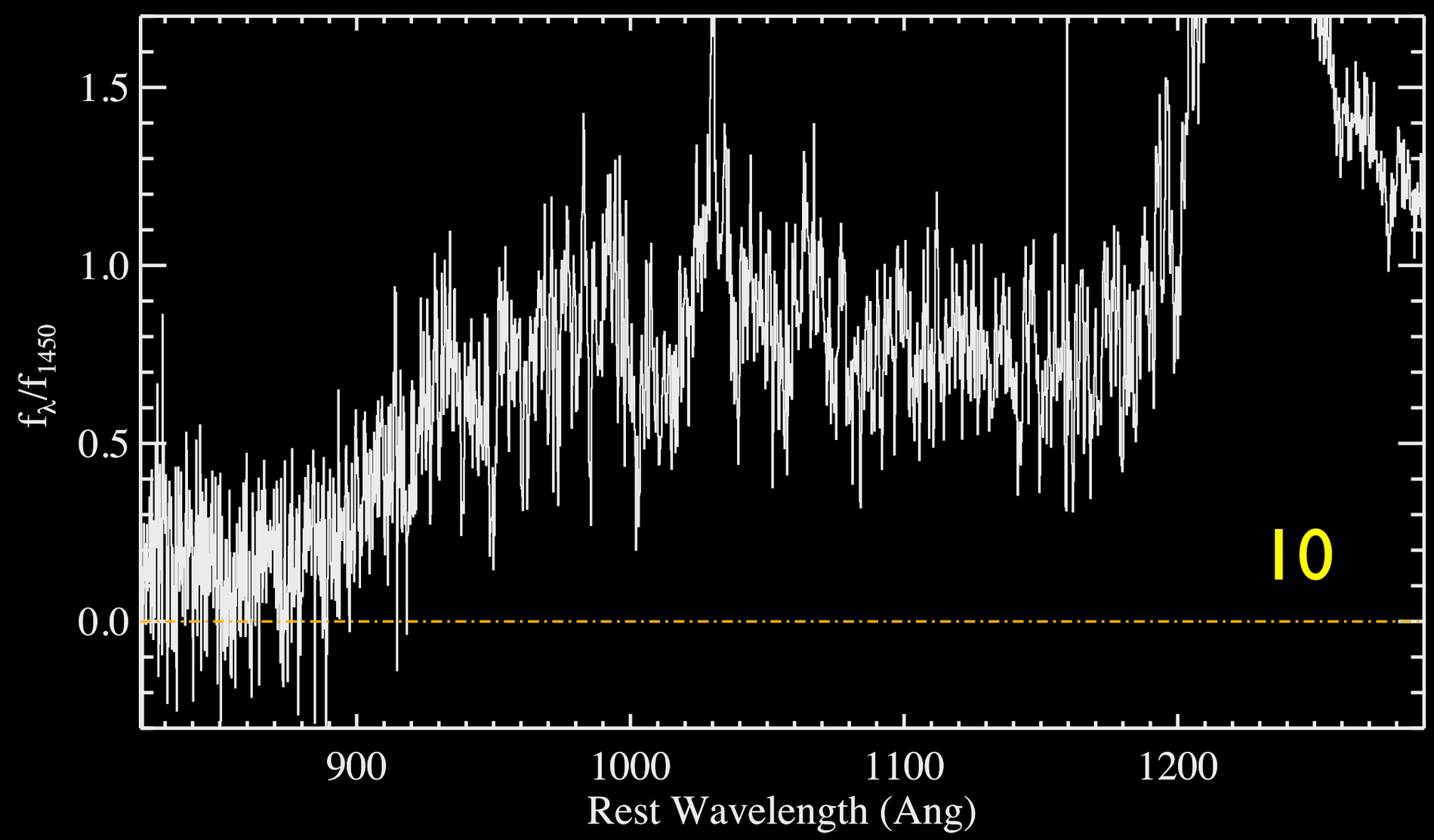

Flux
Wavelength (Ang)

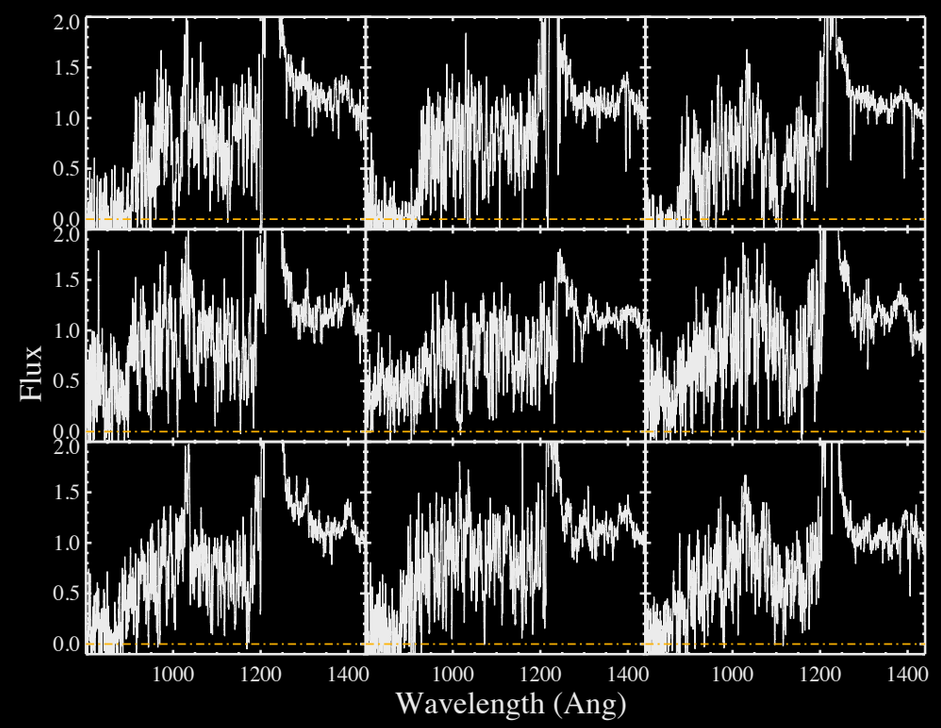

Flux
Wavelength (Ang)

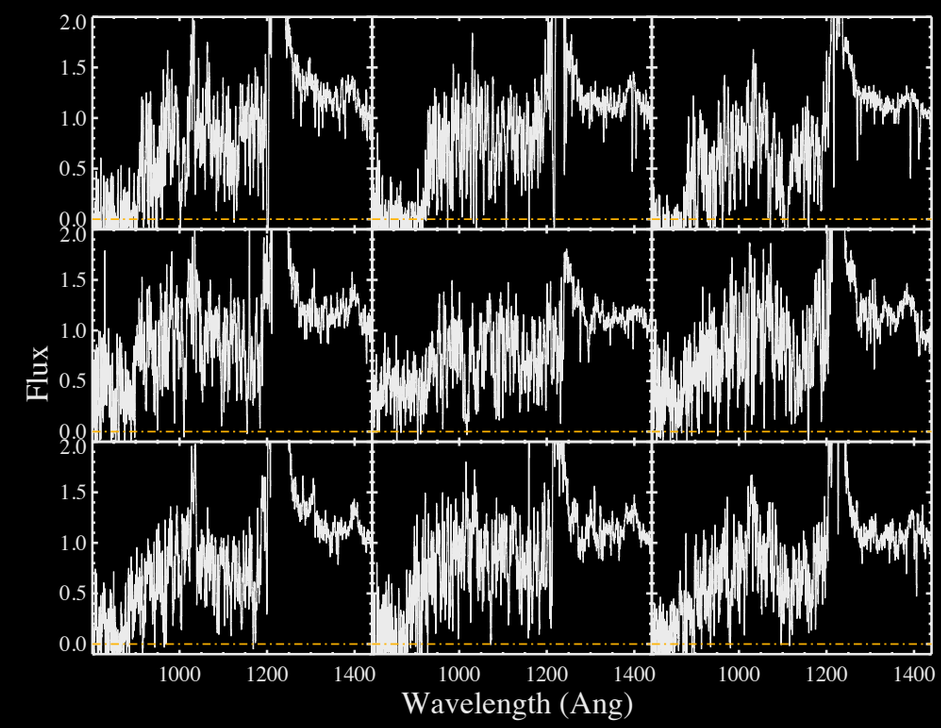

f_λ/f_{1450}
Rest Wavelength (Ang)
9

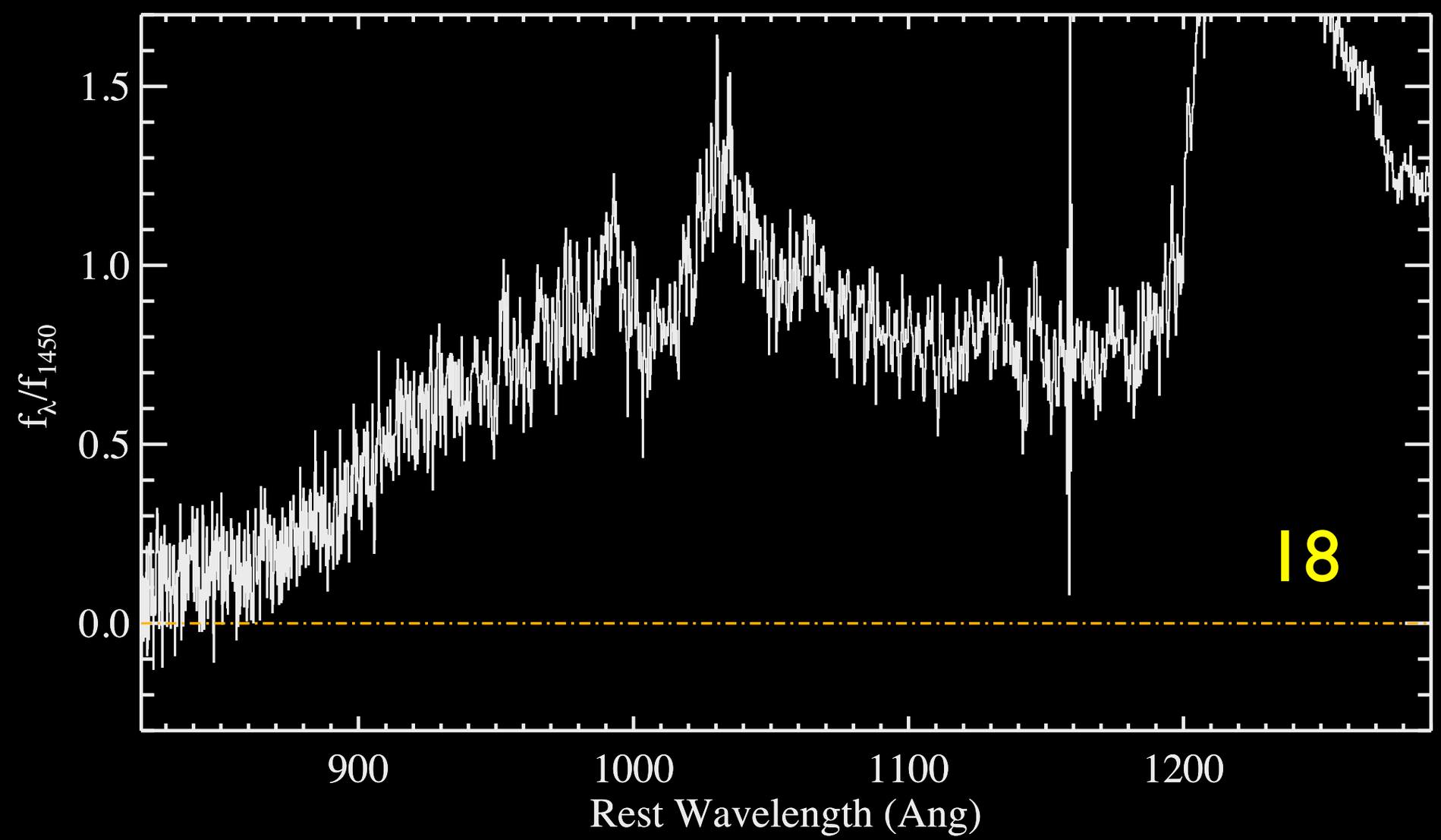

Flux
Wavelength (Ang)

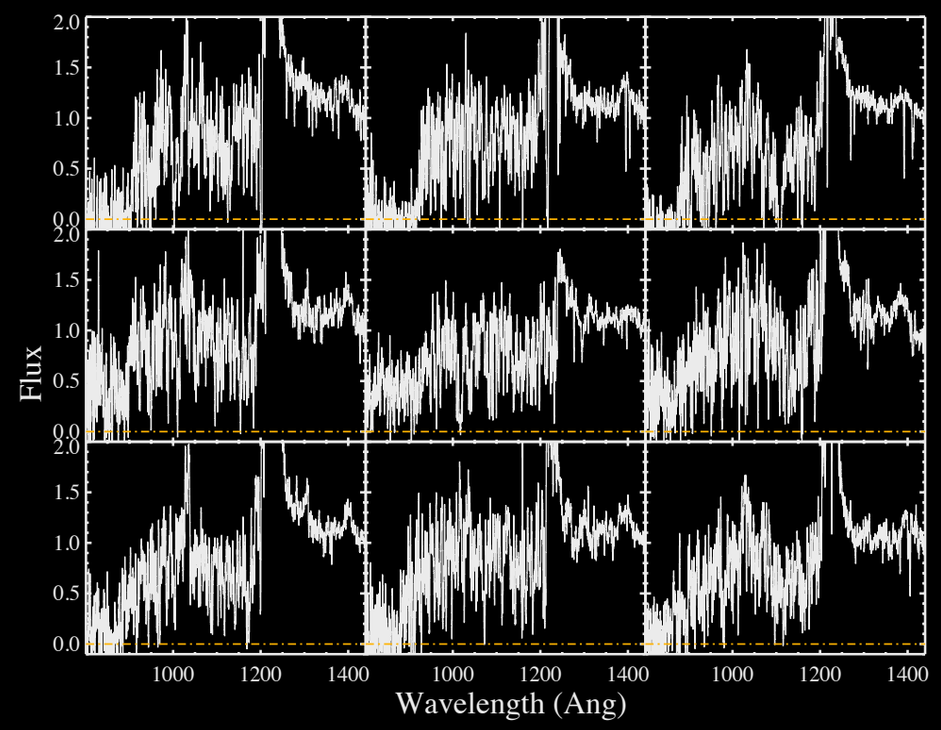

Flux
Wavelength (Ang)

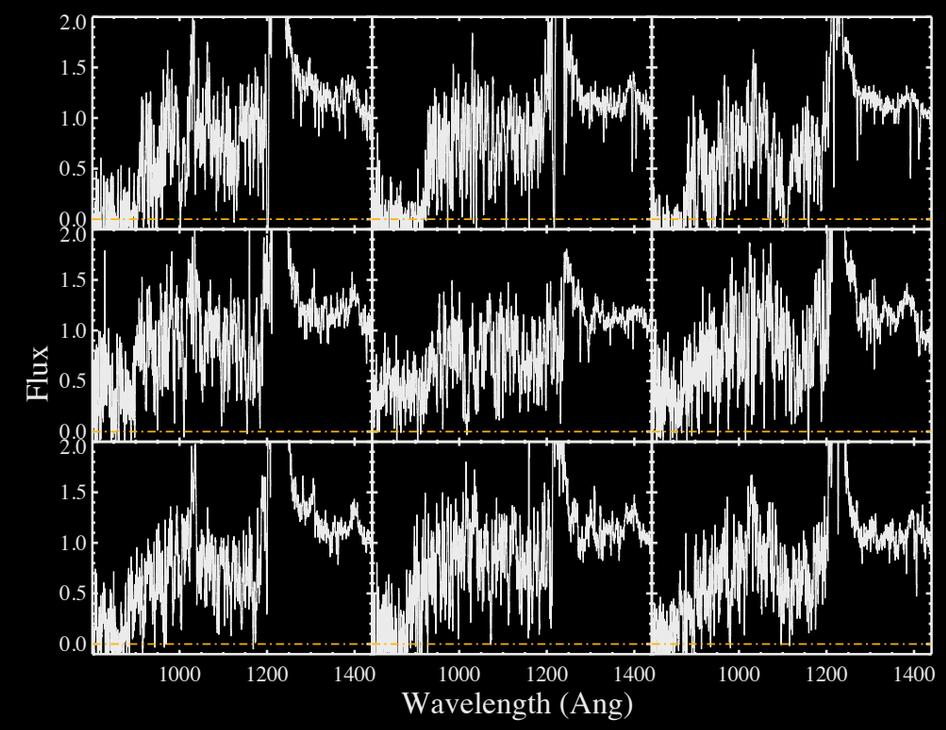

f_λ/f_{1450}
Rest Wavelength (Ang)
10

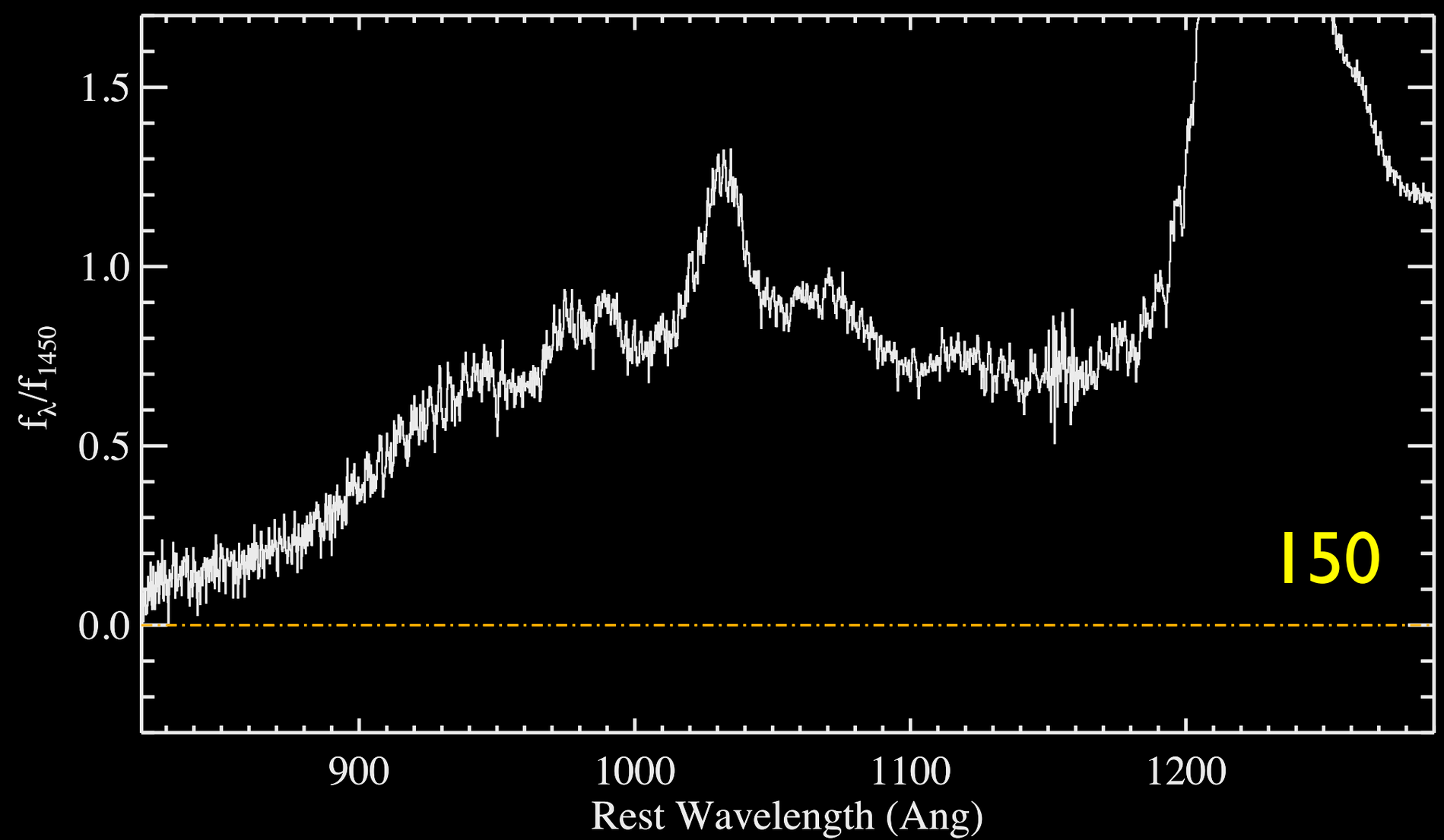

Flux
Wavelength (Ang)


Flux
Wavelength (Ang)

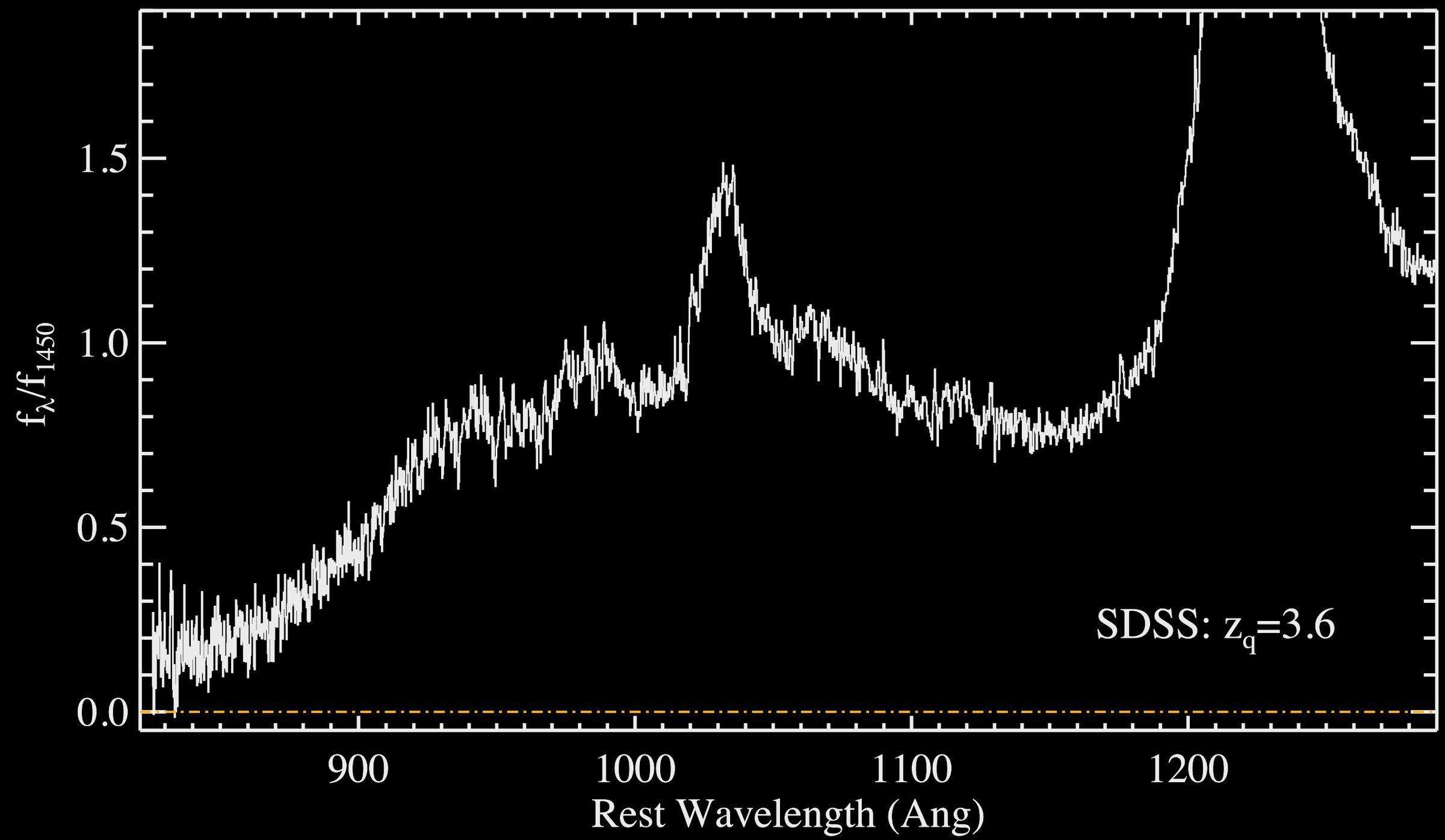

f_λ/f_{1450}
Rest Wavelength (Ang)
18


Flux
Wavelength (Ang)

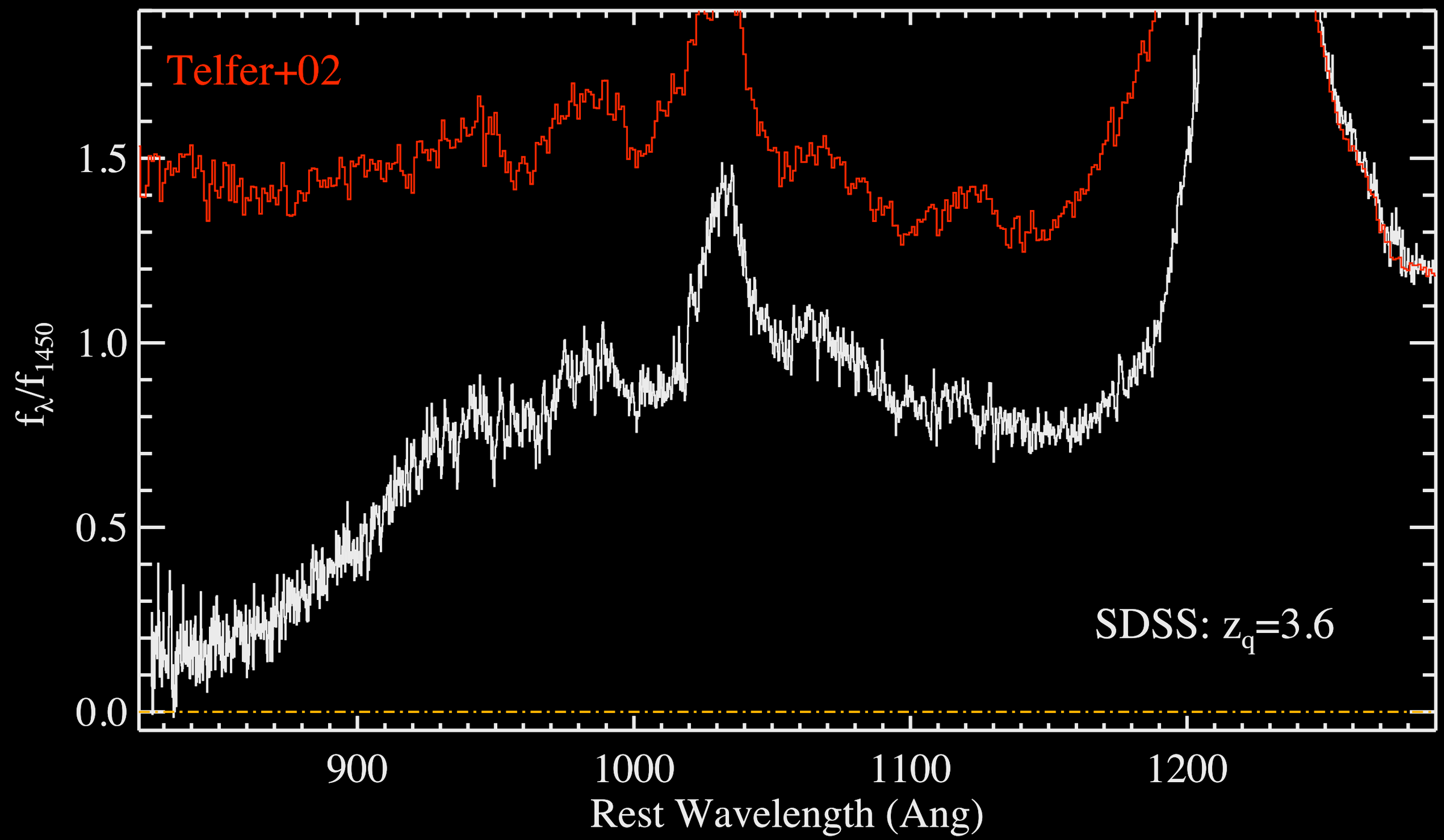

Flux
Wavelength (Ang)


f_λ/f_{1450}
Rest Wavelength (Ang)
150

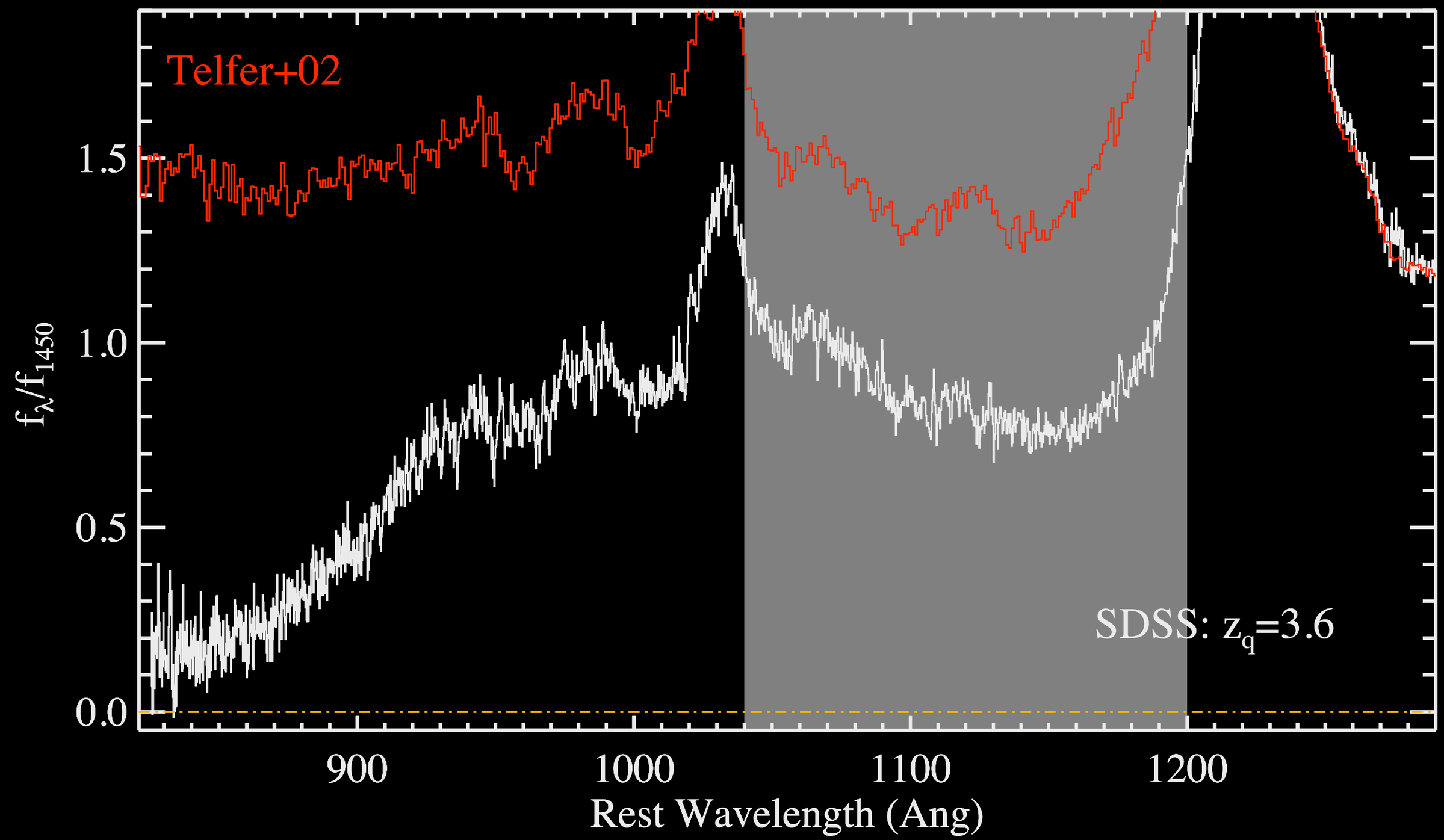
Lyα Opacity


1.5
1.0
0.5
0.0
f_λ/f_{1450}
SDSS: z_q=3.6
900
1000
1100
1200
Rest Wavelength (Ang)

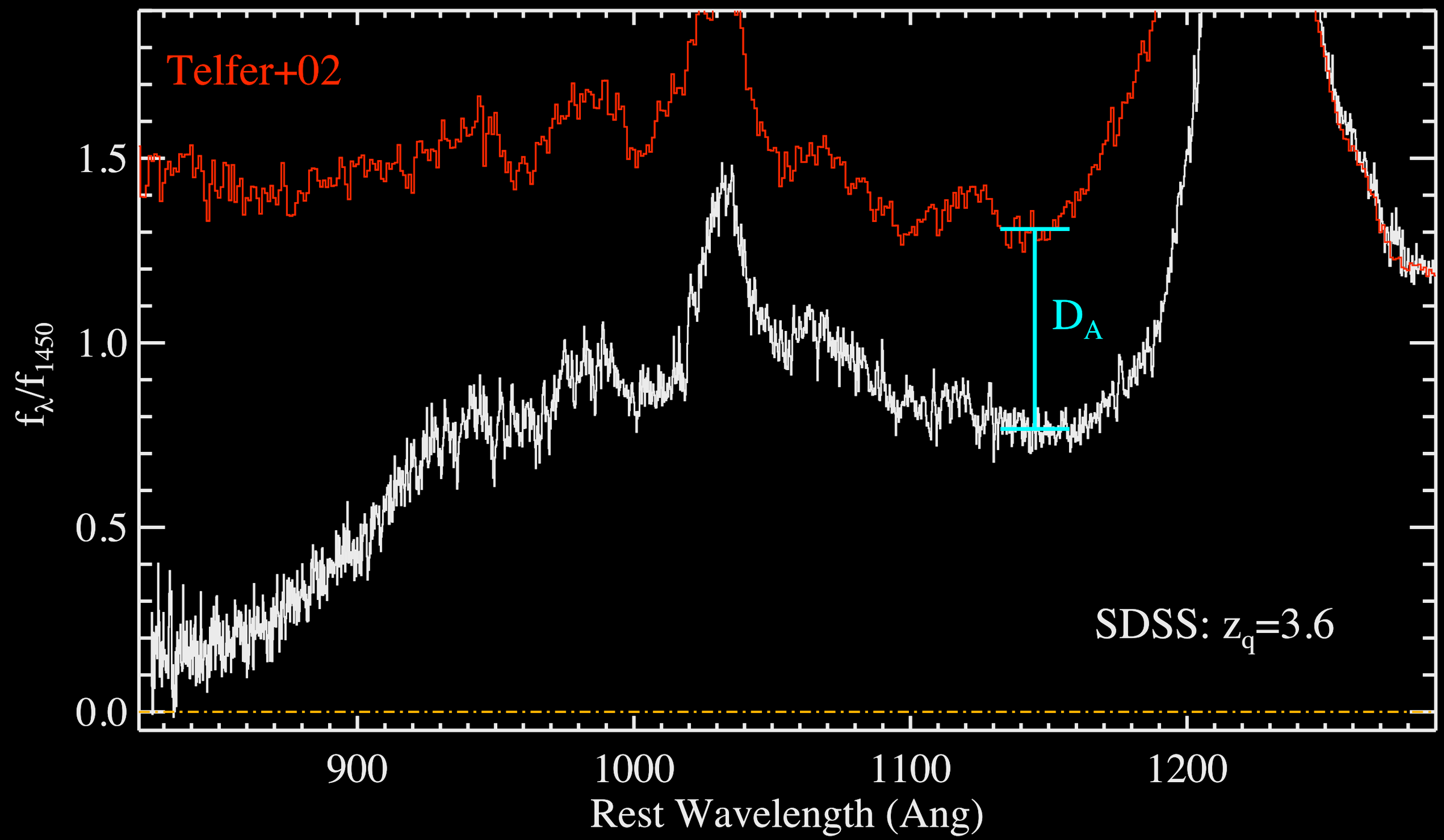
Lyα Opacity


Telfer+02
SDSS: z_q=3.6
f_λ/f_{1450}
0.0
0.5
1.0
1.5
900
1000
1100
1200
Rest Wavelength (Ang)

Lyα Opacity

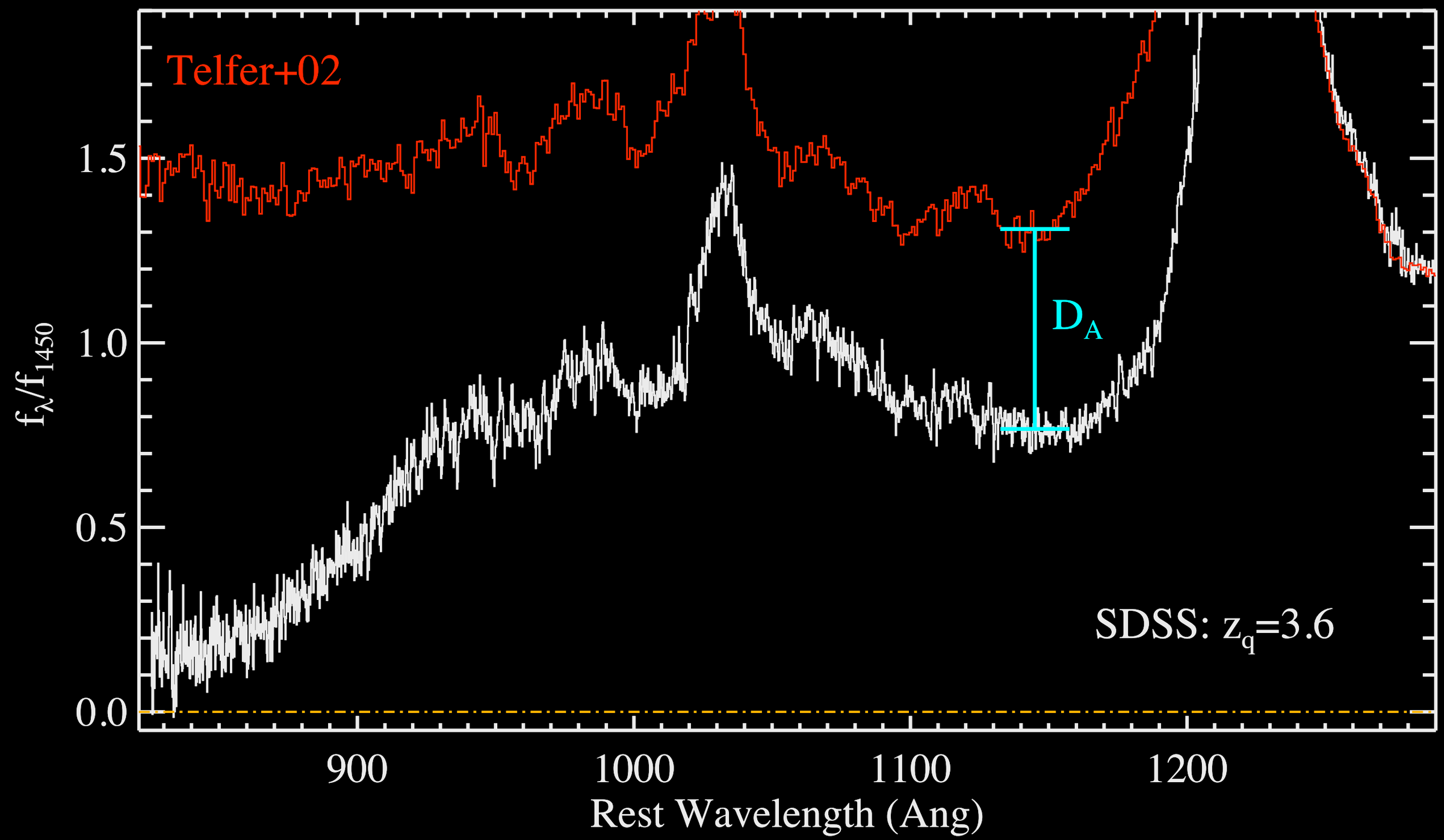

Telfer+02
SDSS: z_q=3.6
f_λ/f_{1450}
0.0
0.5
1.0
1.5
900
1000
1100
1200
Rest Wavelength (Ang)

Lyα Opacity



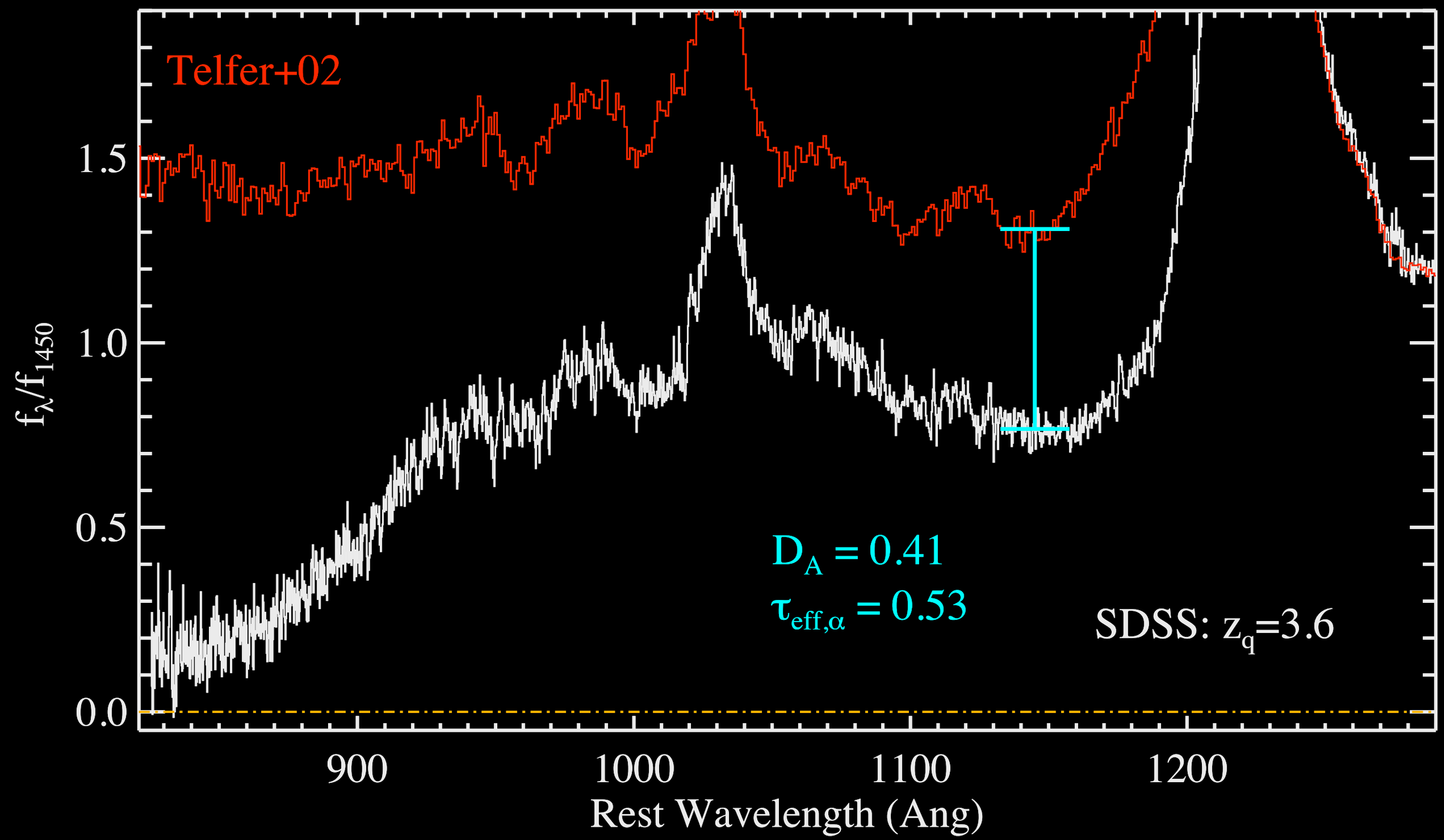
$$D_A = \left\langle 1 - \left(\frac{f_{\rm obs}}{f_{\rm int}} \right) \right\rangle$$

Lyα Opacity



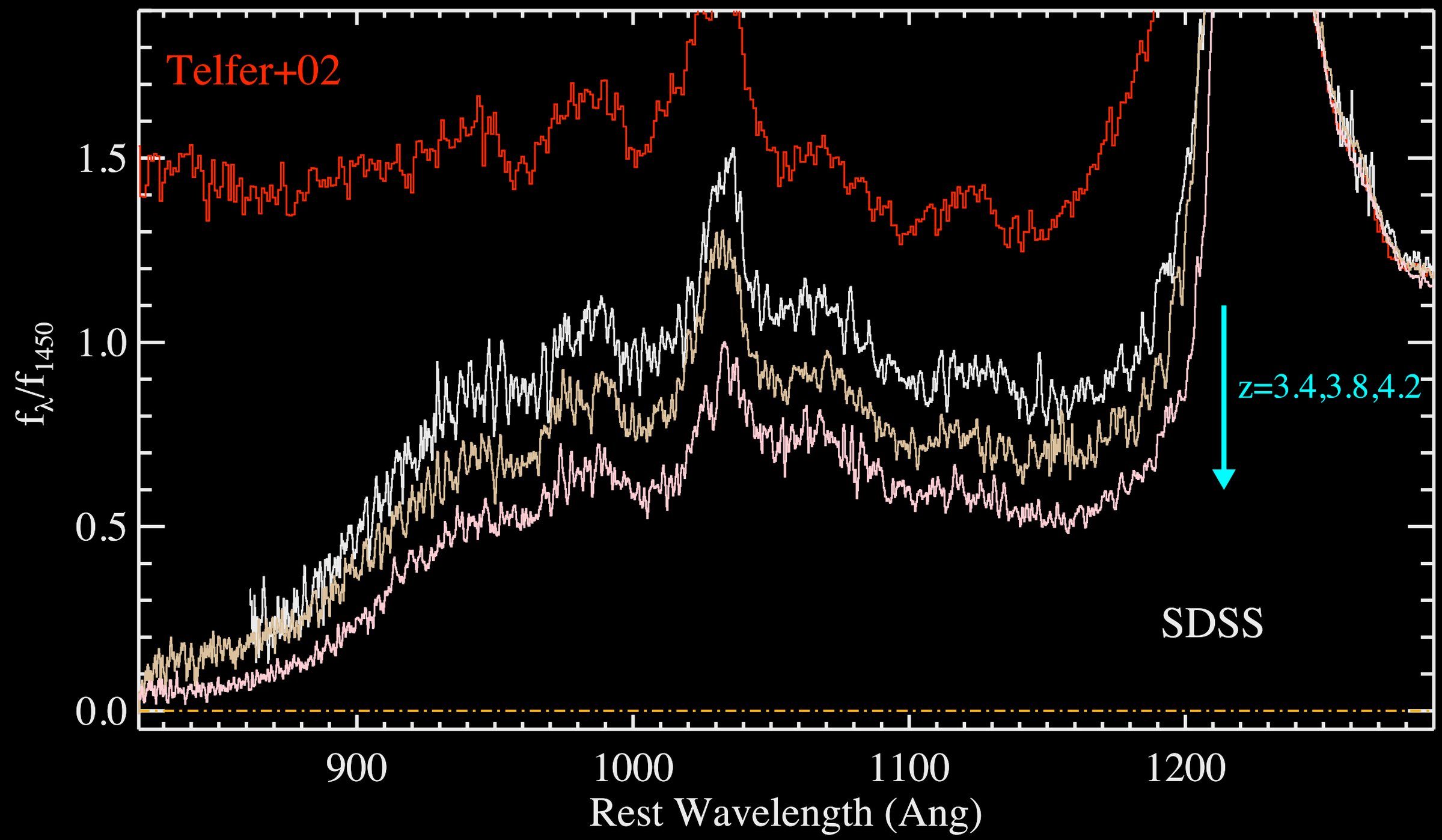
$$D_A = \left\langle 1 - \left(\frac{f_{\rm obs}}{f_{\rm int}} \right) \right\rangle \qquad \tau_{{\rm eff},\alpha} = -\ln\left[1 - D_A\right]$$

Lyα Opacity



$$D_A = \left\langle 1 - \left(\frac{f_{\rm obs}}{f_{\rm int}} \right) \right\rangle \qquad \tau_{\rm eff,\alpha} = -\ln\left[1 - D_A\right]$$

Lyα Opacity



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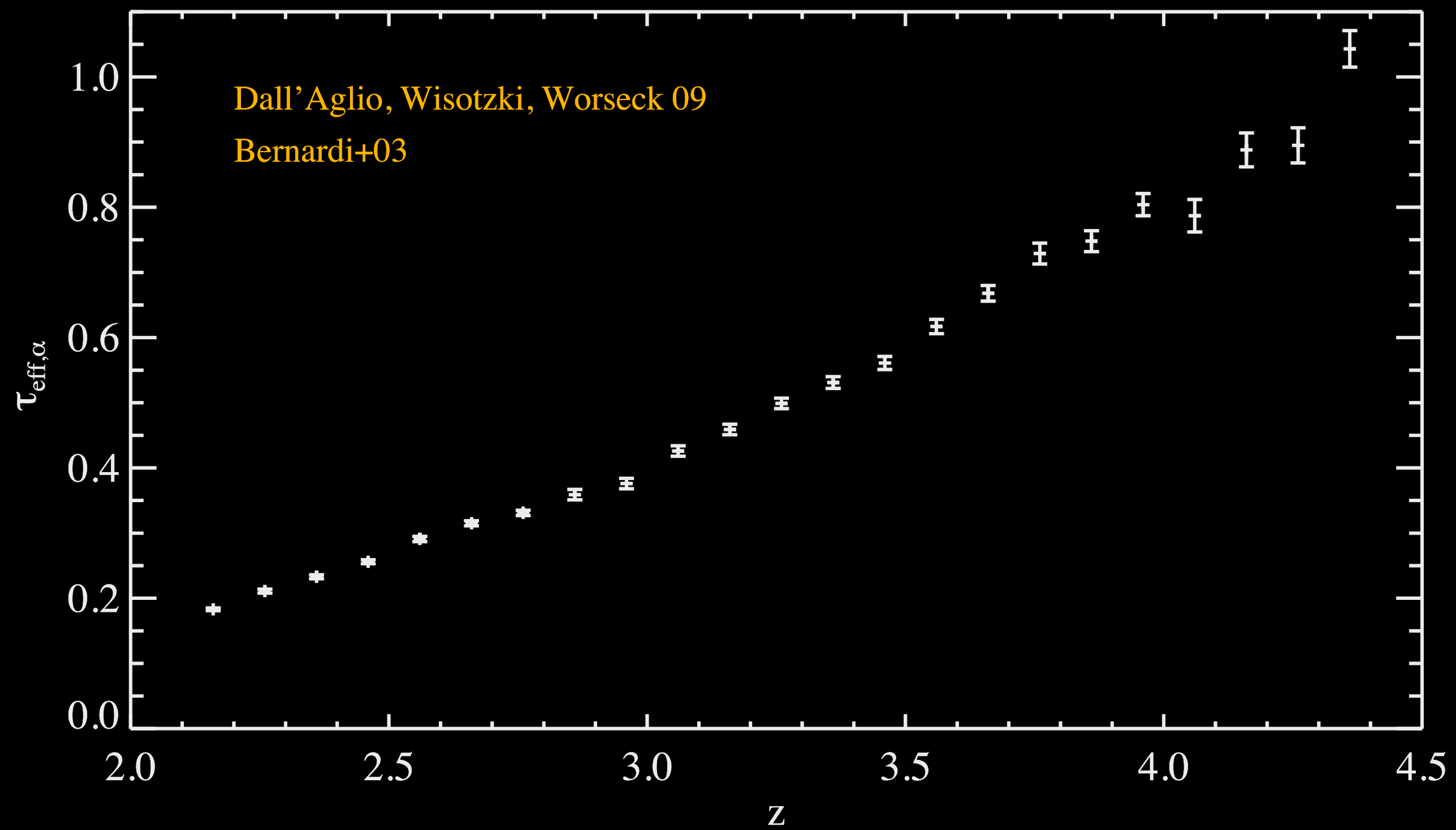
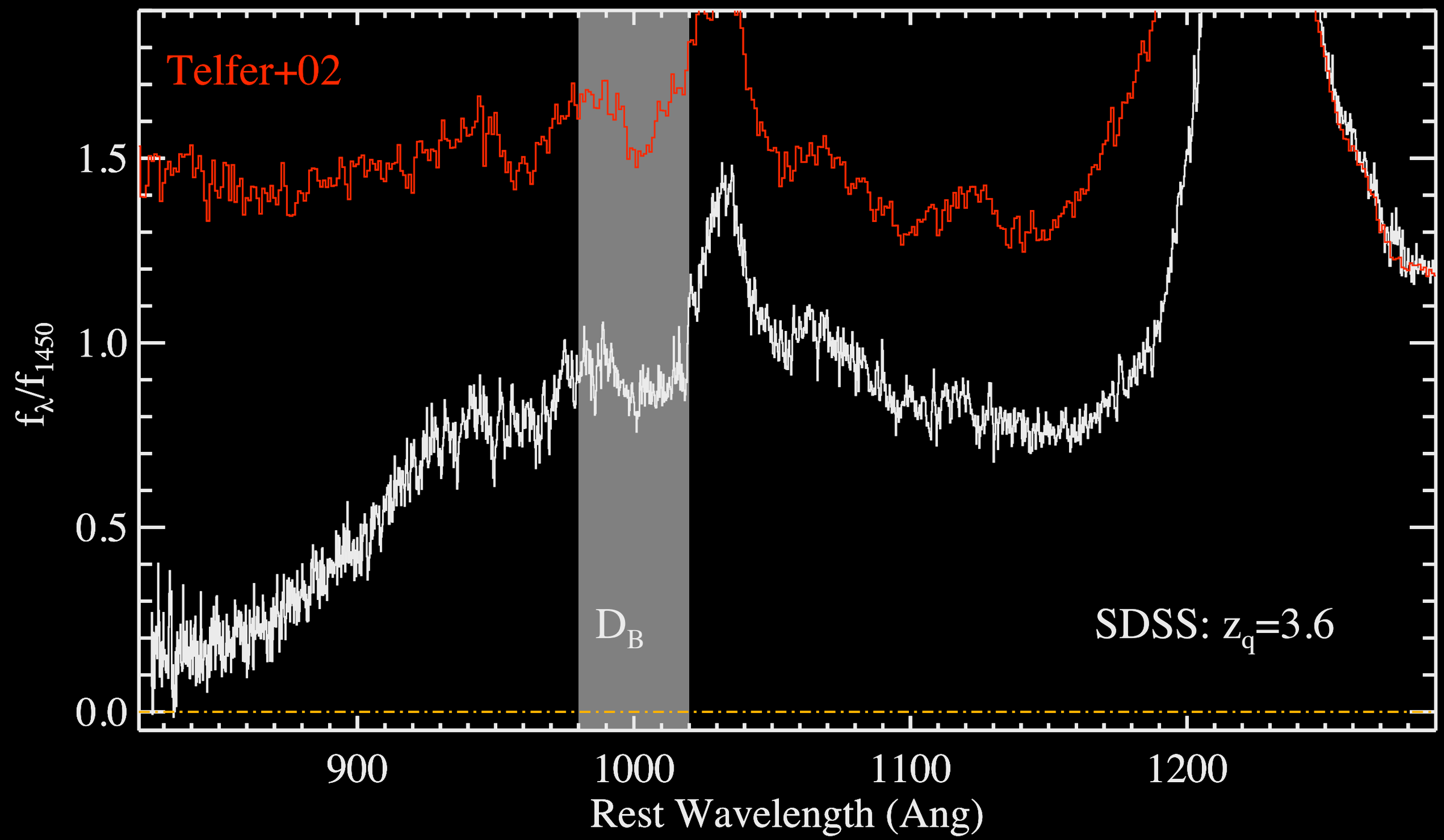
Lyα Opacity



$$D_A = \left\langle 1 - \left(\frac{f_{\mathrm{obs}}}{f_{\mathrm{int}}} \right) \right\rangle \qquad \tau_{\mathrm{eff},\alpha} = -\ln\left[1 - D_A\right]$$

Lyα Opacity



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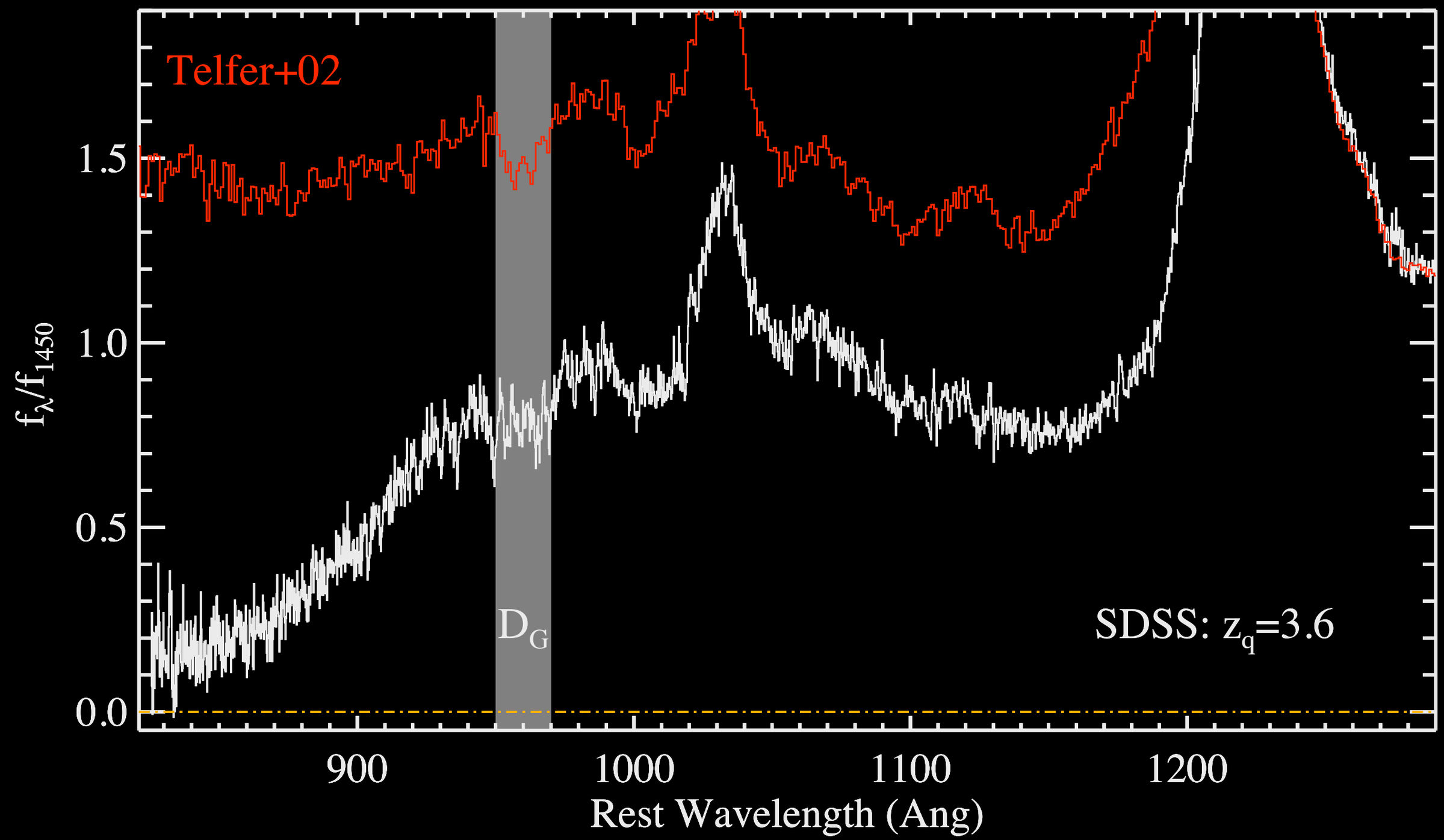
Lyα Opacity



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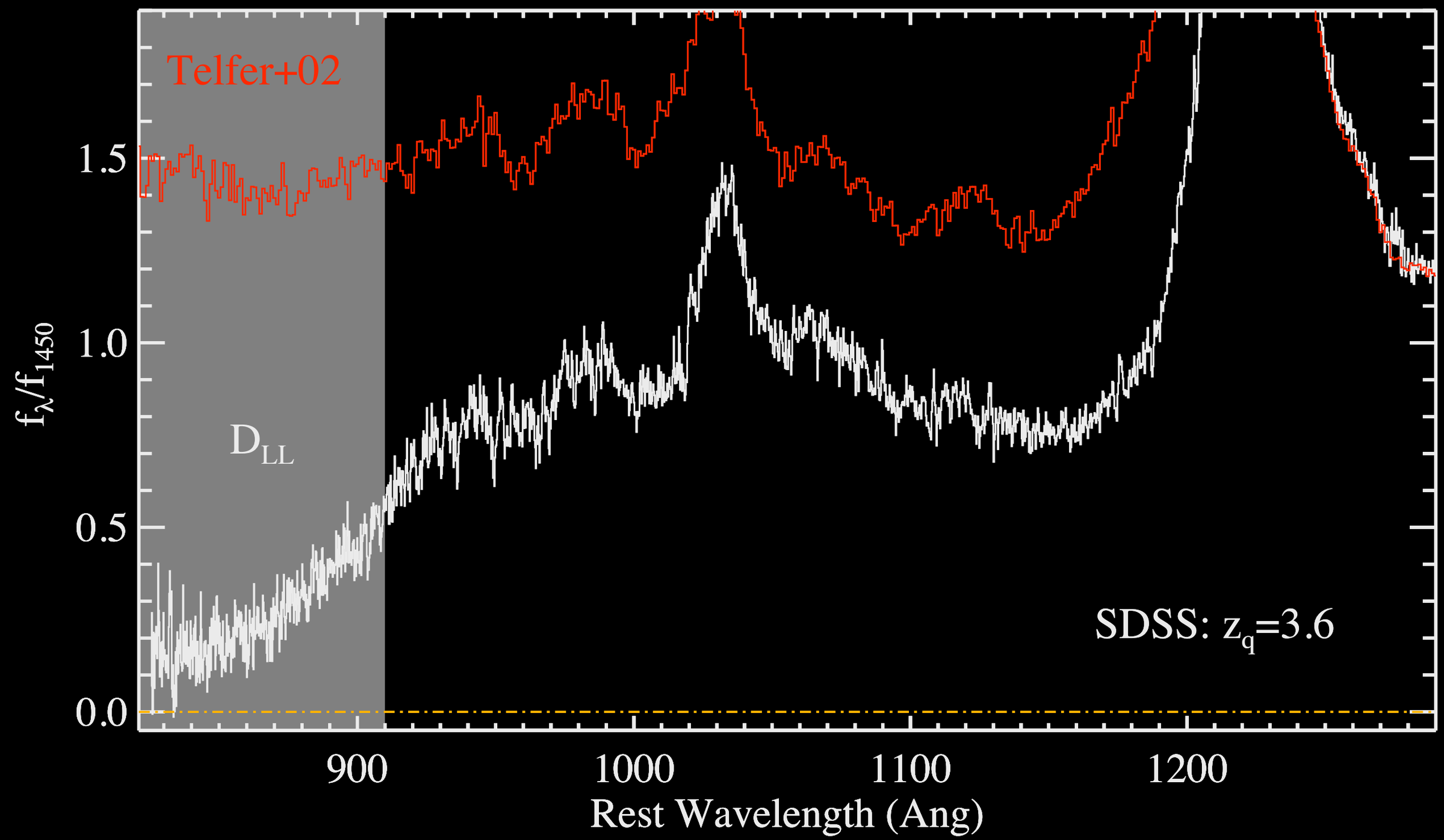
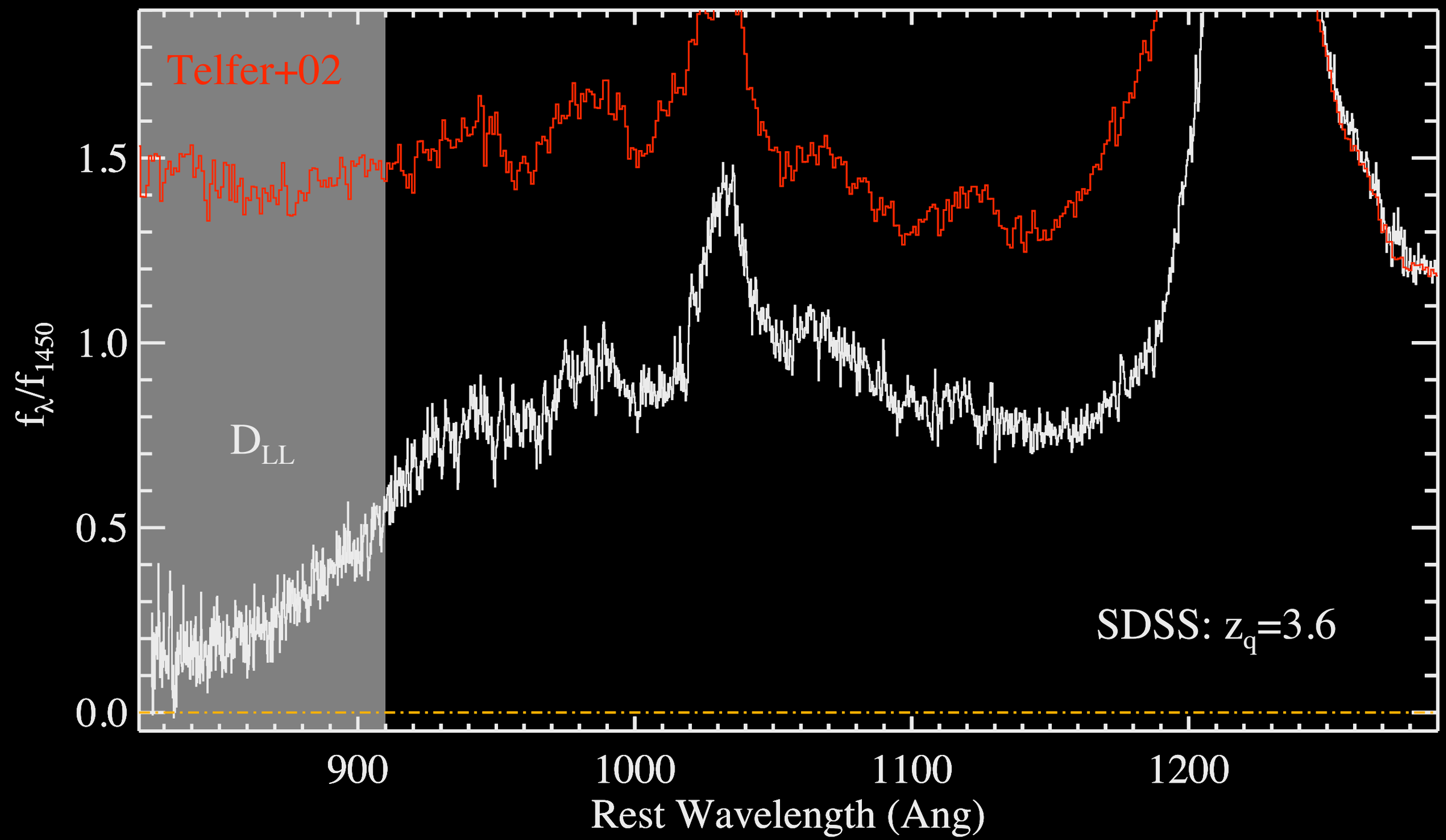
Lyα Opacity

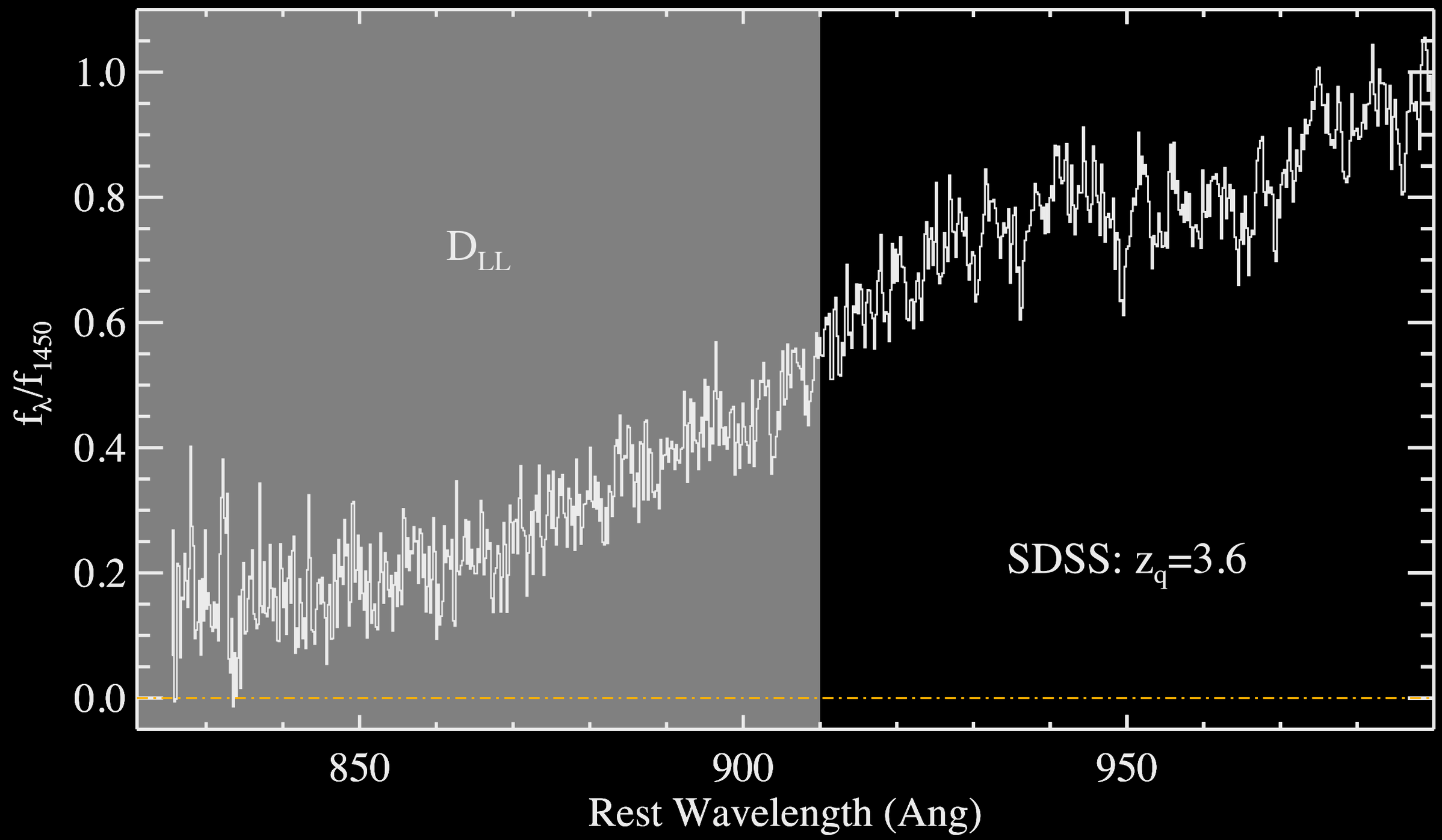


$$D_A = \left\langle 1 - \left(\frac{f_{\rm obs}}{f_{\rm int}} \right) \right\rangle \qquad \tau_{{\rm eff},\alpha} = -\ln\left[1 - D_A\right]$$

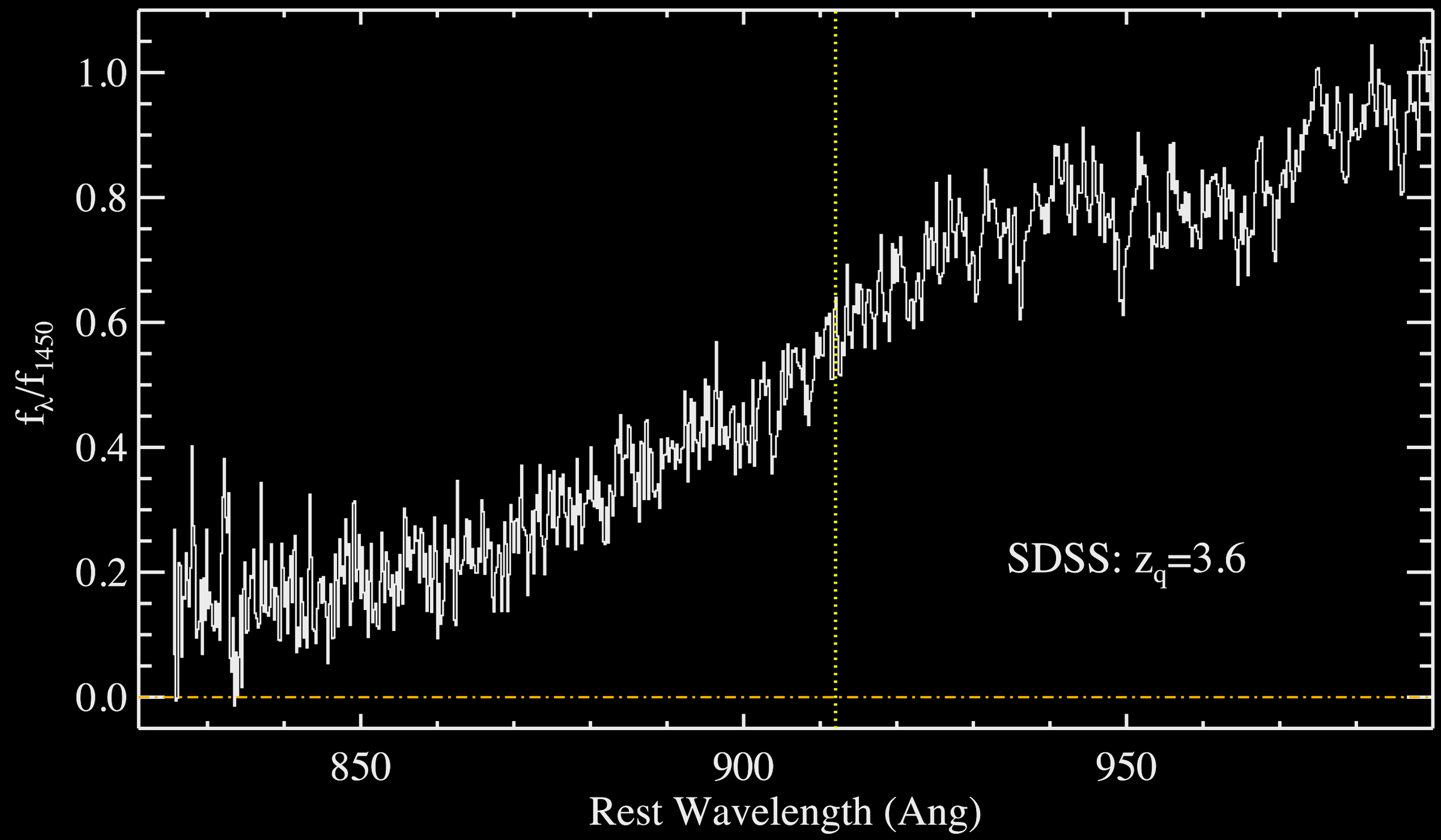
λ_{mfp}: Qualitative View



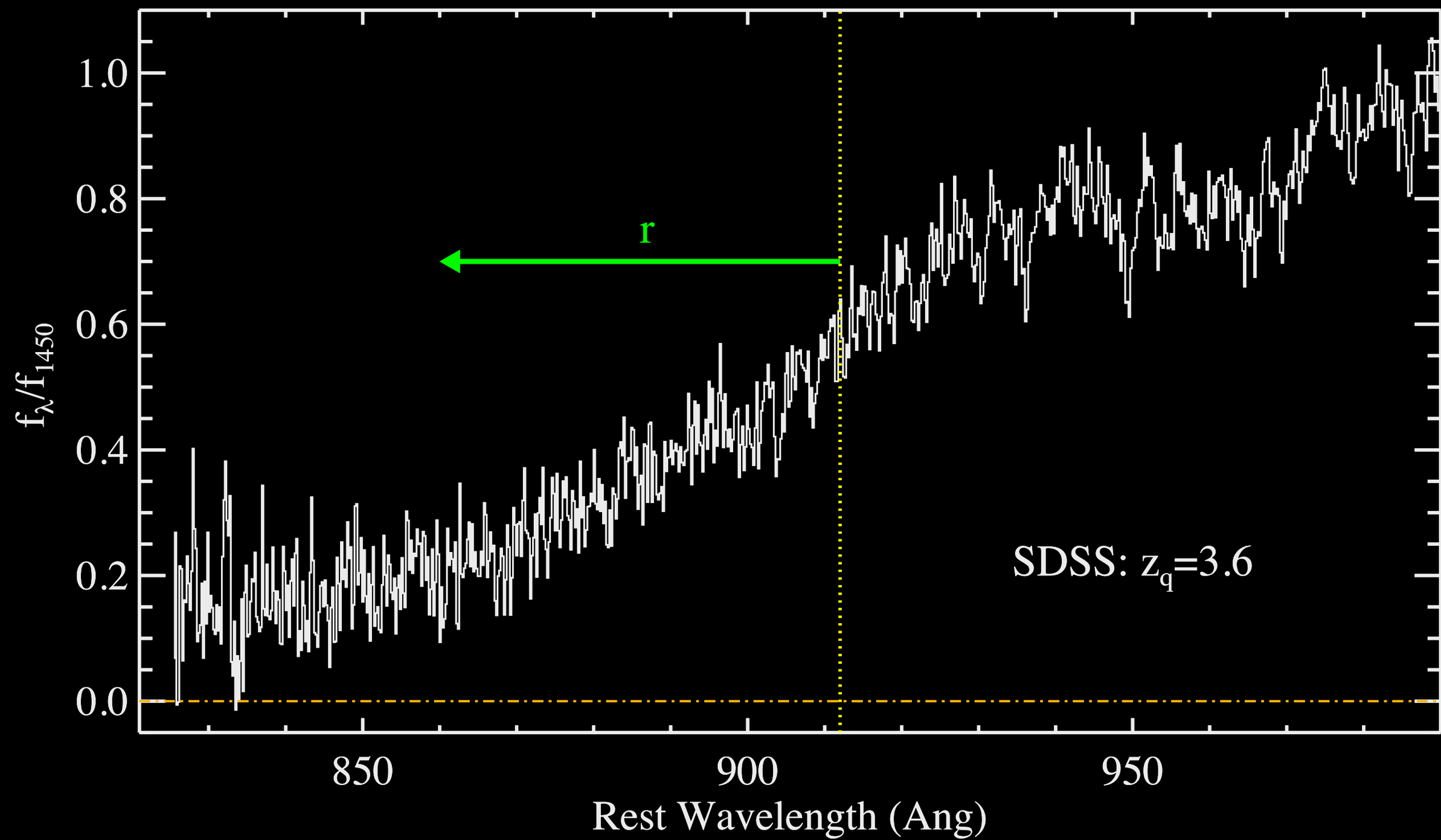
λ_{mfp}: Qualitative View



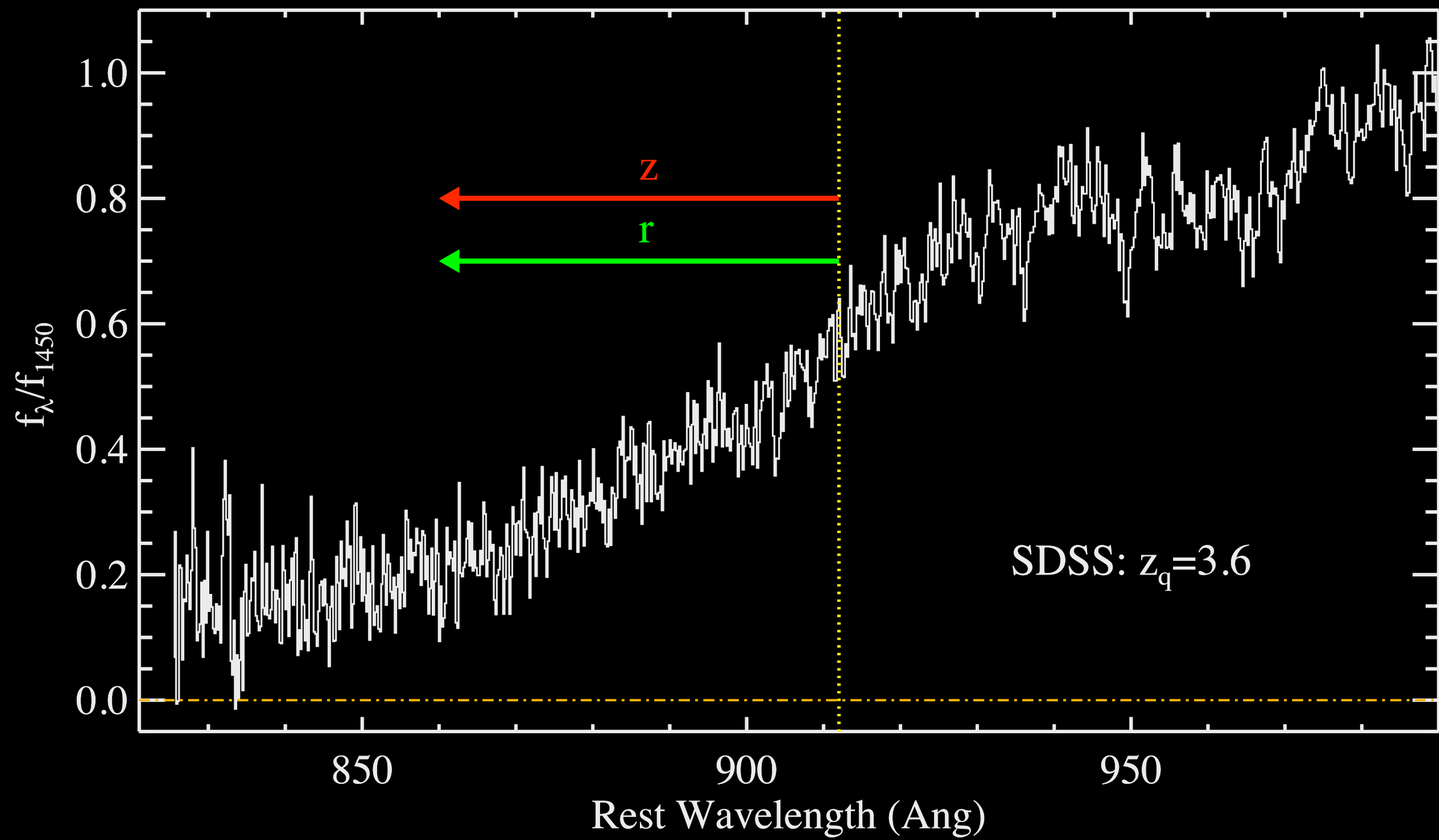
λ_{mfp}: Qualitative View



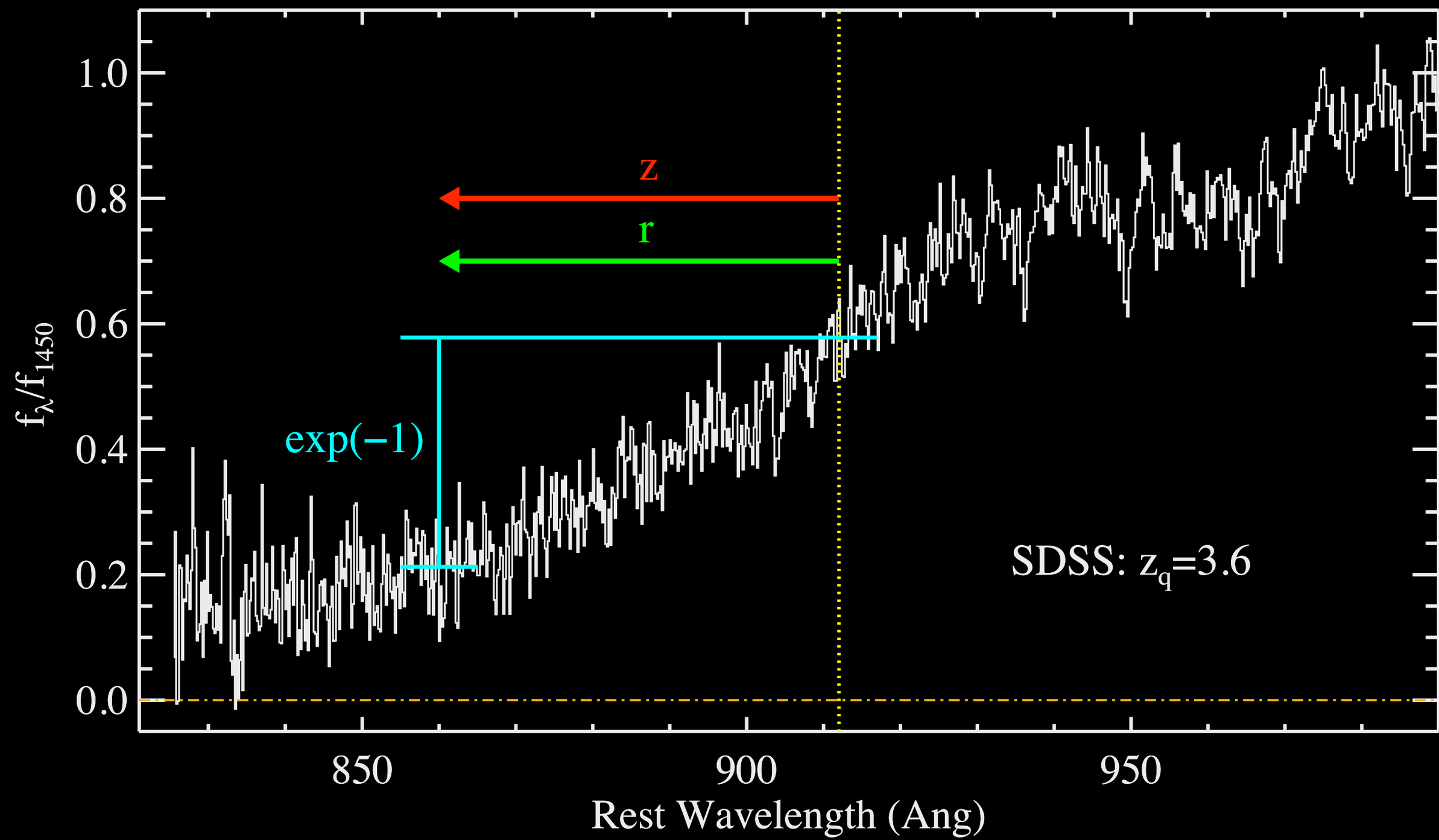
λ_{mfp}: Qualitative View



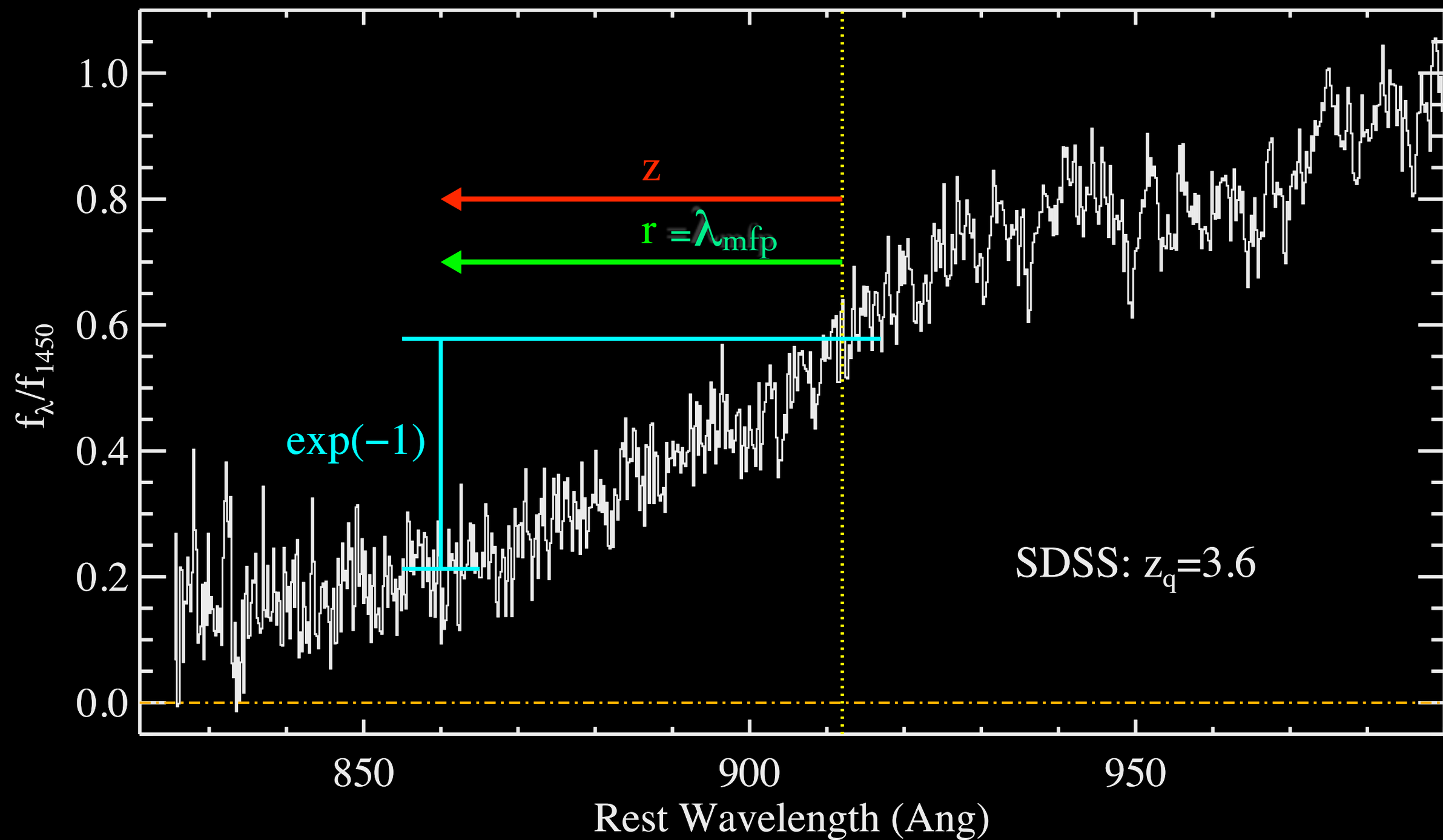
λ_{mfp}: Qualitative View



λ_{mfp}: Qualitative View



λ_{mfp}: Qualitative View



λ_{mfp}: Opacity Method

$$\tau_{\mathrm{eff,LL}}(r,\nu) = \int_0^r \kappa_{\mathrm{LL}}(r',\nu)\, dr'$$

Prochaska, Worseck, O'Meara 09

λ_{mfp}: Opacity Method

- Treat (average) LL absorption as a traditional opacity: $\kappa_{LL}(r,\nu)$
  - Integrate over the path traveled
    - Photon 'feels' the IGM opacity from $z=z_q$ until it redshifts beyond 1Ryd
    - Define this lower redshift as z_{912}

$$\tau_{\rm eff,LL}(r,\nu) = \int_0^r \kappa_{\rm LL}(r',\nu)\, dr'$$

$$z_{912}(\nu) \equiv \frac{\nu_{912}}{\nu}(1+z_q) \; - \; 1$$

Prochaska, Worseck, O'Meara 09

λ_{mfp}: Opacity Method

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  - Integrate over the path traveled
    - Photon 'feels' the IGM opacity from $z=z_q$ until it redshifts beyond 1Ryd
    - Define this lower redshift as z_{912}
- LL 'Opacity'
  - Separate frequency dependence
    - Photoionization: $\sigma \sim \nu^{-3}$
    - This is approximate and it ignores stimulated emission
  - Convert to redshift
    - Assume standard cosmology

$$\tau_{\rm eff,LL}(r,\nu) = \int_0^r \kappa_{\rm LL}(r',\nu)\, dr'$$

$$z_{912}(\nu) \equiv \frac{\nu_{912}}{\nu}(1+z_q) - 1$$

$$\kappa_{\rm LL}(r,\nu) \equiv \tilde{\kappa}_{912}(r)\left(\frac{\nu}{\nu_{912}}\right)^{-3}$$

$$\kappa_{\rm LL}(z) = \tilde{\kappa}_{912}(z)\left(\frac{1+z}{1+z_{912}}\right)^{-3}$$

Prochaska, Worseck, O'Meara 09

λ_{mfp}: Opacity Method

- Treat (average) LL absorption as a traditional opacity: $\kappa_{LL}(r,\nu)$
  - Integrate over the path traveled
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$$z_{912}(\nu) \equiv \frac{\nu_{912}}{\nu}(1+z_q) - 1$$

$$\kappa_{\rm LL}(r,\nu) \equiv \tilde{\kappa}_{912}(r)\left(\frac{\nu}{\nu_{912}}\right)^{-3}$$

$$\kappa_{\rm LL}(z) = \tilde{\kappa}_{912}(z)\left(\frac{1+z}{1+z_{912}}\right)^{-3}$$

$$\frac{dr}{dz} \equiv \frac{c}{H(z)(1+z)} \approx \frac{c}{H_0\Omega_{\rm m}^{1/2}}(1+z)^{-5/2}$$

Prochaska, Worseck, O'Meara 09

λ_{mfp}: Opacity Method

- Treat (average) LL absorption as a traditional opacity: $\kappa_{LL}(r,\nu)$
  - Integrate over the path traveled
    - Photon 'feels' the IGM opacity from $z=z_q$ until it redshifts beyond 1Ryd
    - Define this lower redshift as z_{912}
- LL 'Opacity'
  - Separate frequency dependence
    - Photoionization: $\sigma \sim \nu^{-3}$
    - This is approximate and it ignores stimulated emission
  - Convert to redshift
    - Assume standard cosmology
- Calculate $\tau_{eff,LL}$
  - In practice, $\tilde{\kappa}_{912}(z')$ may be considered a constant
    - If so, we have a <u>one parameter</u> model!

$$\tau_{\rm eff,LL}(r,\nu) = \int_0^r \kappa_{\rm LL}(r',\nu)\, dr'$$

$$z_{912}(\nu) \equiv \frac{\nu_{912}}{\nu}(1+z_q) \; - \; 1$$

$$\kappa_{\rm LL}(r,\nu) \equiv \tilde{\kappa}_{912}(r)\left(\frac{\nu}{\nu_{912}}\right)^{-3}$$

$$\kappa_{\rm LL}(z) = \tilde{\kappa}_{912}(z)\left(\frac{1+z}{1+z_{912}}\right)^{-3}$$

$$\frac{dr}{dz} \equiv \frac{c}{H(z)(1+z)} \approx \frac{c}{H_0\Omega_{\rm m}^{1/2}}\,(1+z)^{-5/2}$$

$$\tau_{\rm eff,LL}(z_{912}, z_q) = \frac{c}{H_0\Omega_{\rm m}^{1/2}}(1+z_{912})^3 \int_{z_{912}}^{z_q} \tilde{\kappa}_{912}(z')\,(1+z')^{-11/2}\, dz'$$

Prochaska, Worseck, O'Meara 09

λ_{mfp}: Opacity Method

- Treat (average) LL absorption as a traditional opacity: $\kappa_{LL}(r,\nu)$
  - Integrate over the path traveled
    - Photon 'feels' the IGM opacity from $z=z_q$ until it redshifts beyond 1Ryd
    - Define this lower redshift as z_{912}
- LL 'Opacity'
  - Separate frequency dependence
    - Photoionization: $\sigma \sim \nu^{-3}$
    - This is approximate and it ignores stimulated emission
  - Convert to redshift
    - Assume standard cosmology
- Calculate $\tau_{eff,LL}$
  - In practice, $\tilde{\kappa}_{912}(z')$ may be considered a constant
    - If so, we have a one parameter model!

$$\tau_{\rm eff,LL}(r,\nu) = \int_0^r \kappa_{\rm LL}(r',\nu)\, dr'$$

$$z_{912}(\nu) \equiv \frac{\nu_{912}}{\nu}(1+z_q) - 1$$

$$\kappa_{\rm LL}(r,\nu) \equiv \tilde{\kappa}_{912}(r)\left(\frac{\nu}{\nu_{912}}\right)^{-3}$$

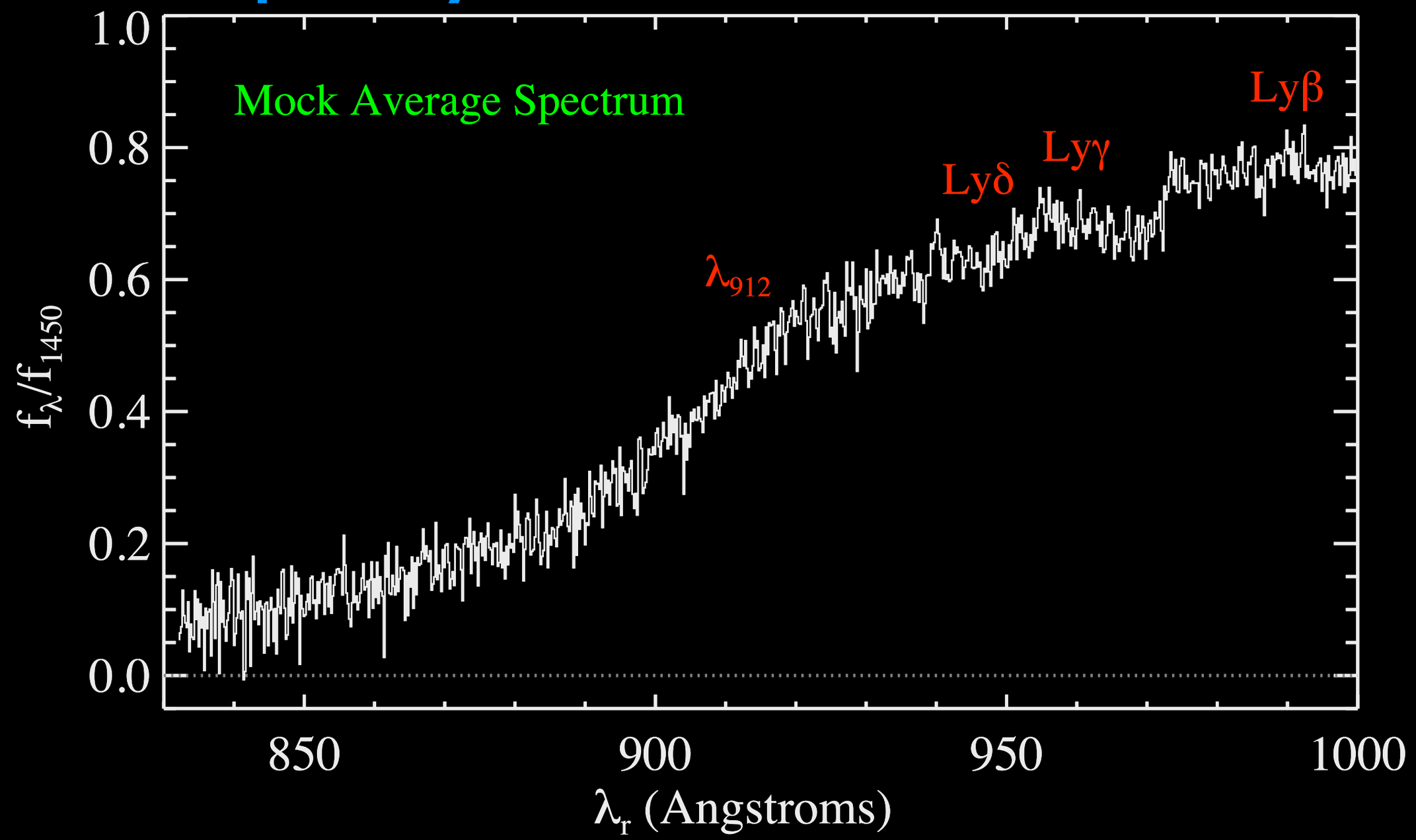
$$\kappa_{\rm LL}(z) = \tilde{\kappa}_{912}(z)\left(\frac{1+z}{1+z_{912}}\right)^{-3}$$

$$\frac{dr}{dz} \equiv \frac{c}{H(z)(1+z)} \approx \frac{c}{H_0\Omega_{\rm m}^{1/2}}\,(1+z)^{-5/2}$$

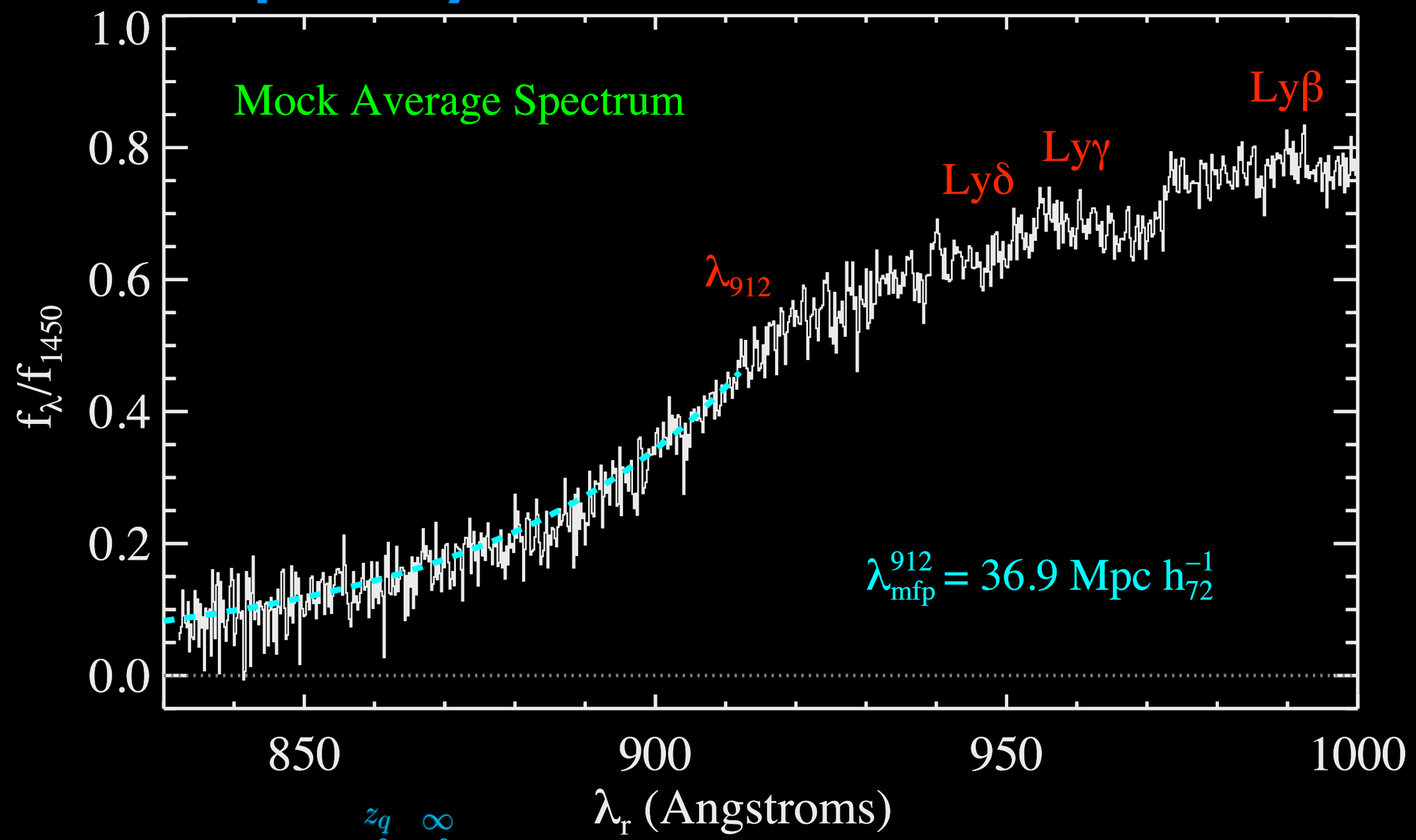
$$\tau_{\rm eff,LL}(z_{912}, z_q) = \frac{c}{H_0\Omega_{\rm m}^{1/2}}(1+z_{912})^3 \int_{z_{912}}^{z_q} \tilde{\kappa}_{912}(z')(1+z')^{-11/2}\, dz'$$

Prochaska, Worseck, O'Meara 09

The Opacity Method: Does it work?

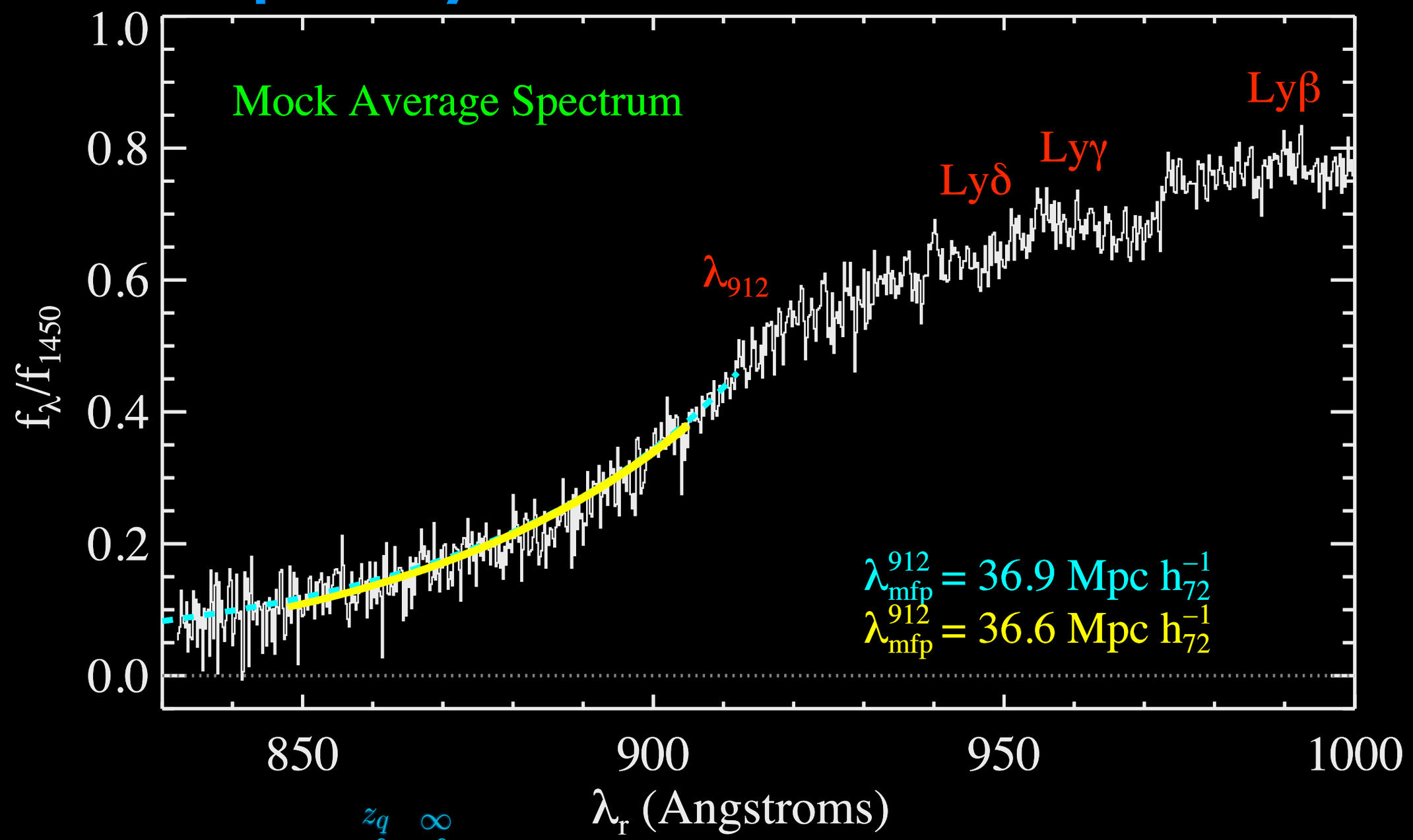


The Opacity Method: Does it work?



$$\tau_{\rm eff,LL}(z_{912}, z_q) = \int_{z_{912}}^{z_q} \int_0^{\infty} f(N_{\rm HI}, z')\{1 - \exp[-N_{\rm HI}\sigma_{\rm ph}(z')]\} dN_{\rm HI} dz'$$

The Opacity Method: Does it work?



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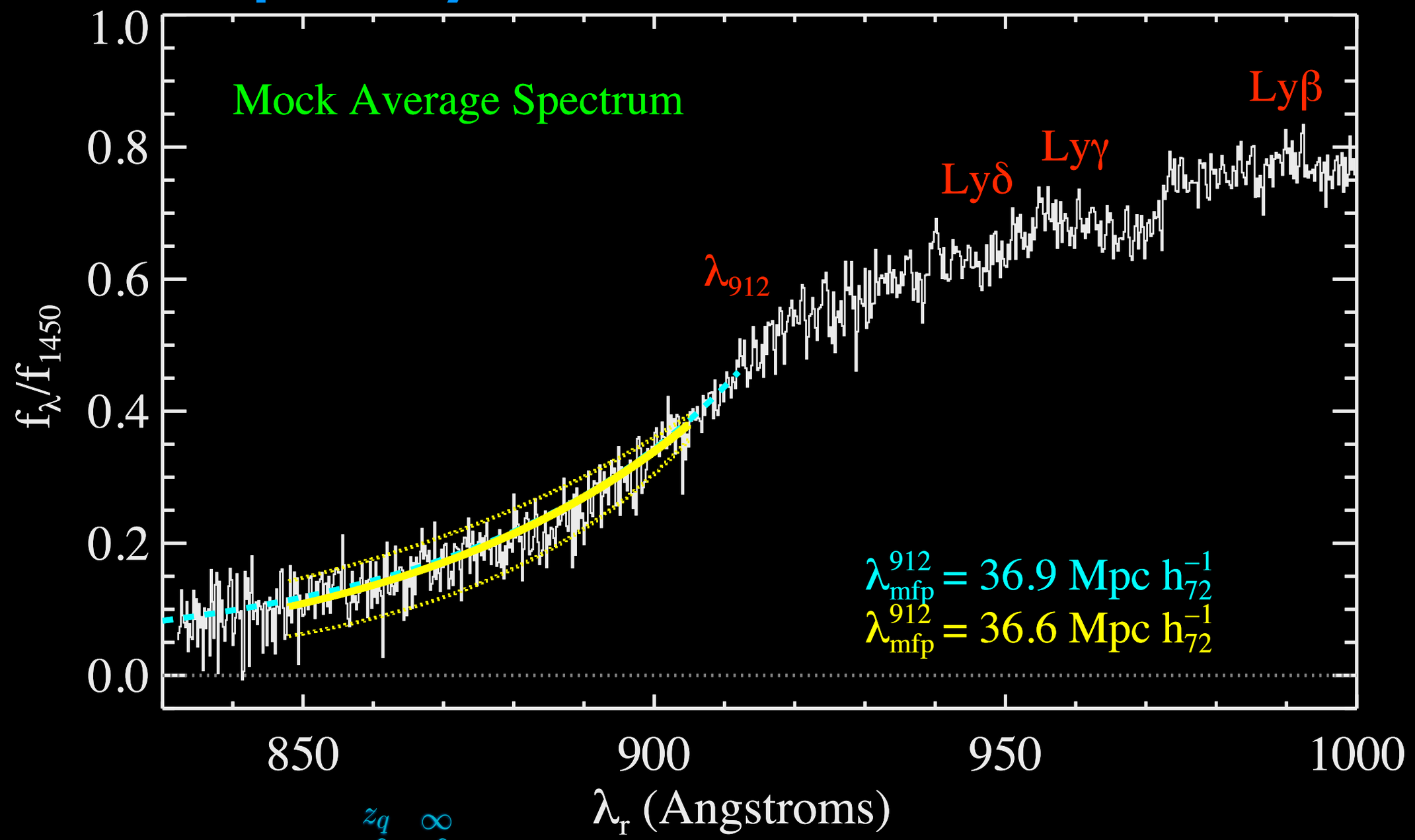

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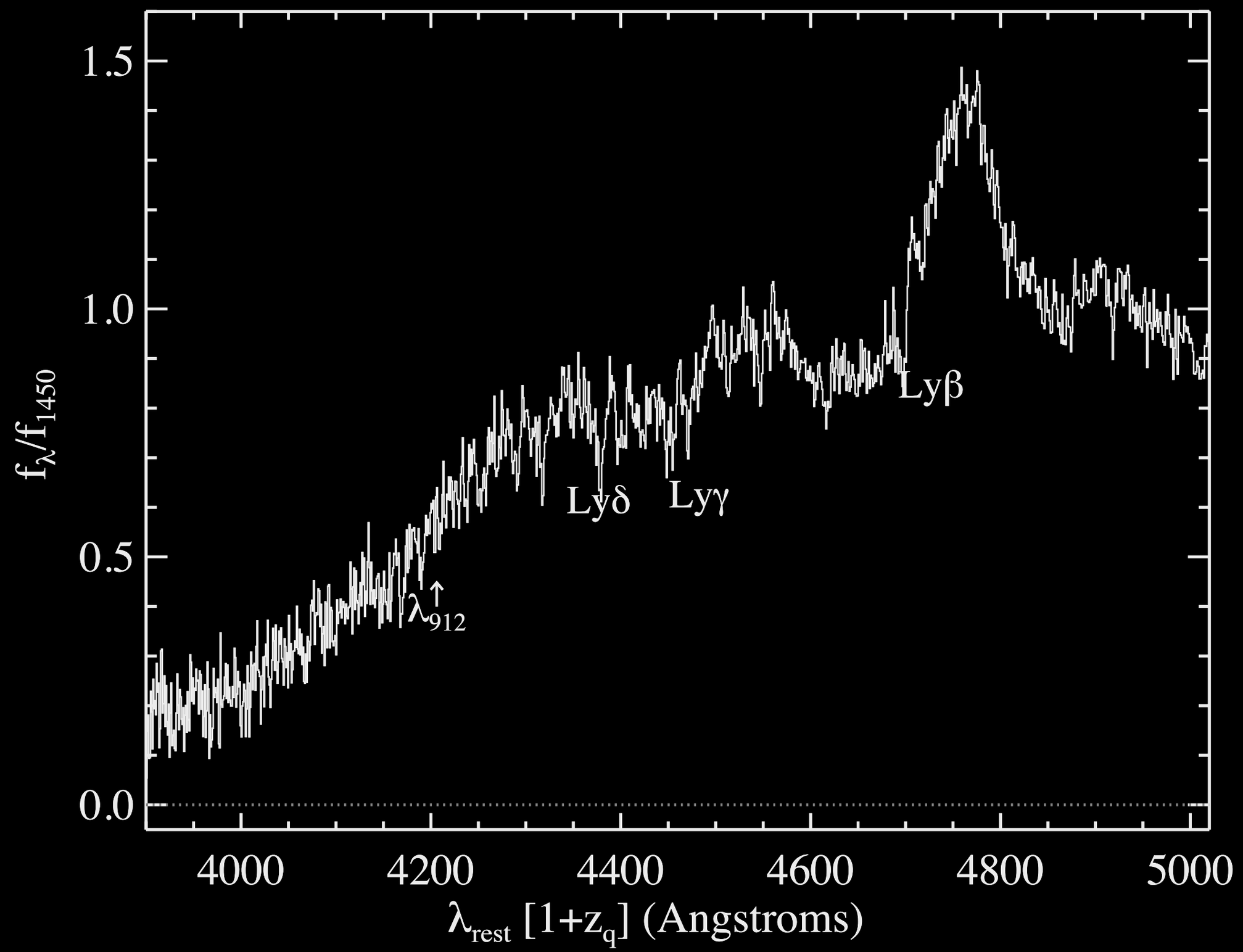
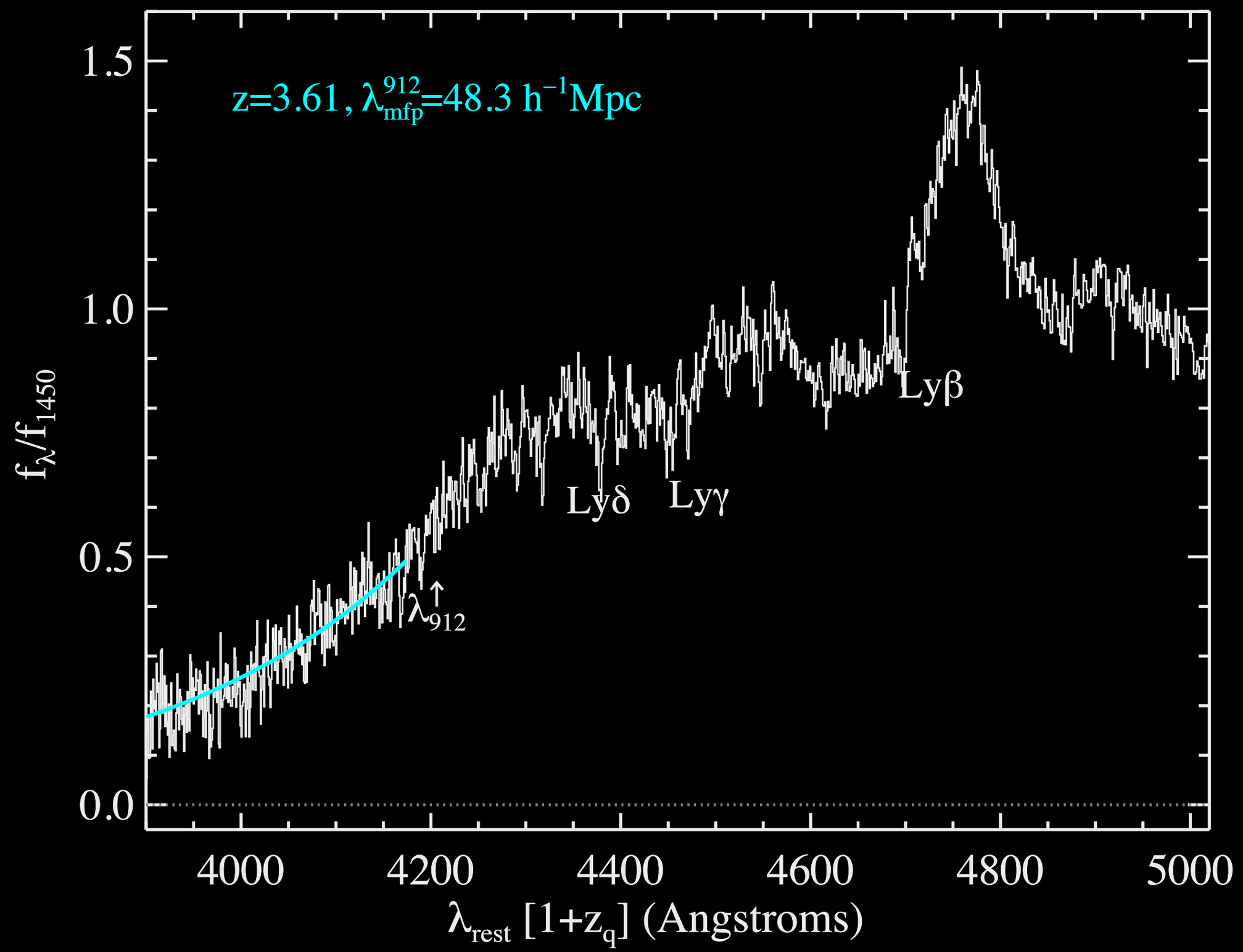
SDSS Stacked Quasar Spectra



SDSS Stacked Quasar Spectra



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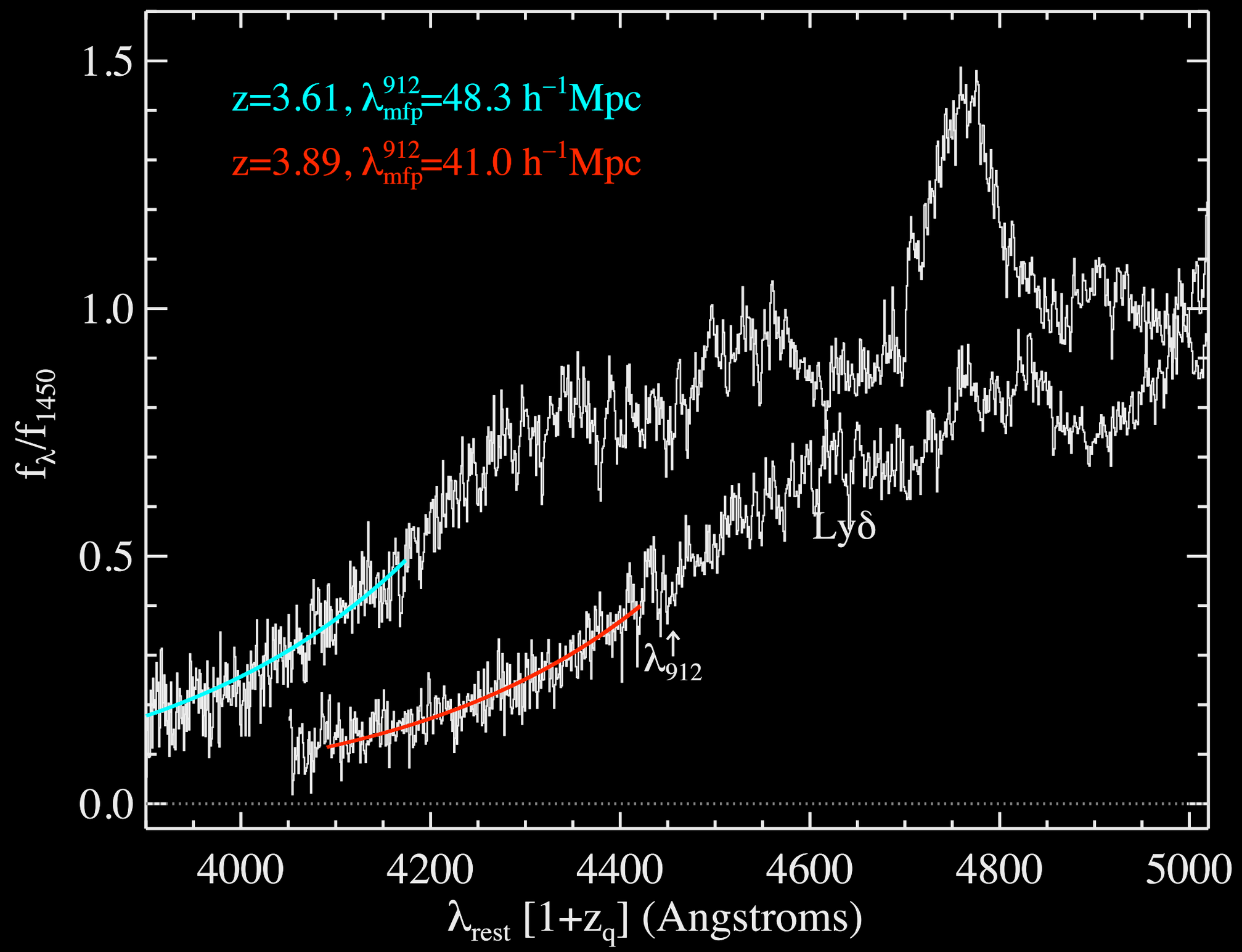

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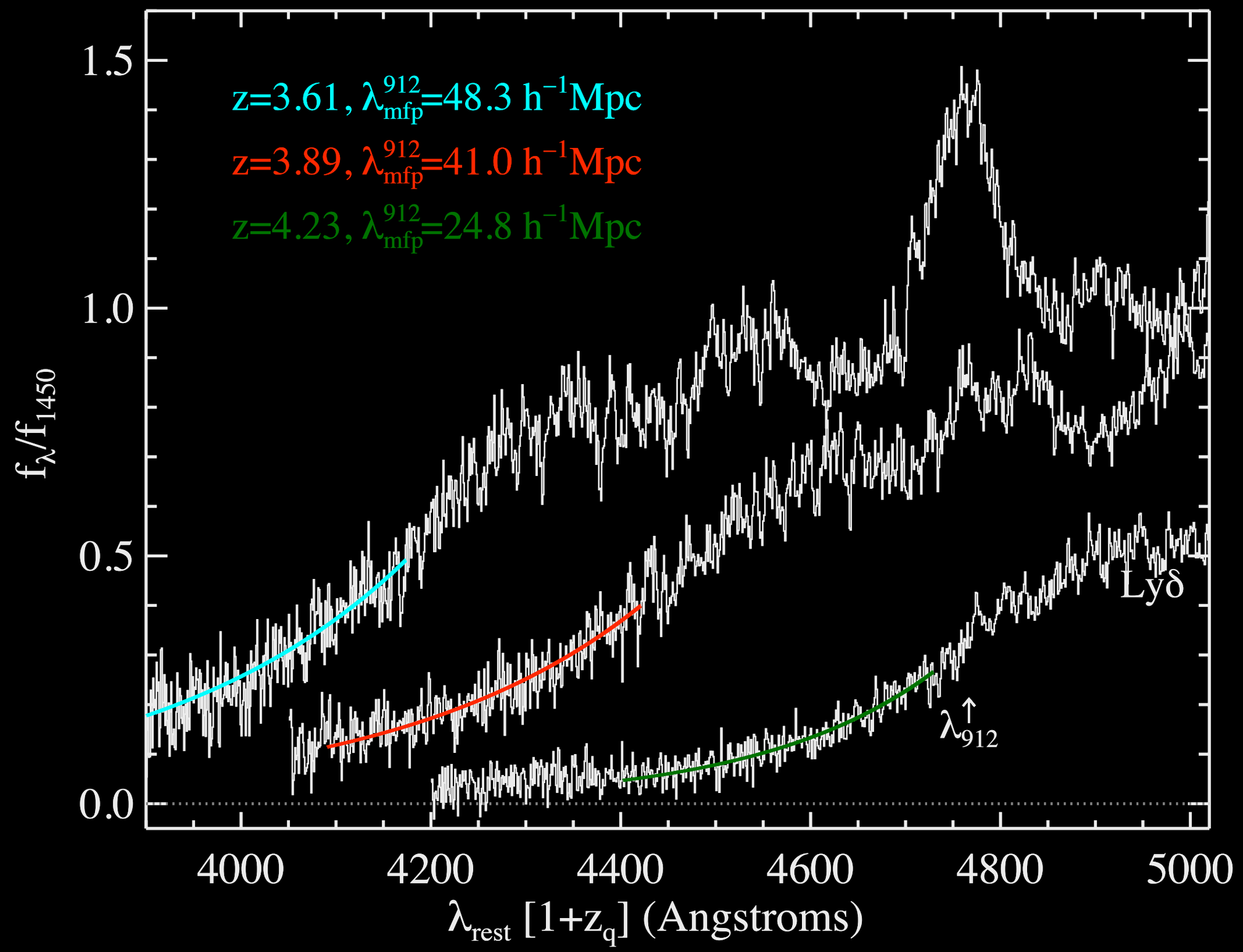
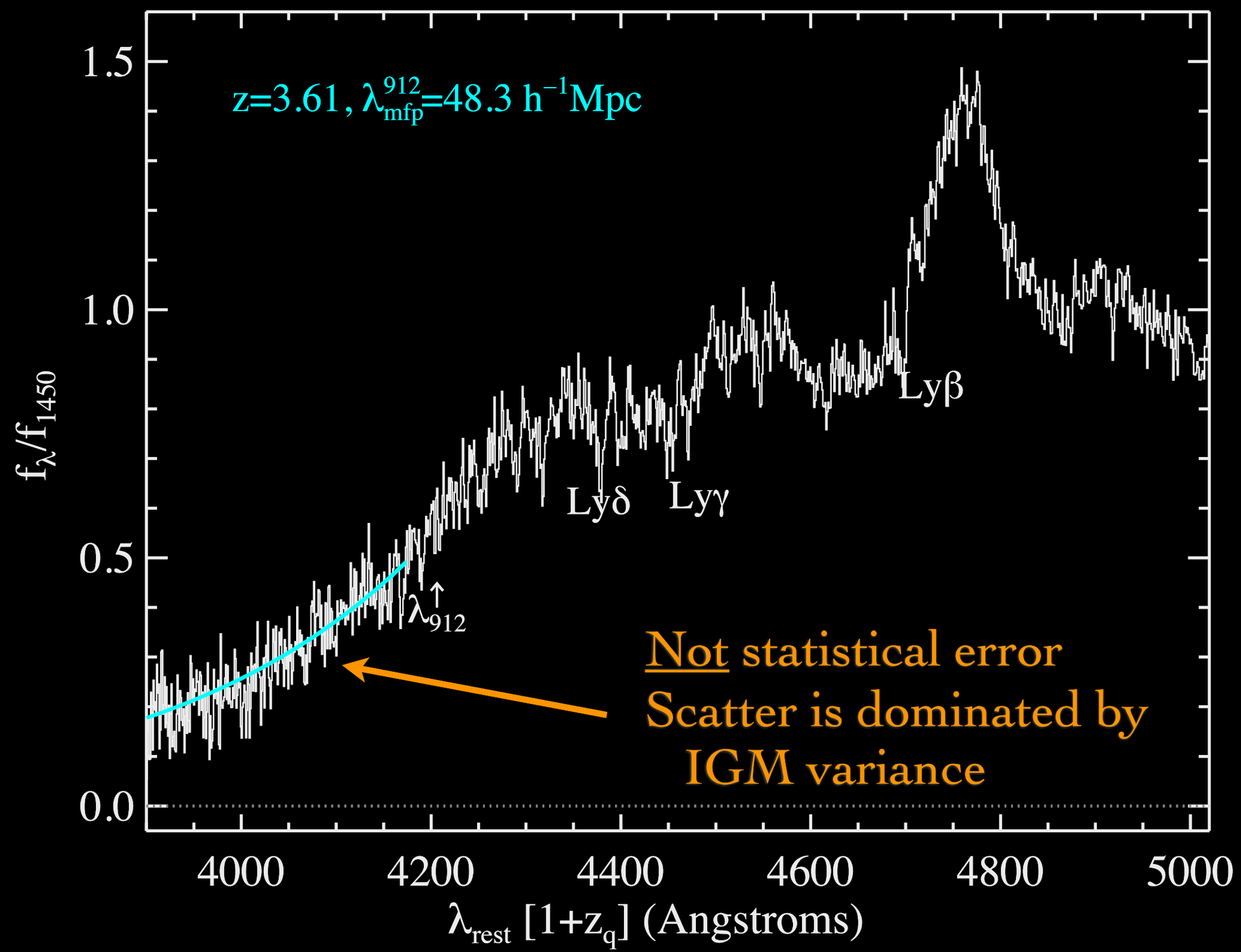
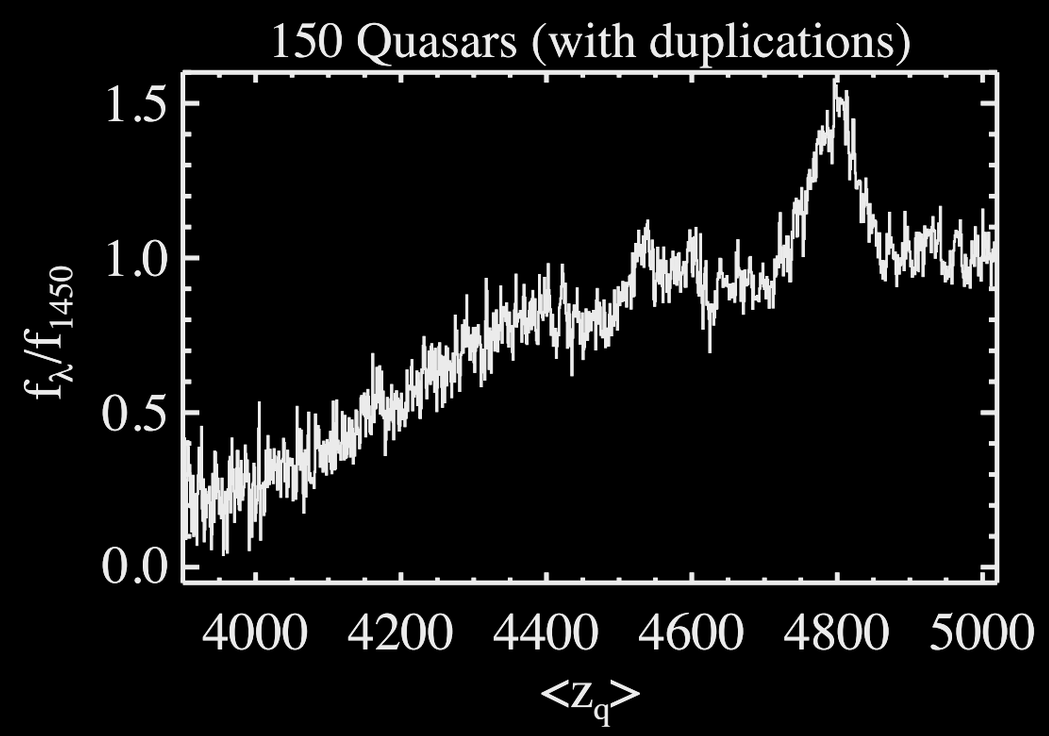


Bootstrap Errors



Not statistical error
Scatter is dominated by IGM variance

Bootstrap Errors



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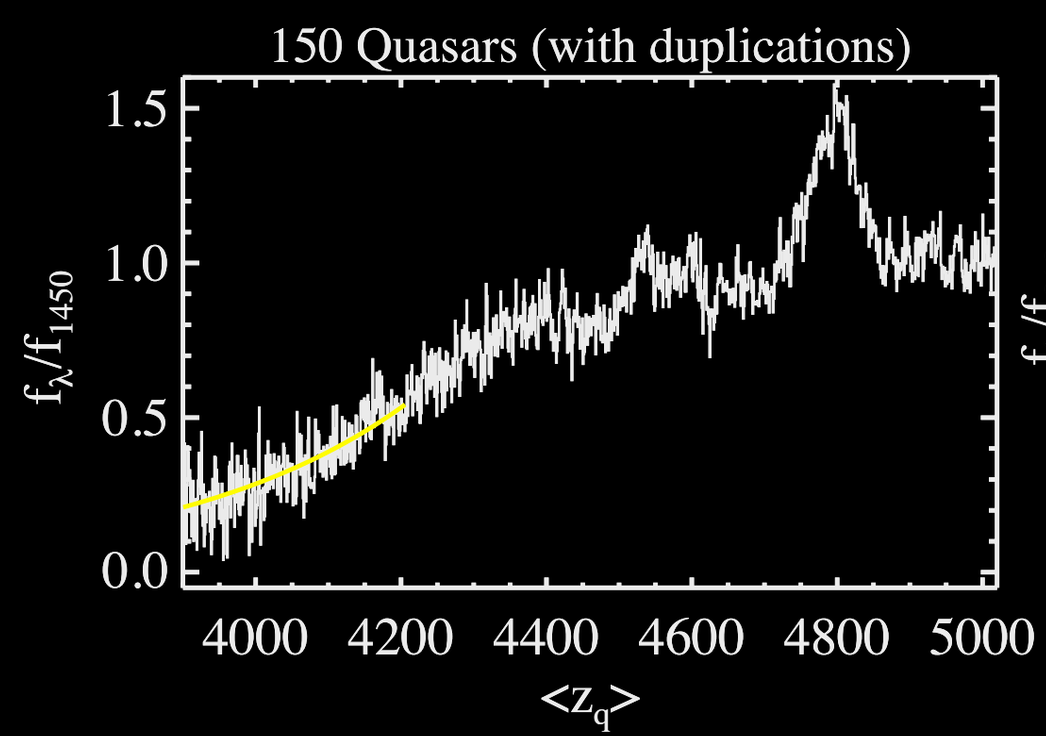

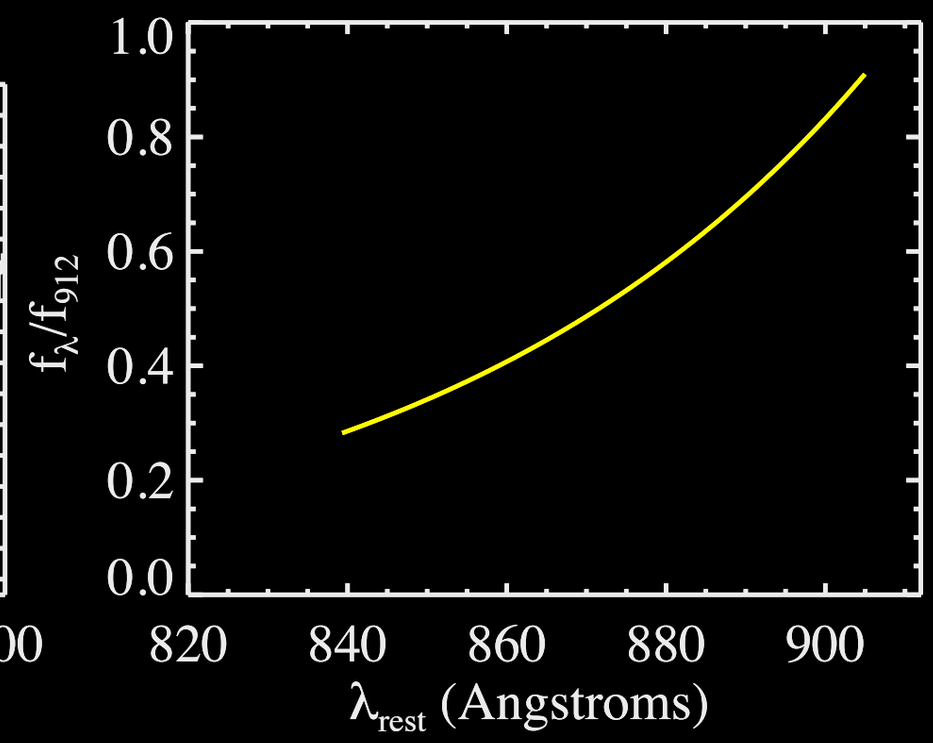

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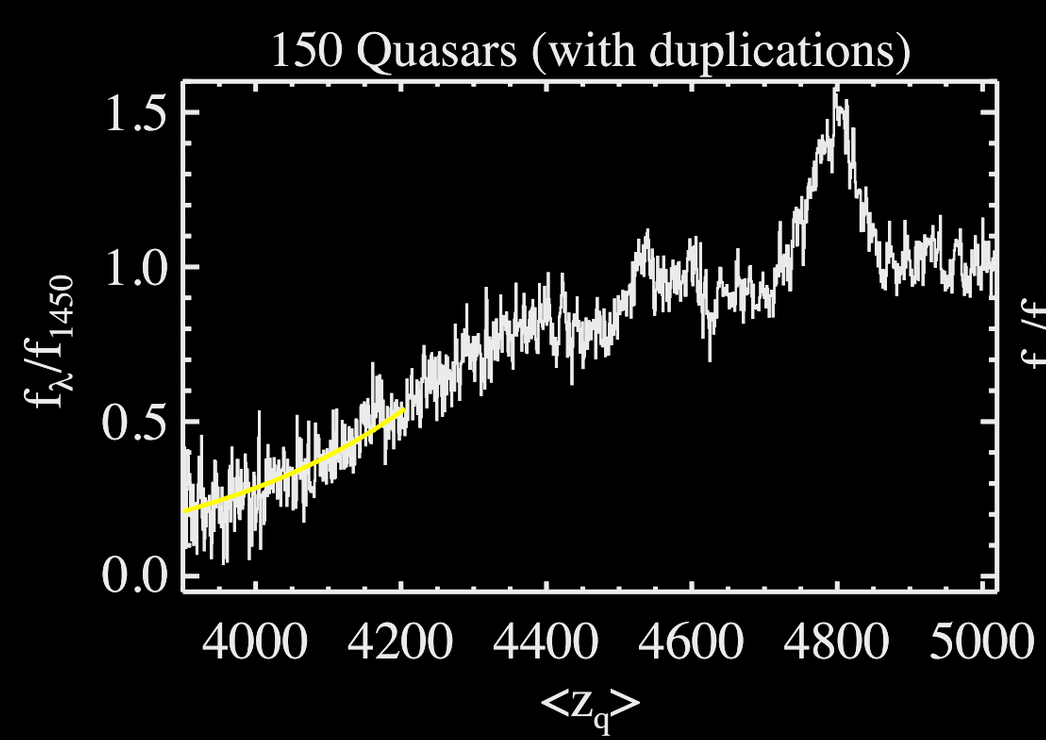

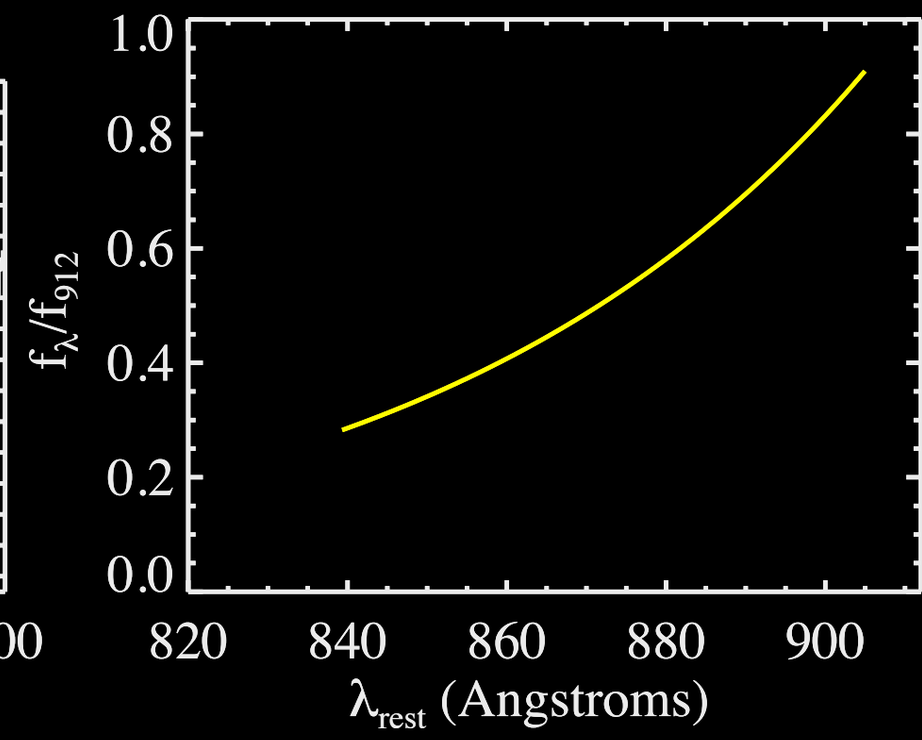

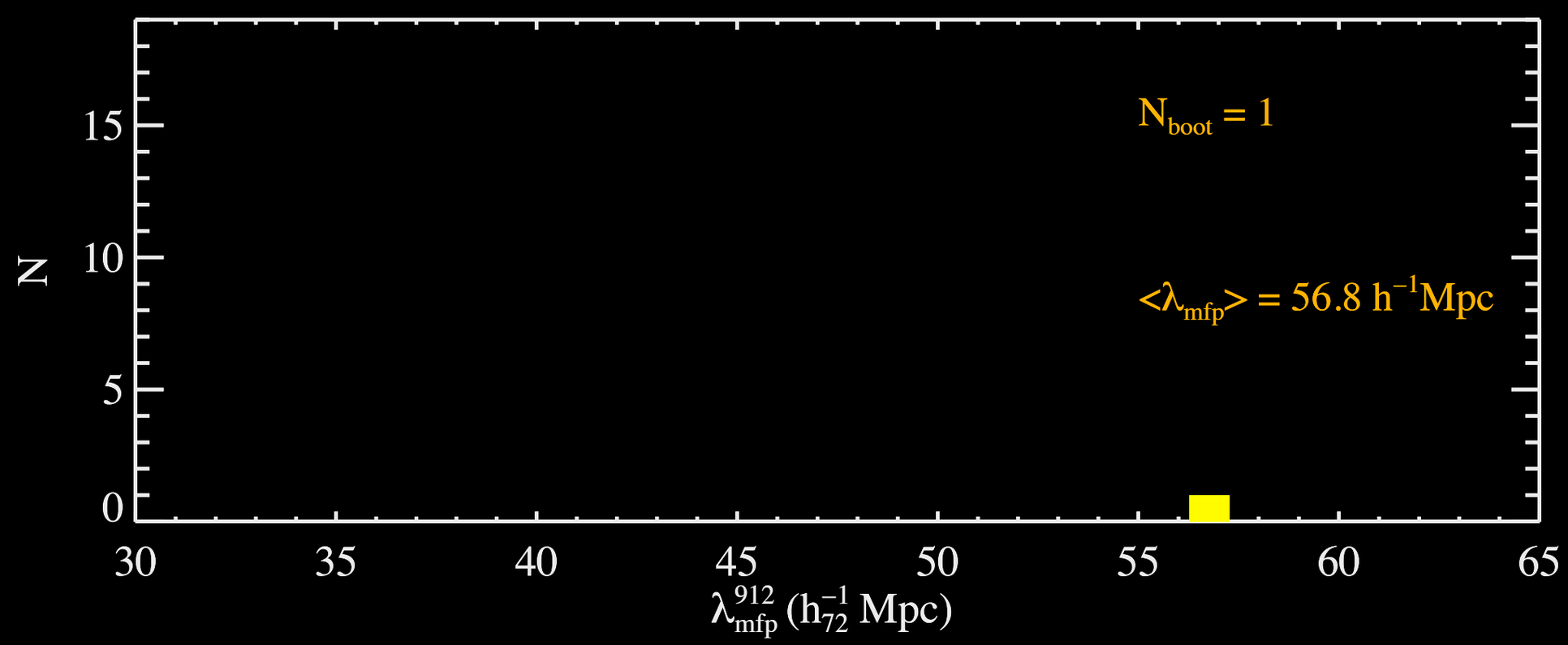

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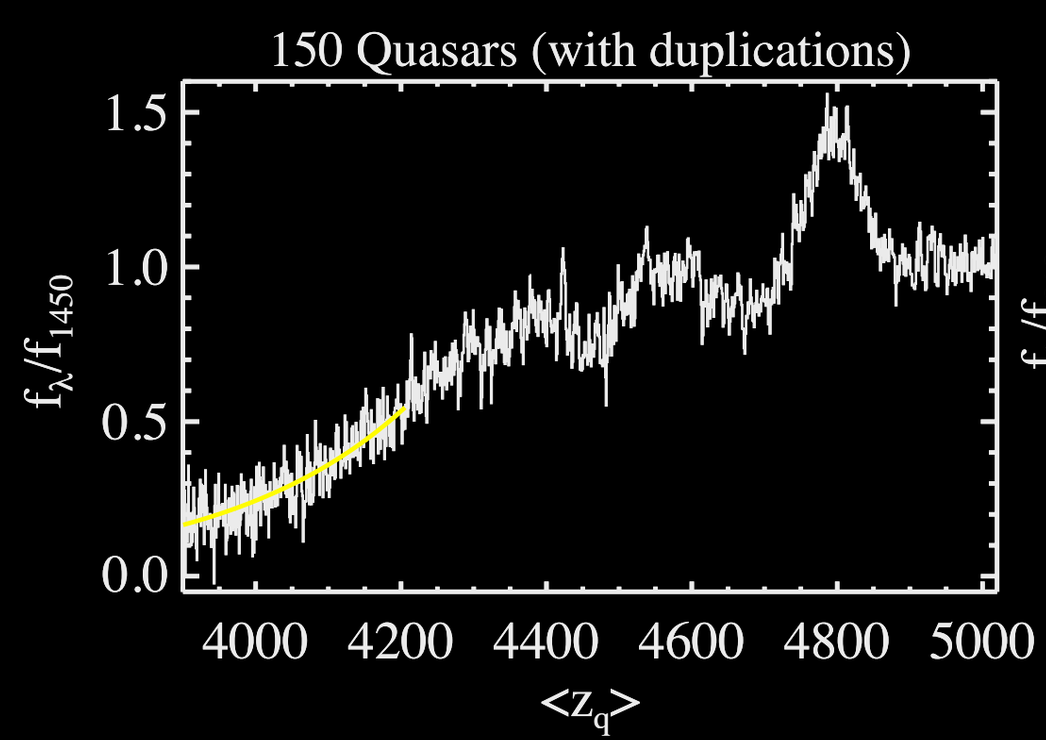

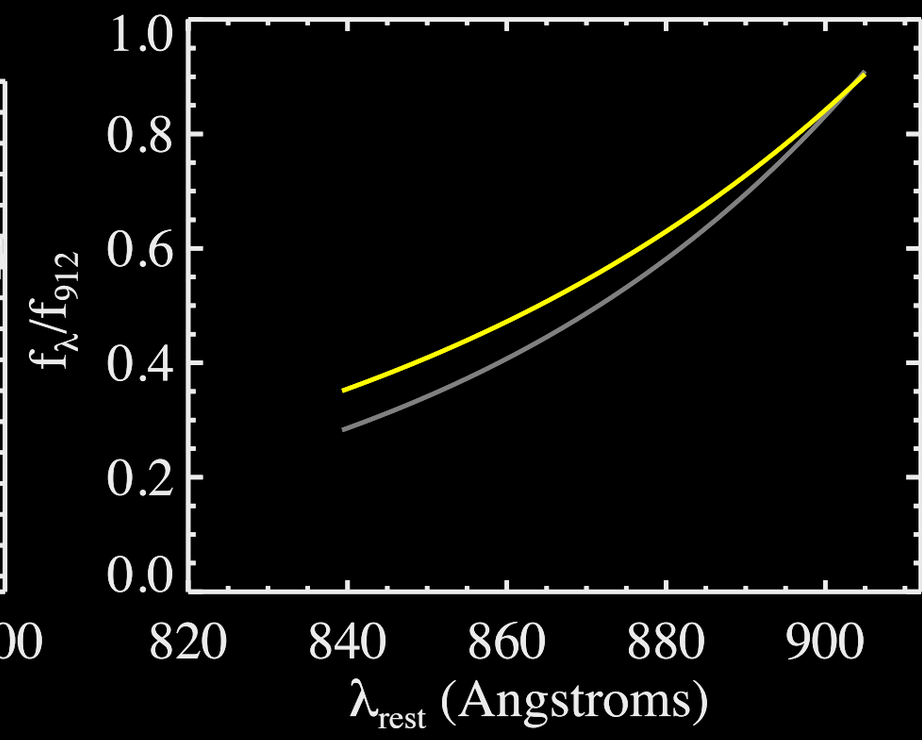

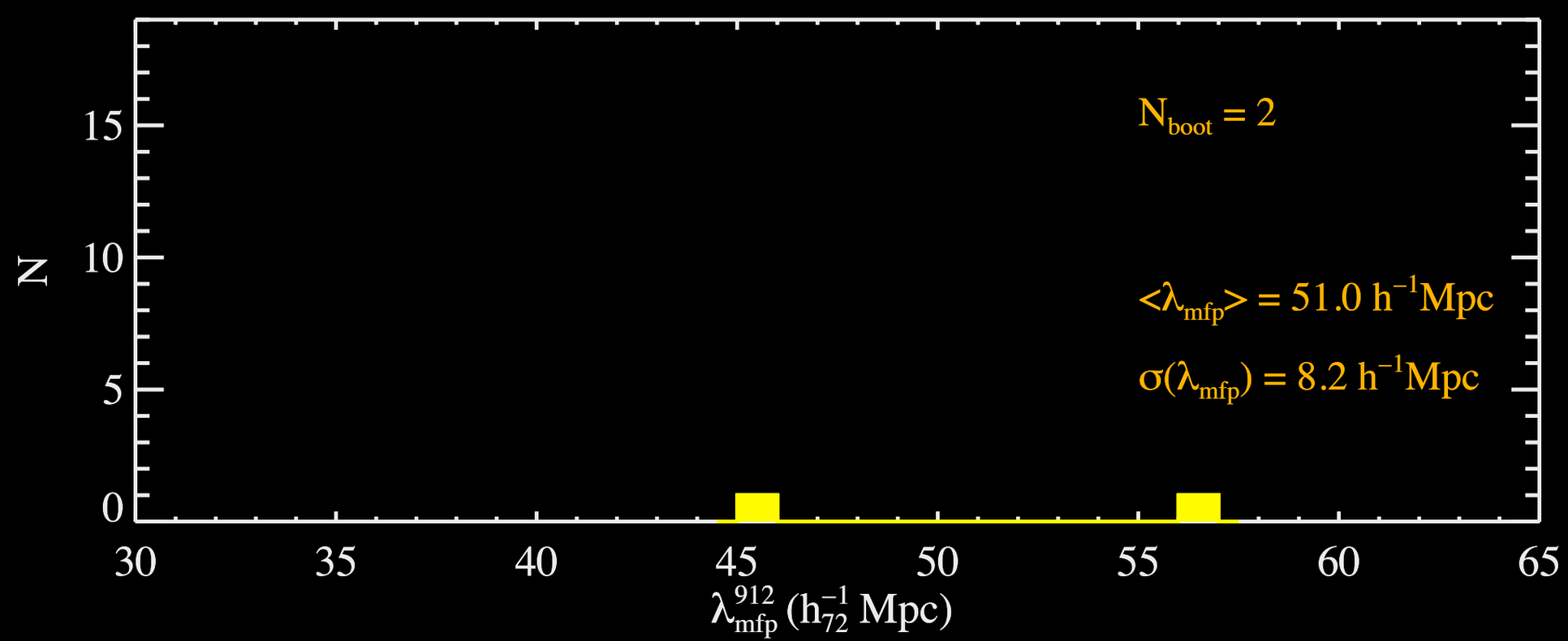

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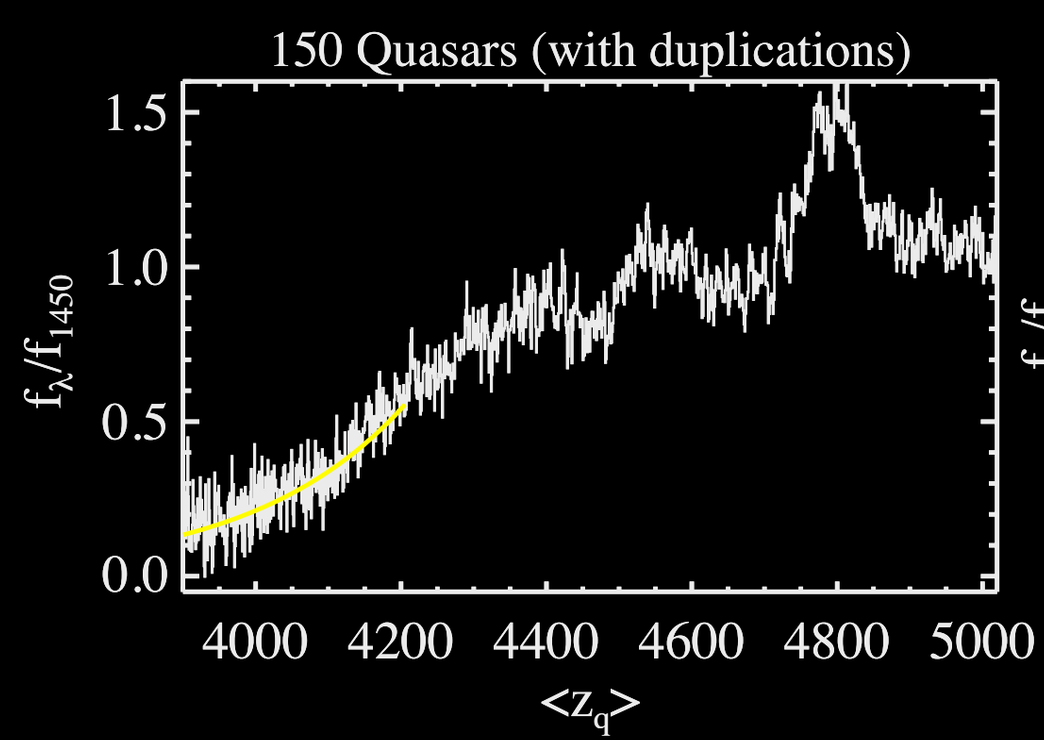

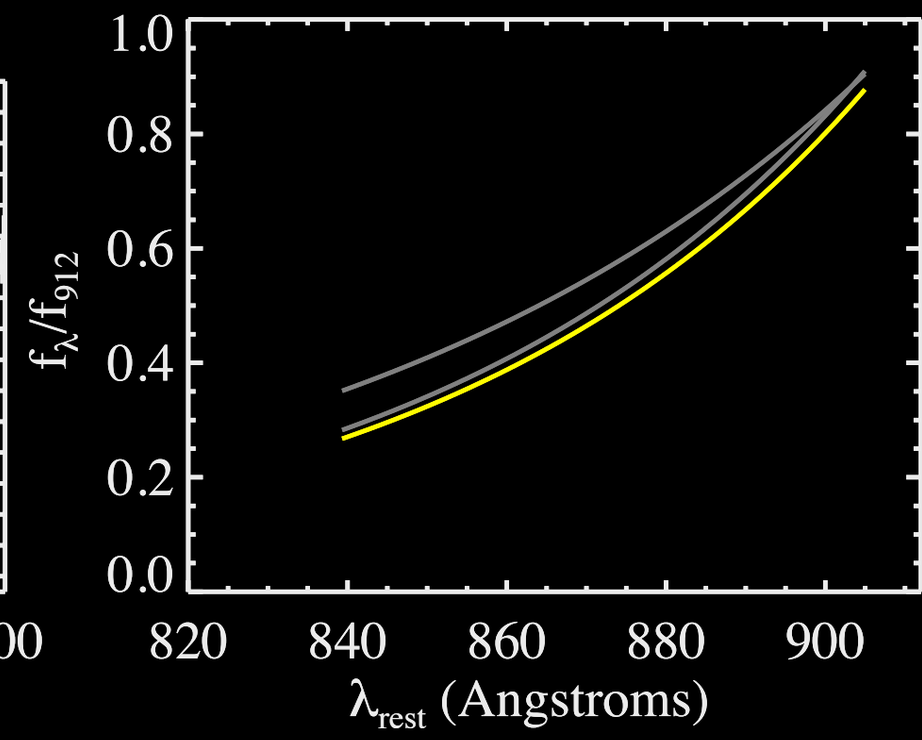

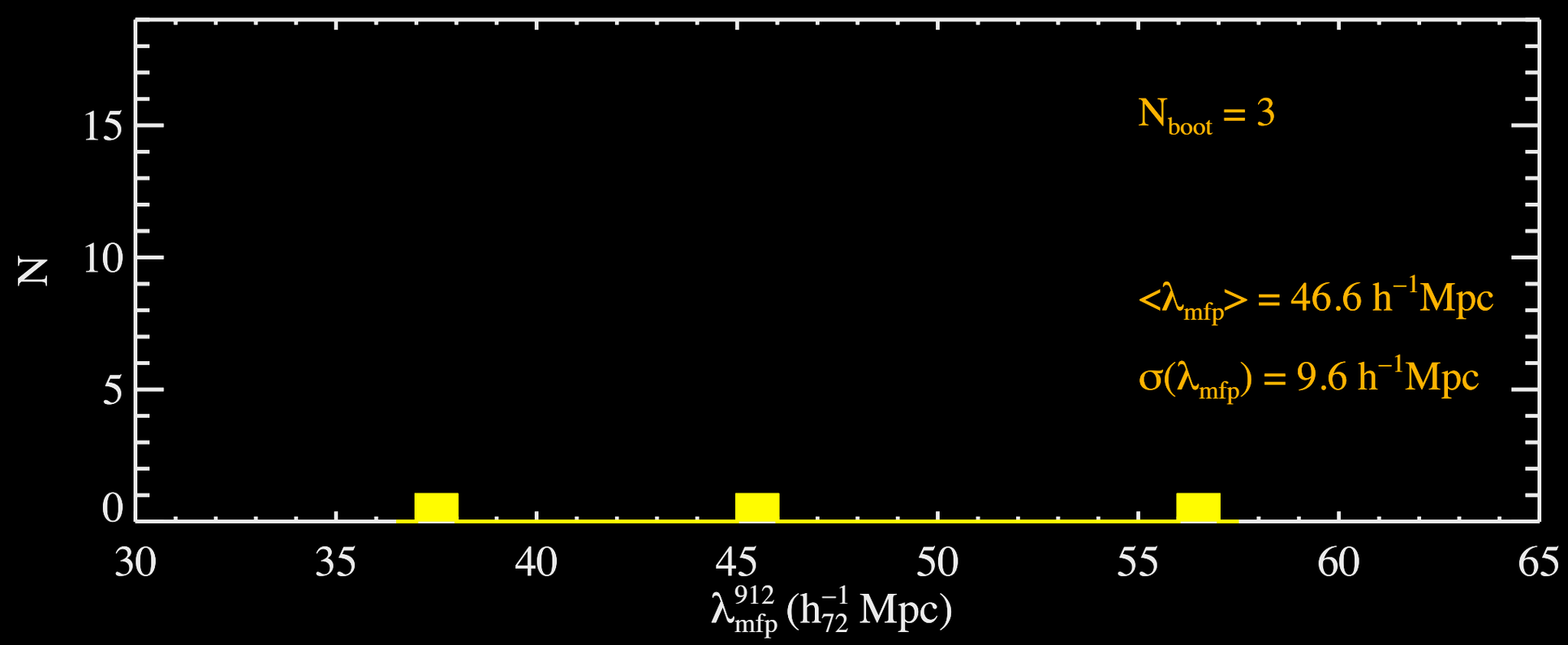

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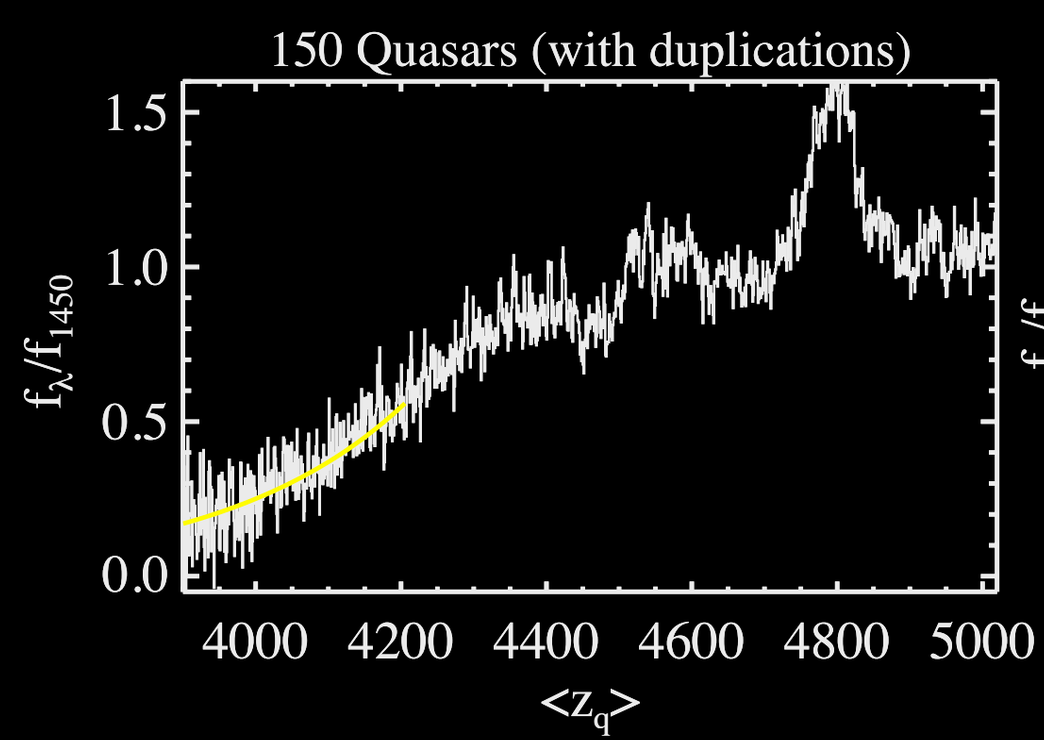

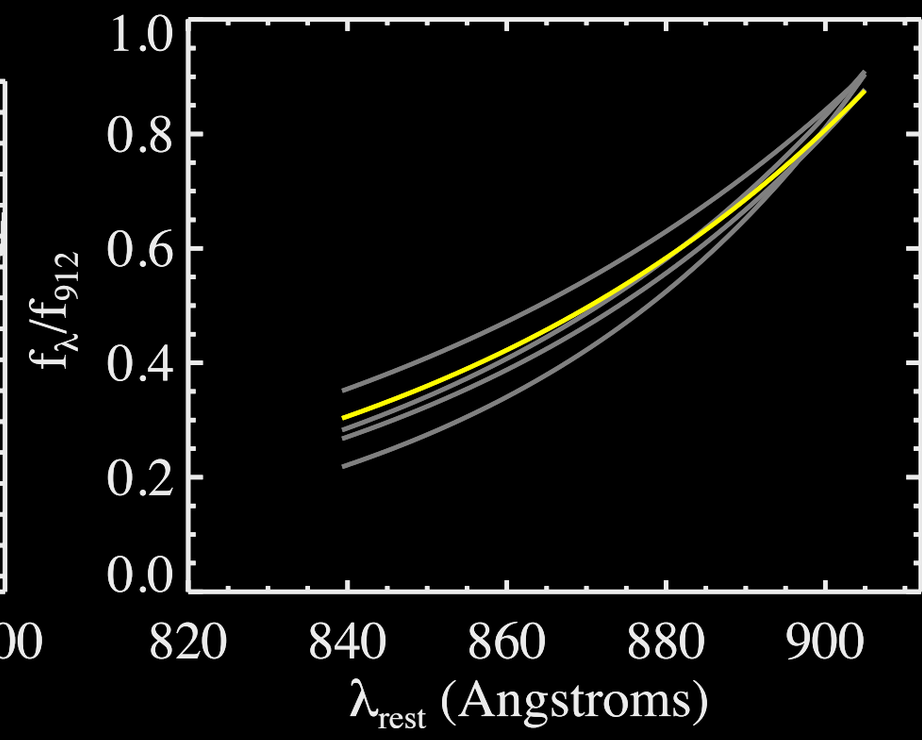

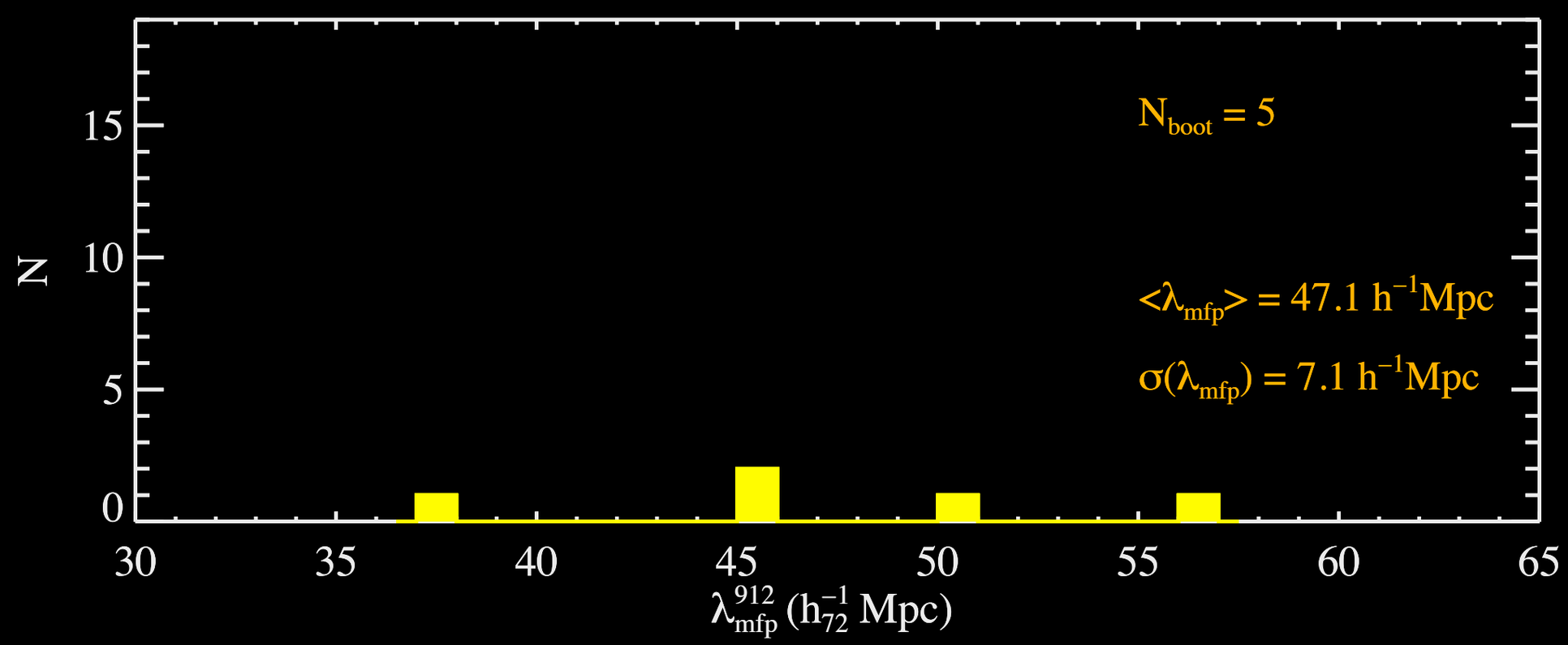

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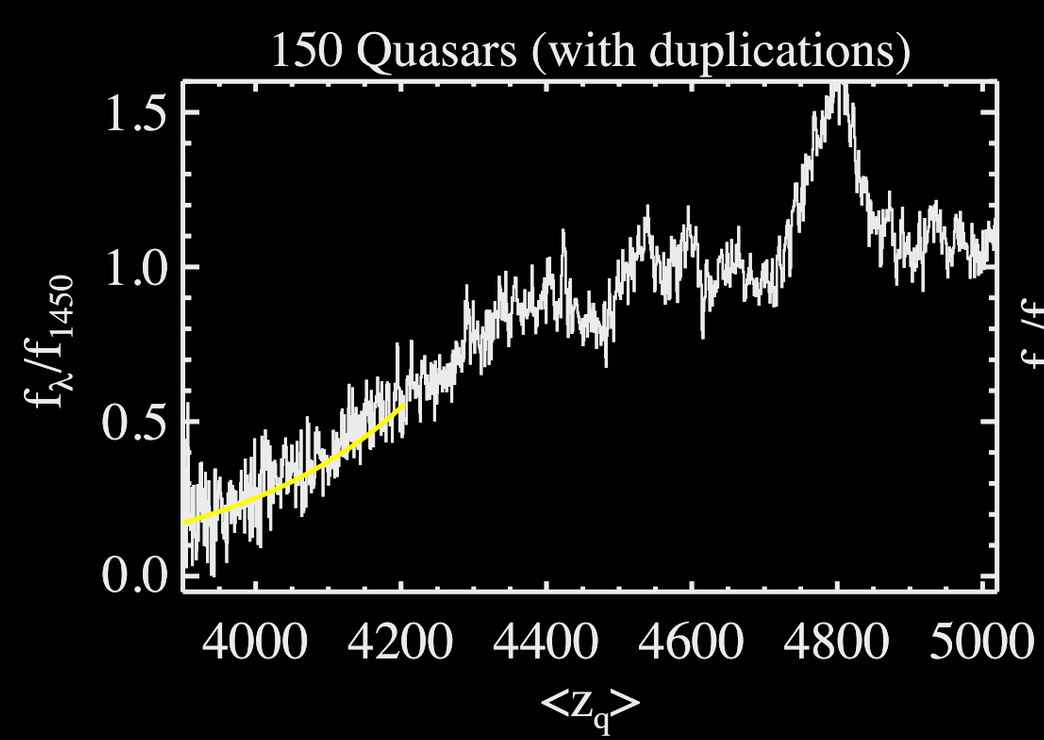

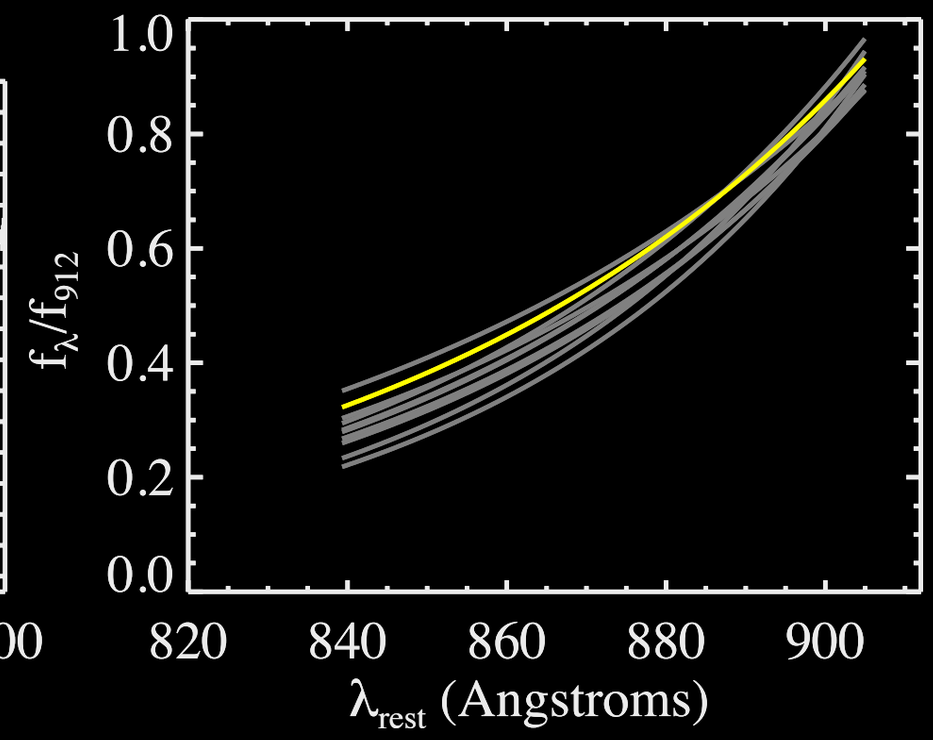

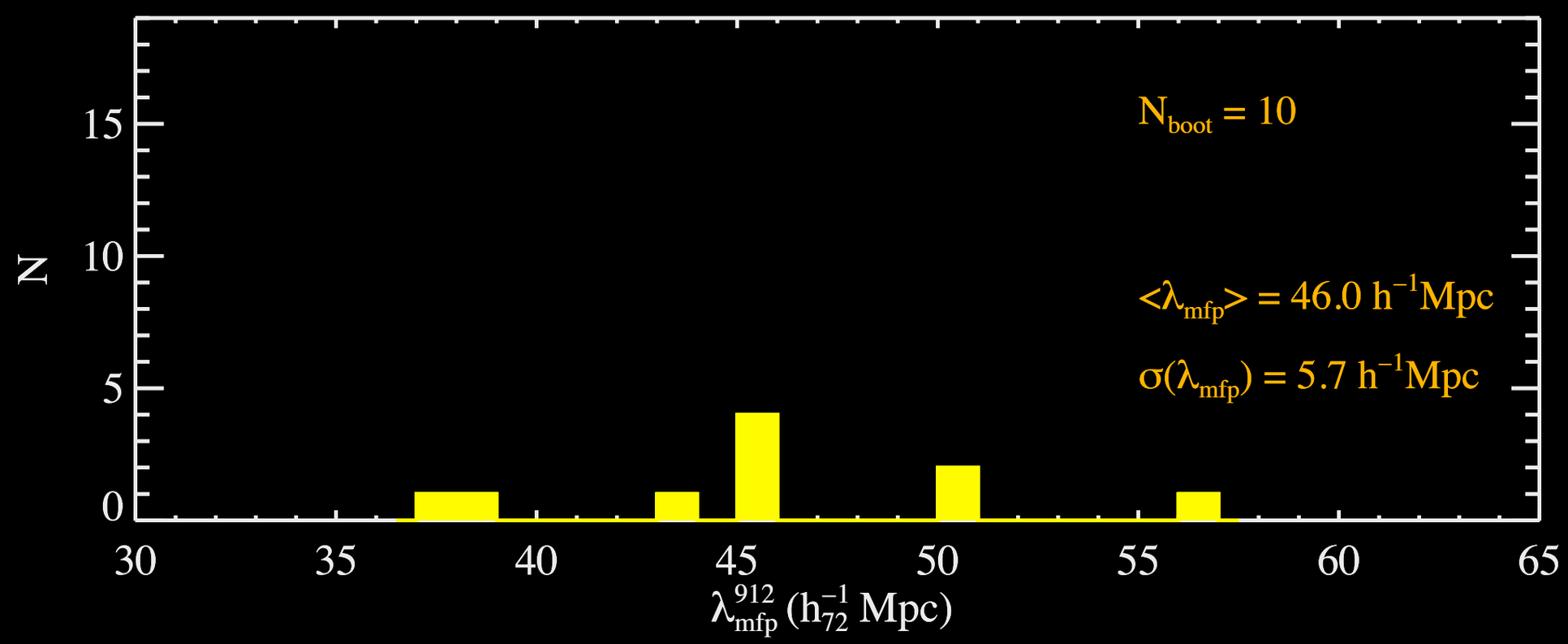

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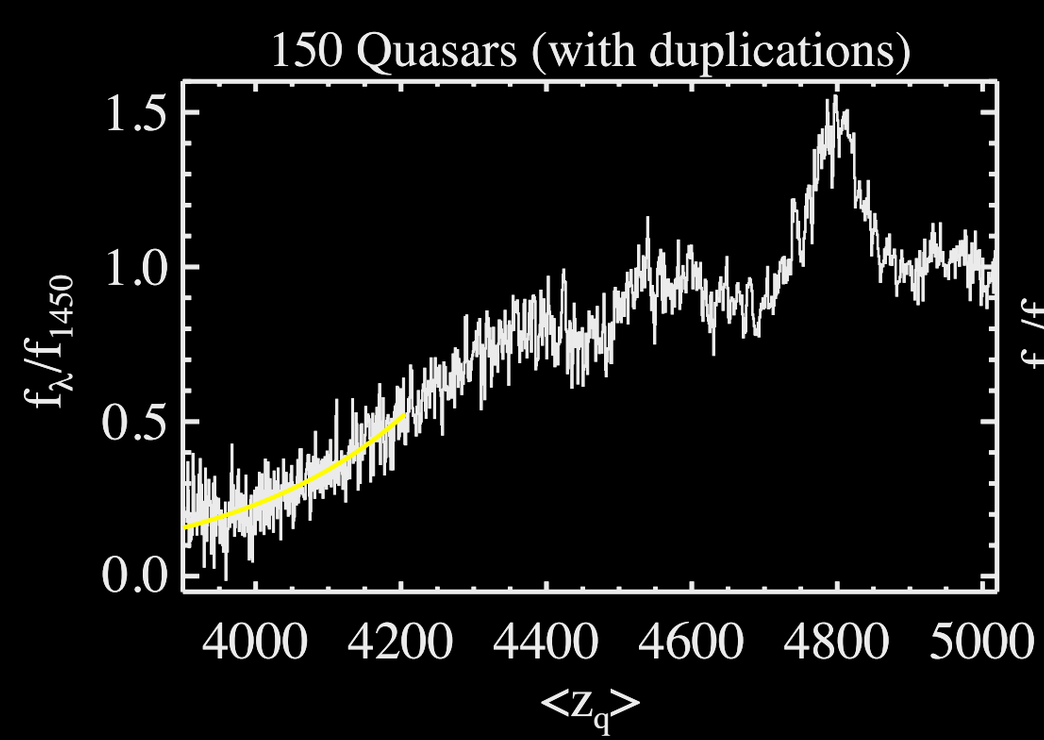

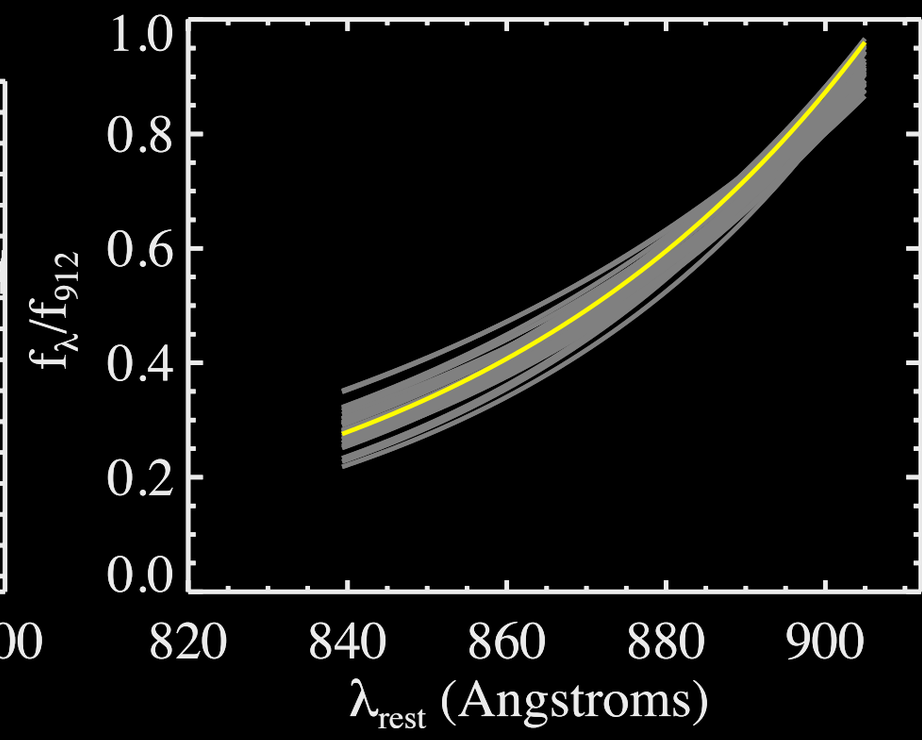

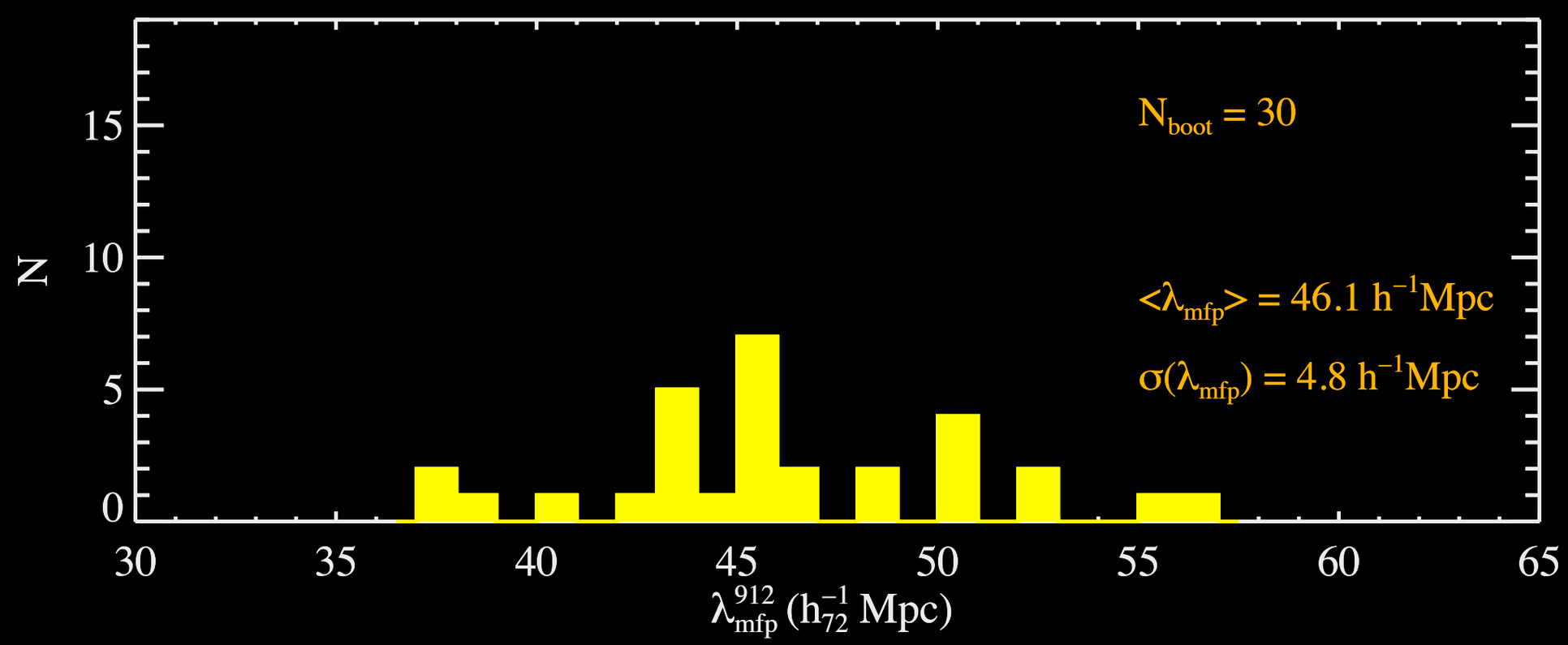

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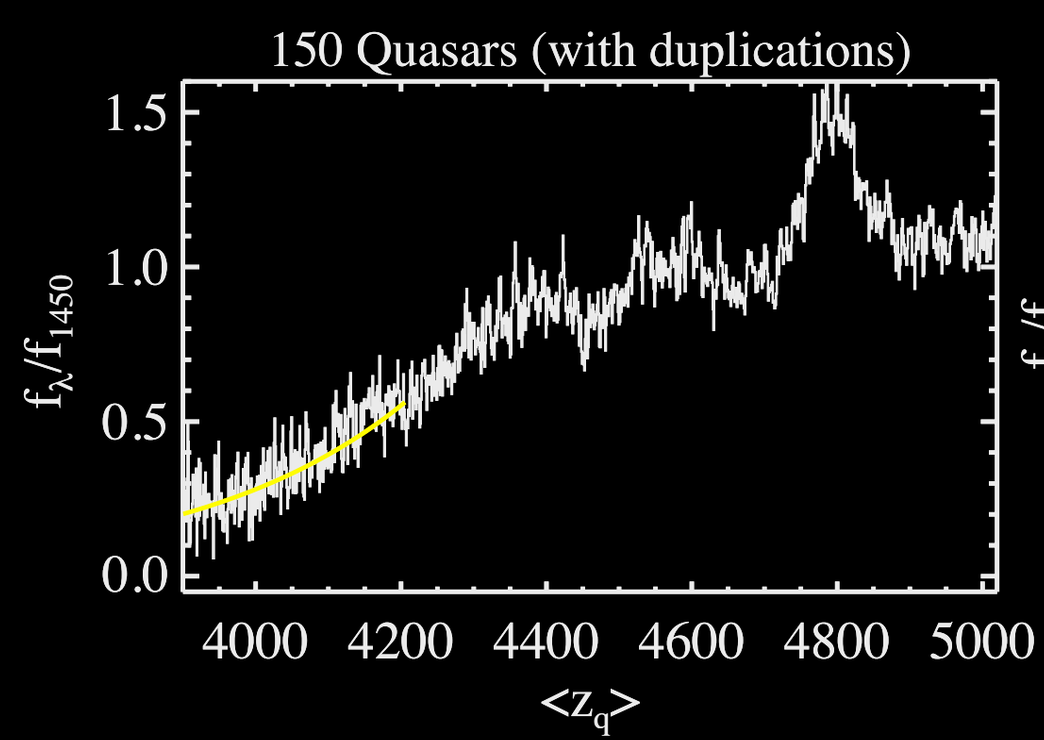

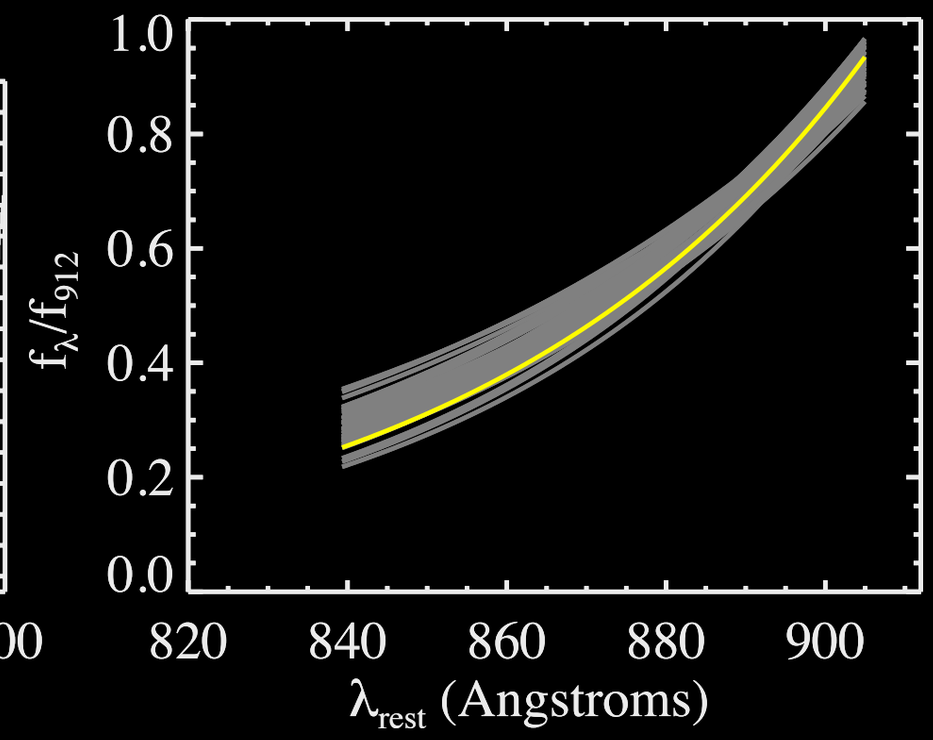

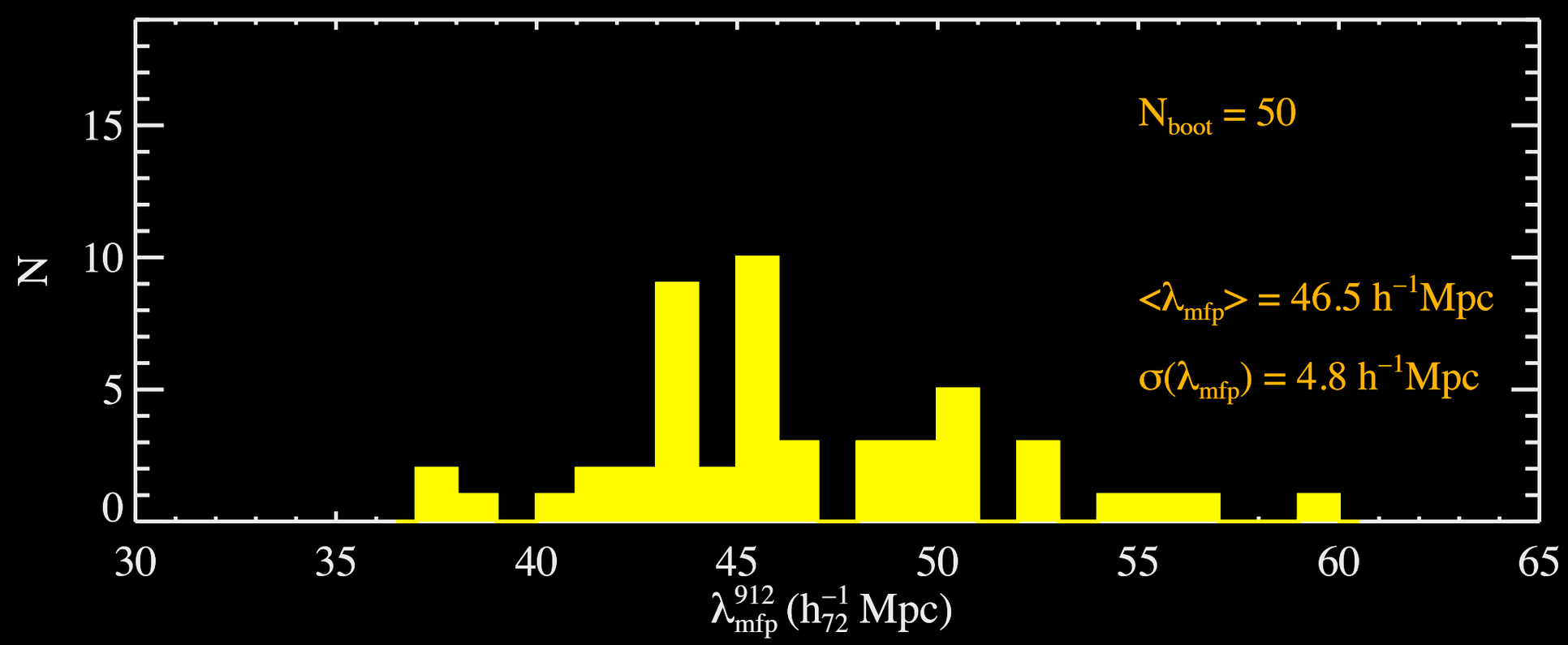

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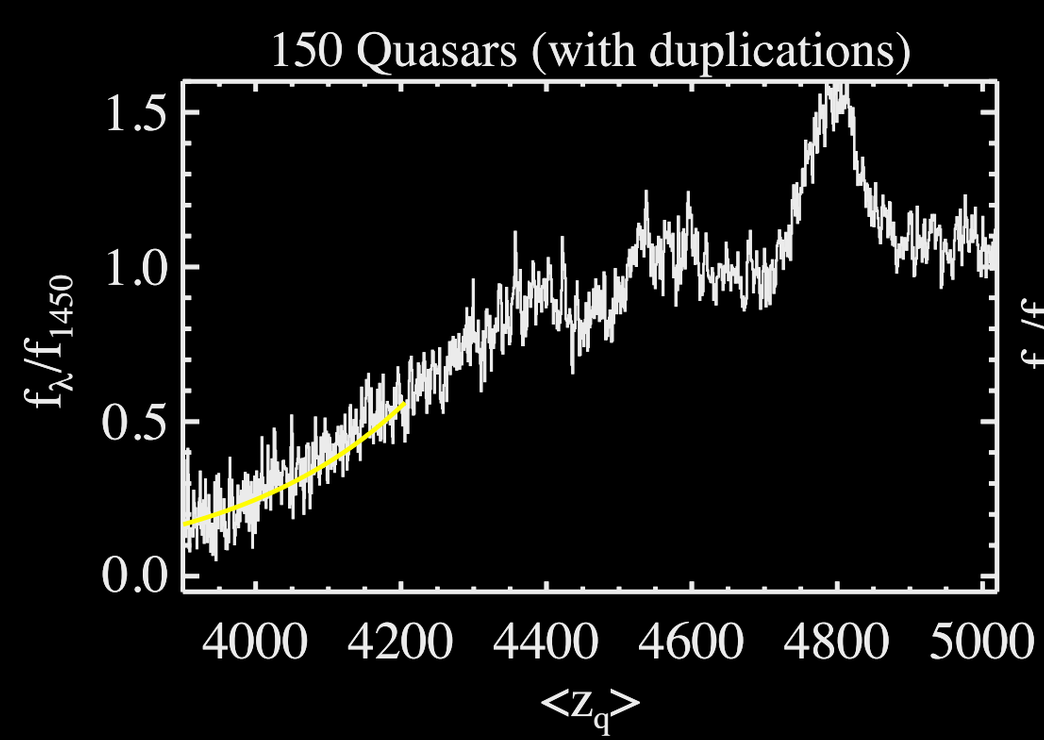

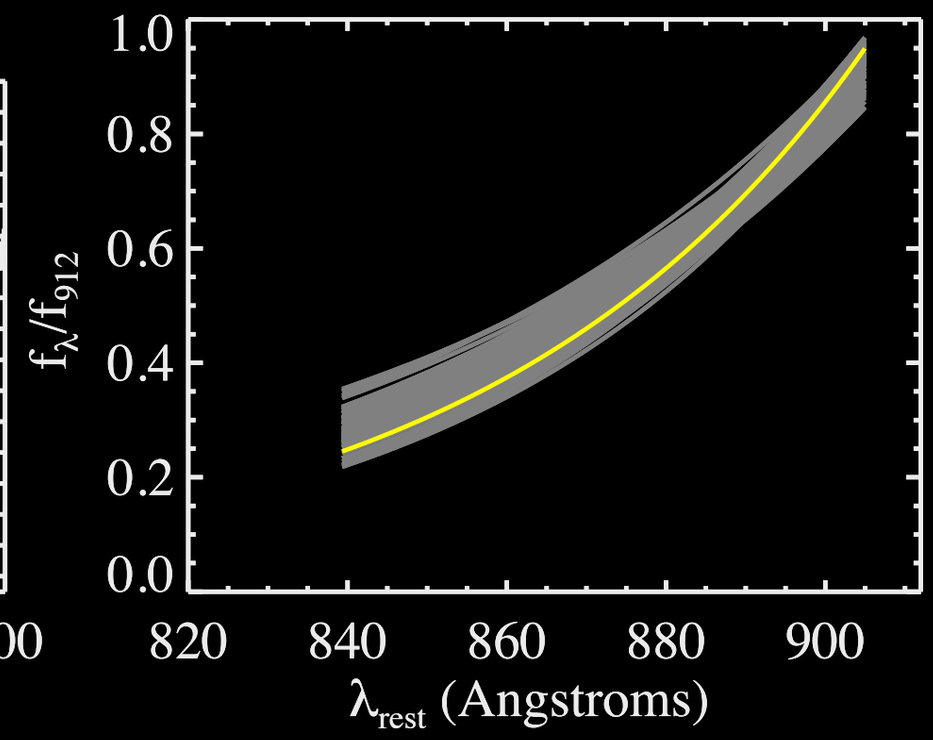

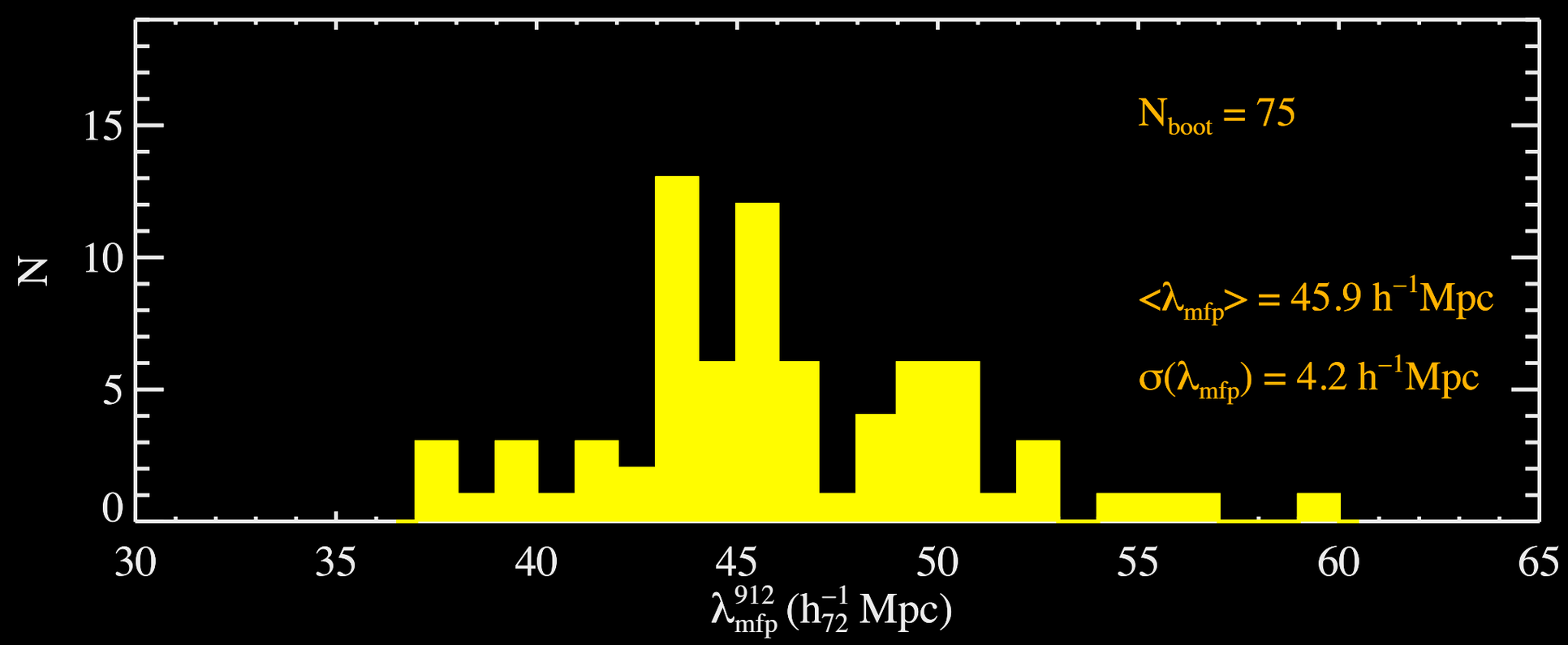

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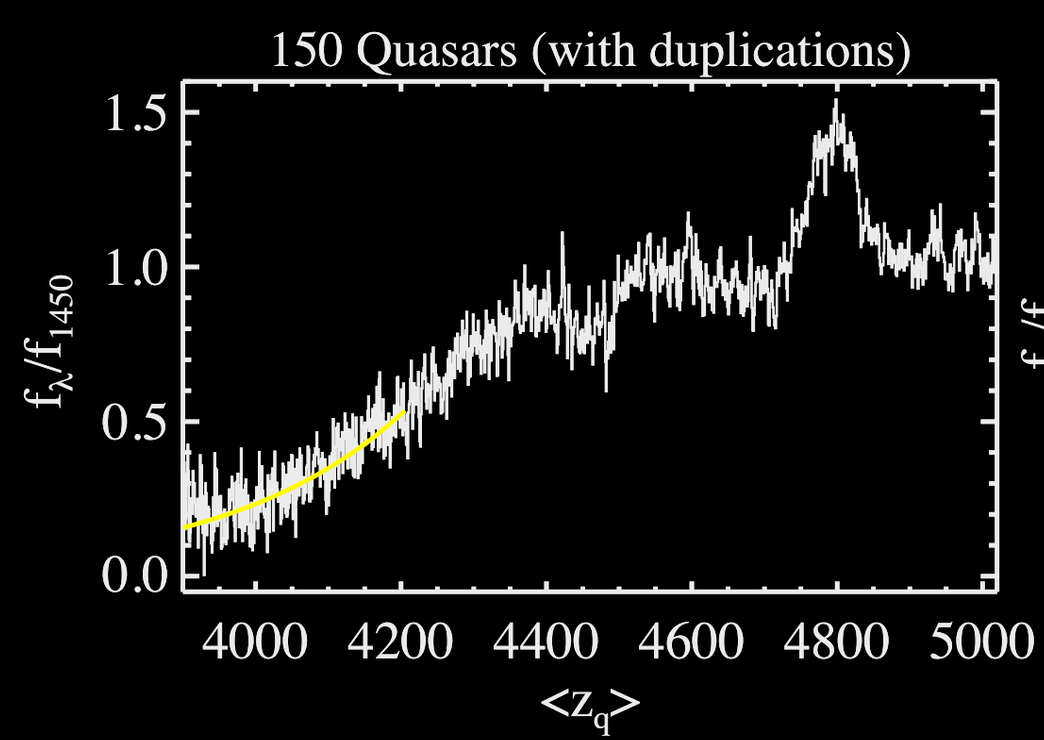
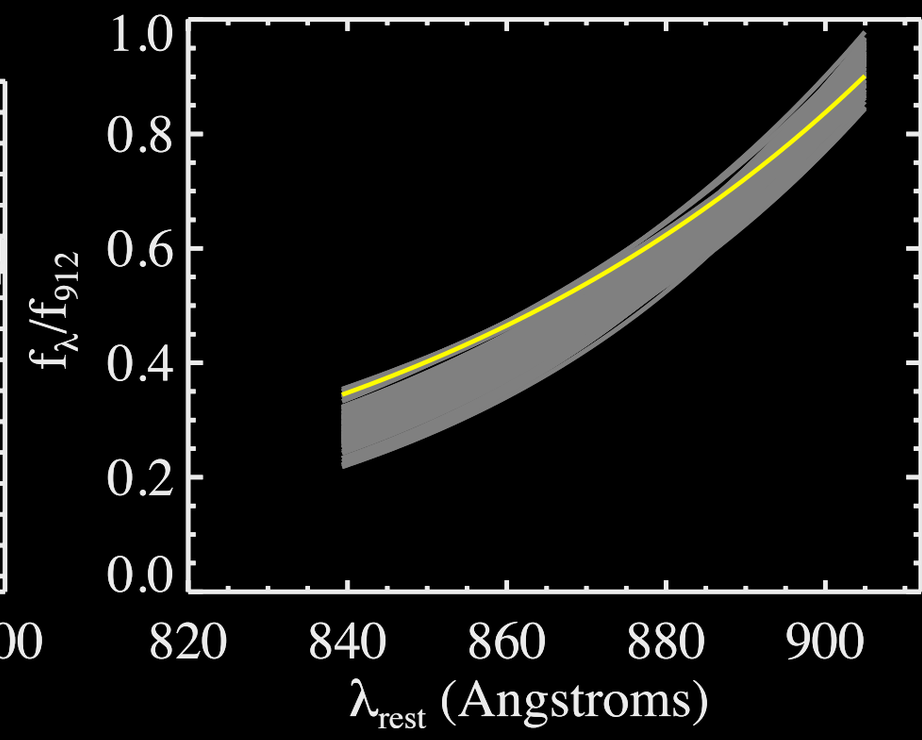
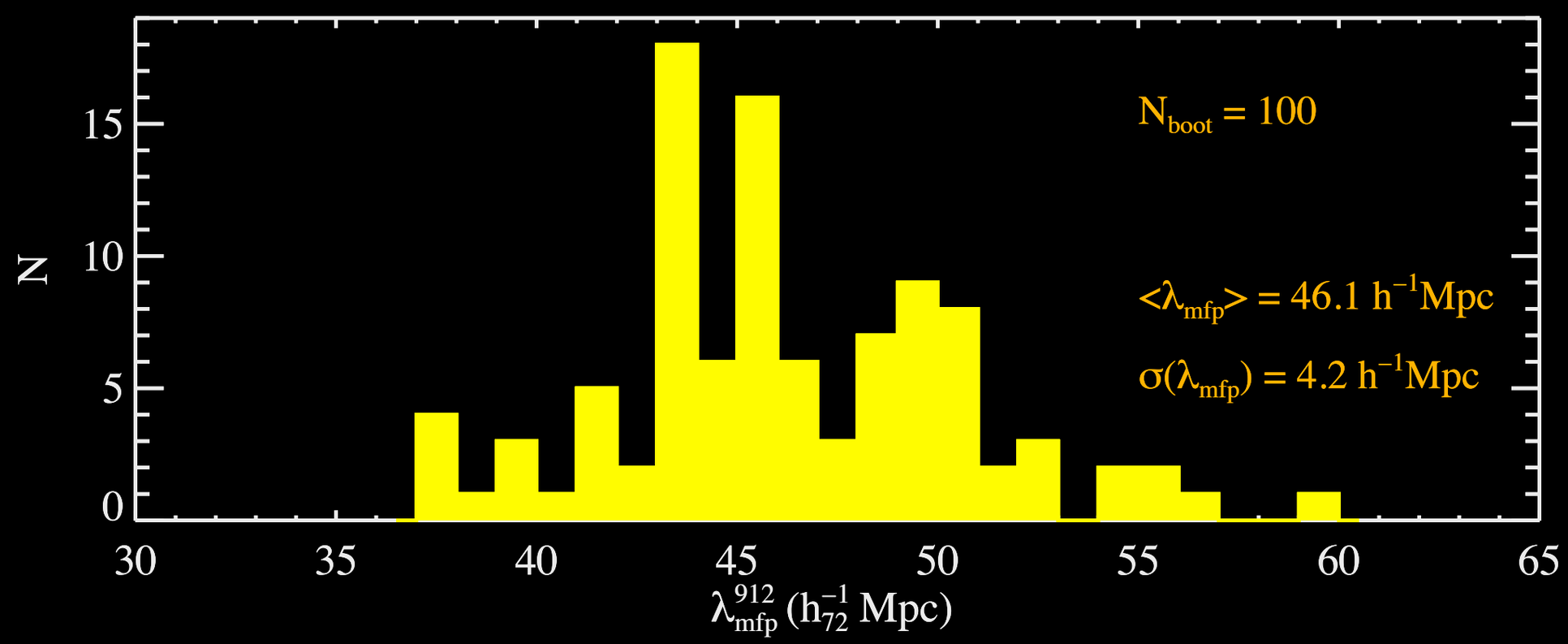
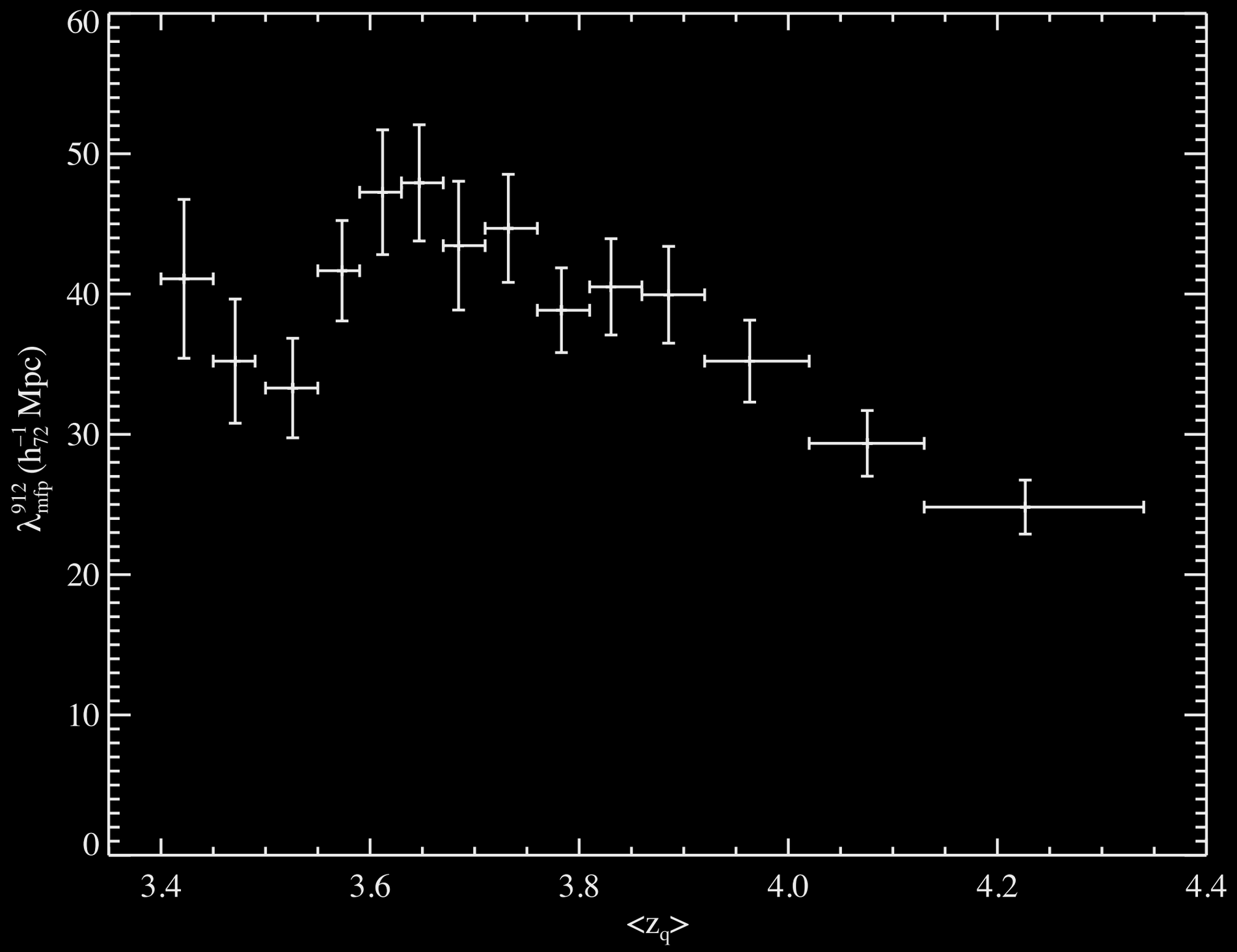


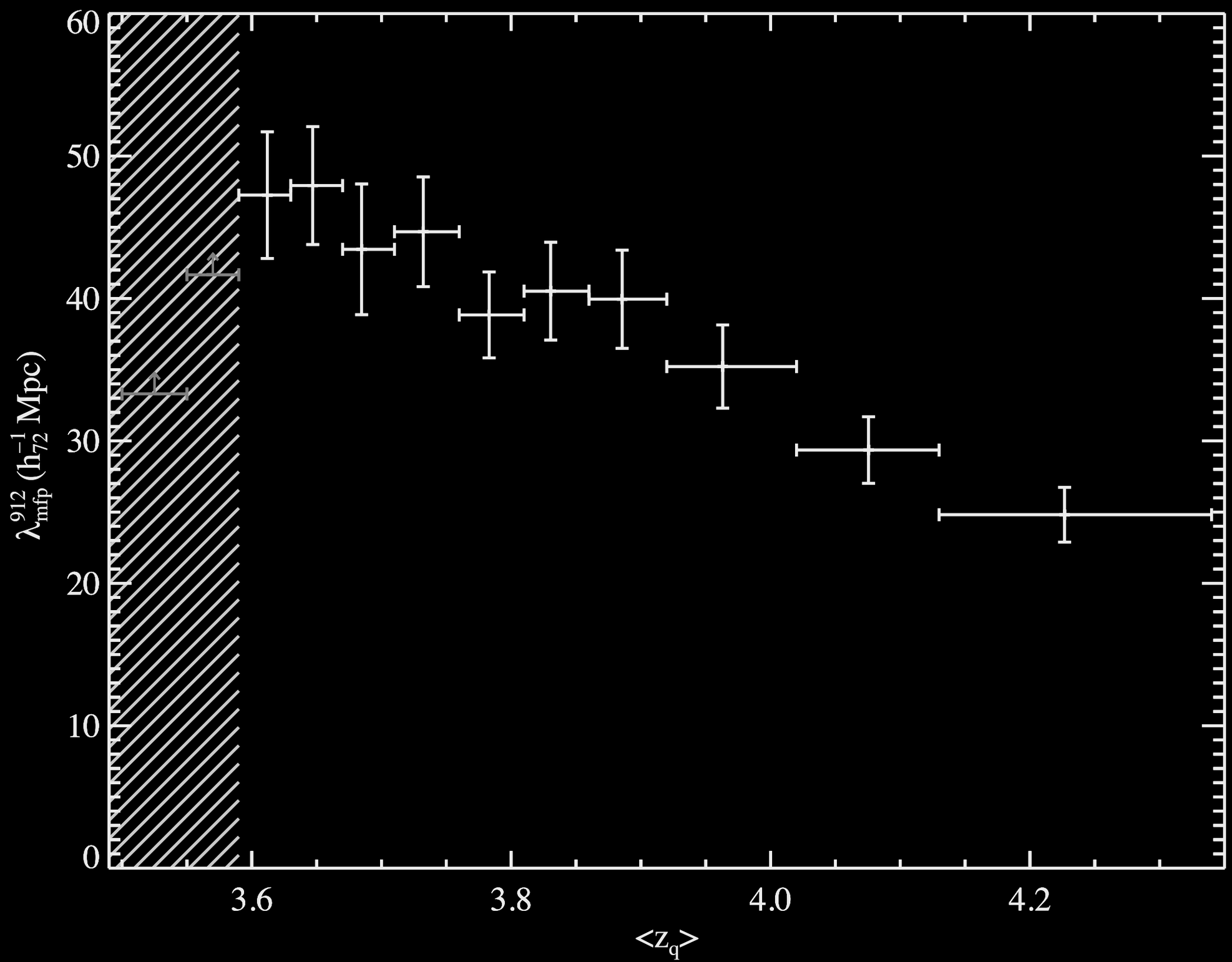




λ_{mfp}: SDSS Measurements (All)



λ_{mfp}: SDSS Measurements (z>3.6)



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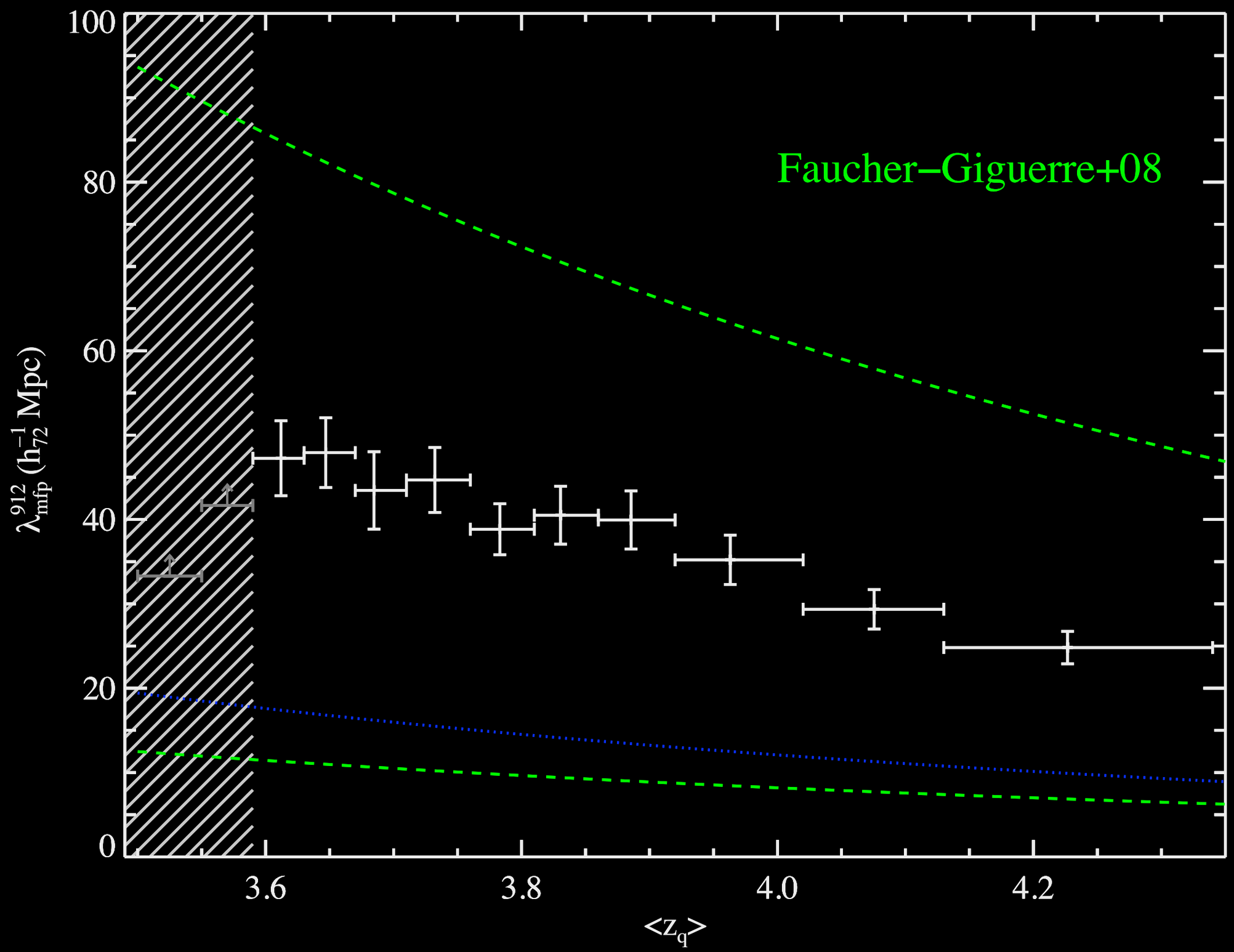

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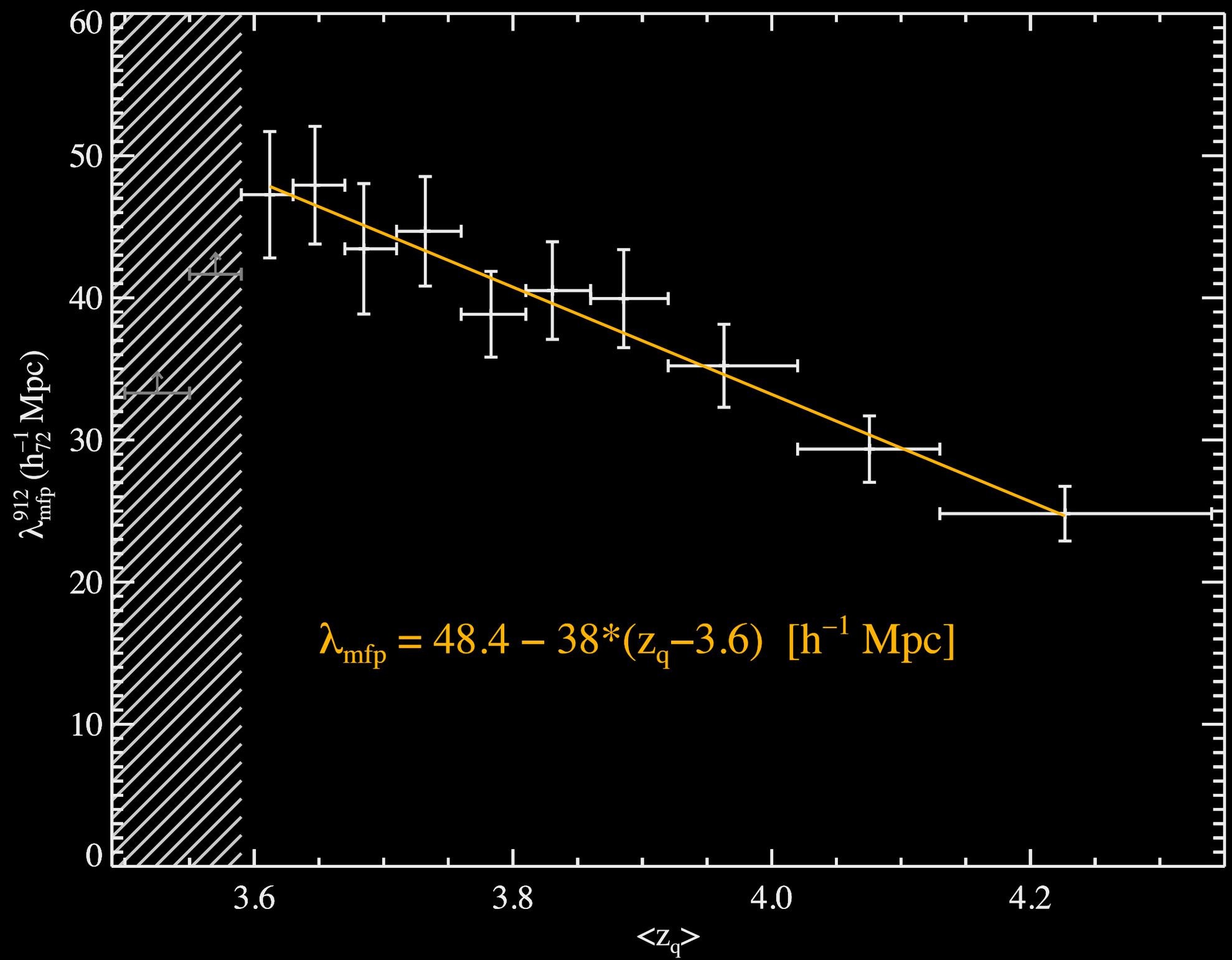
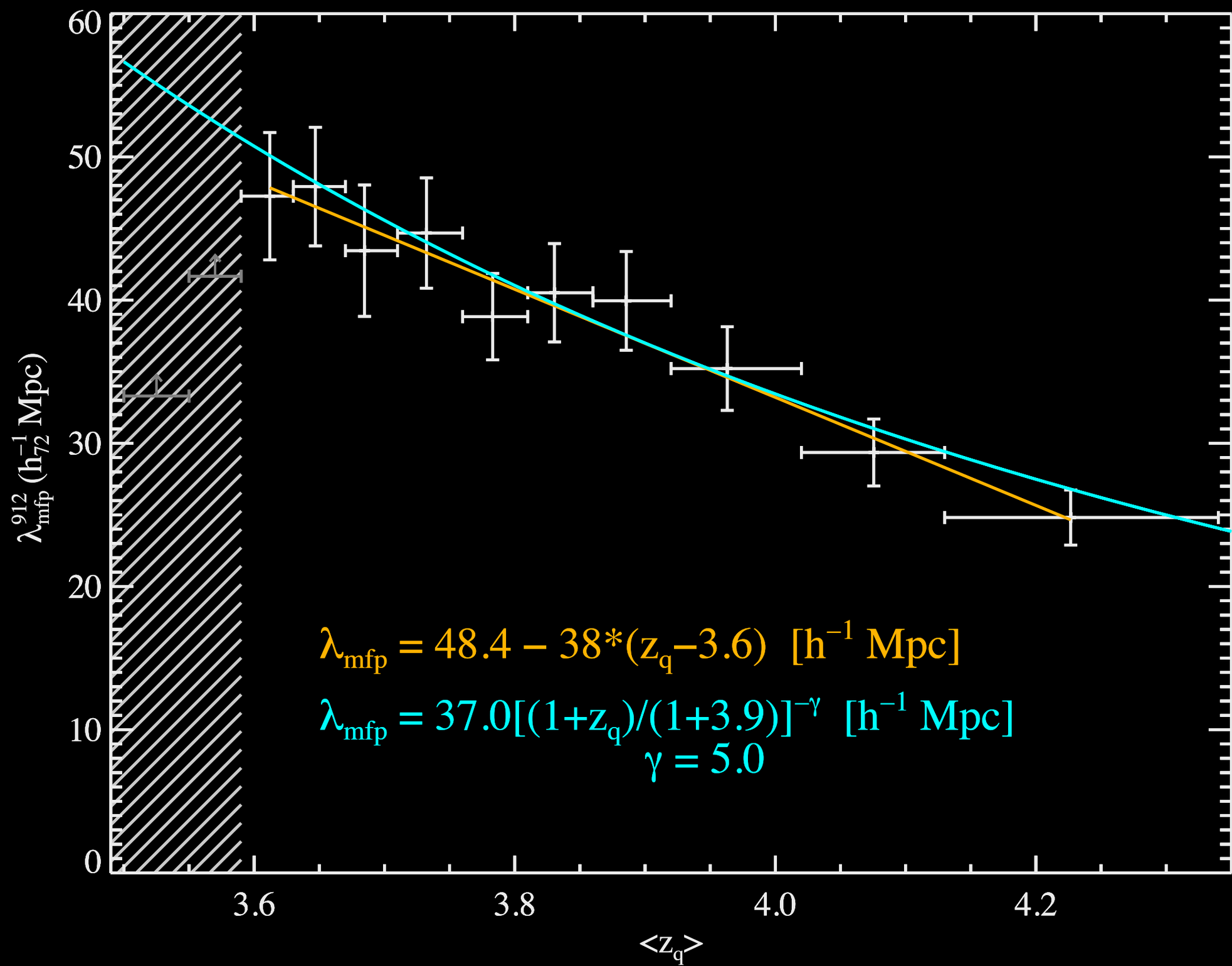


λ_{mfp}: SDSS Measurements (z>3.6)



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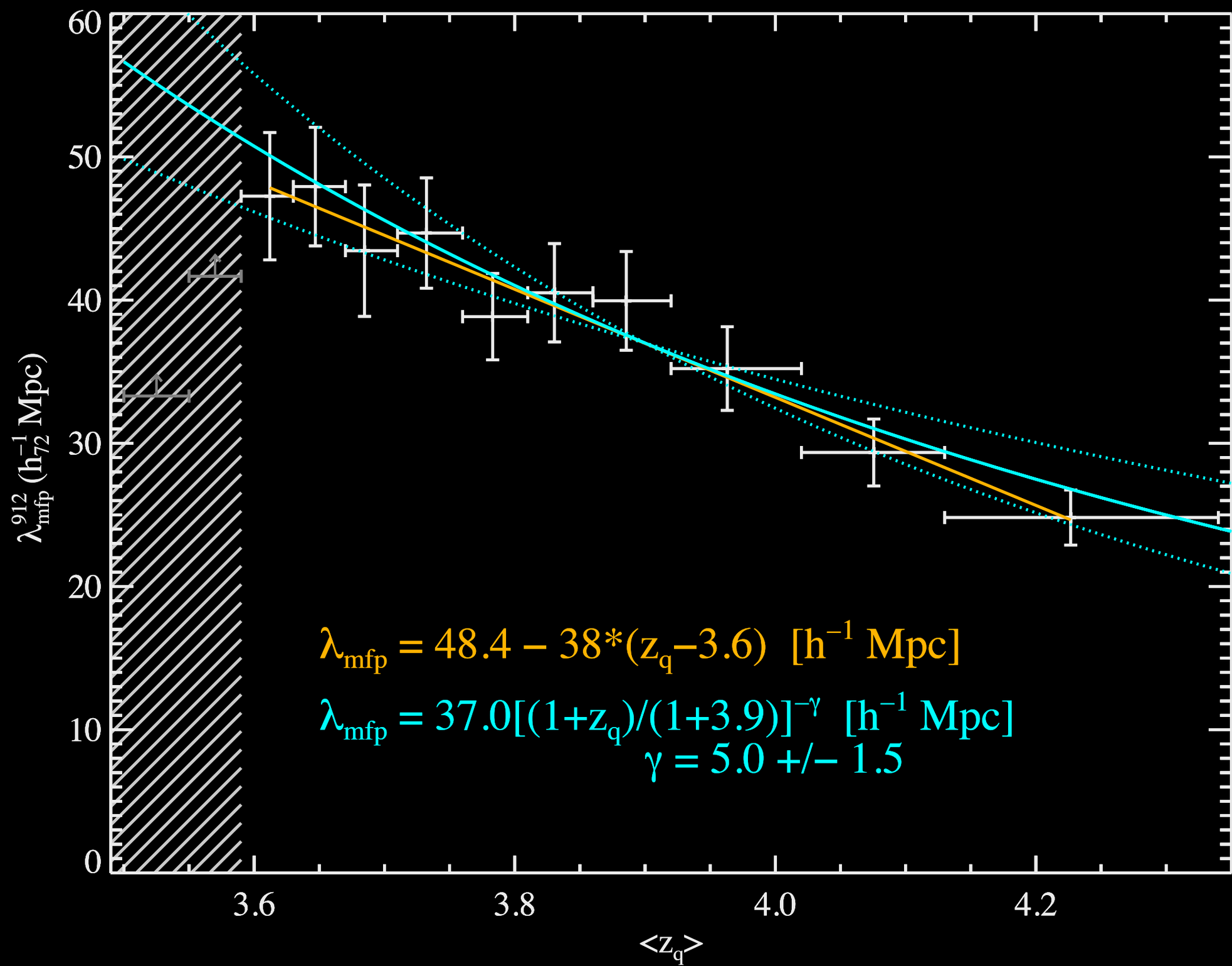
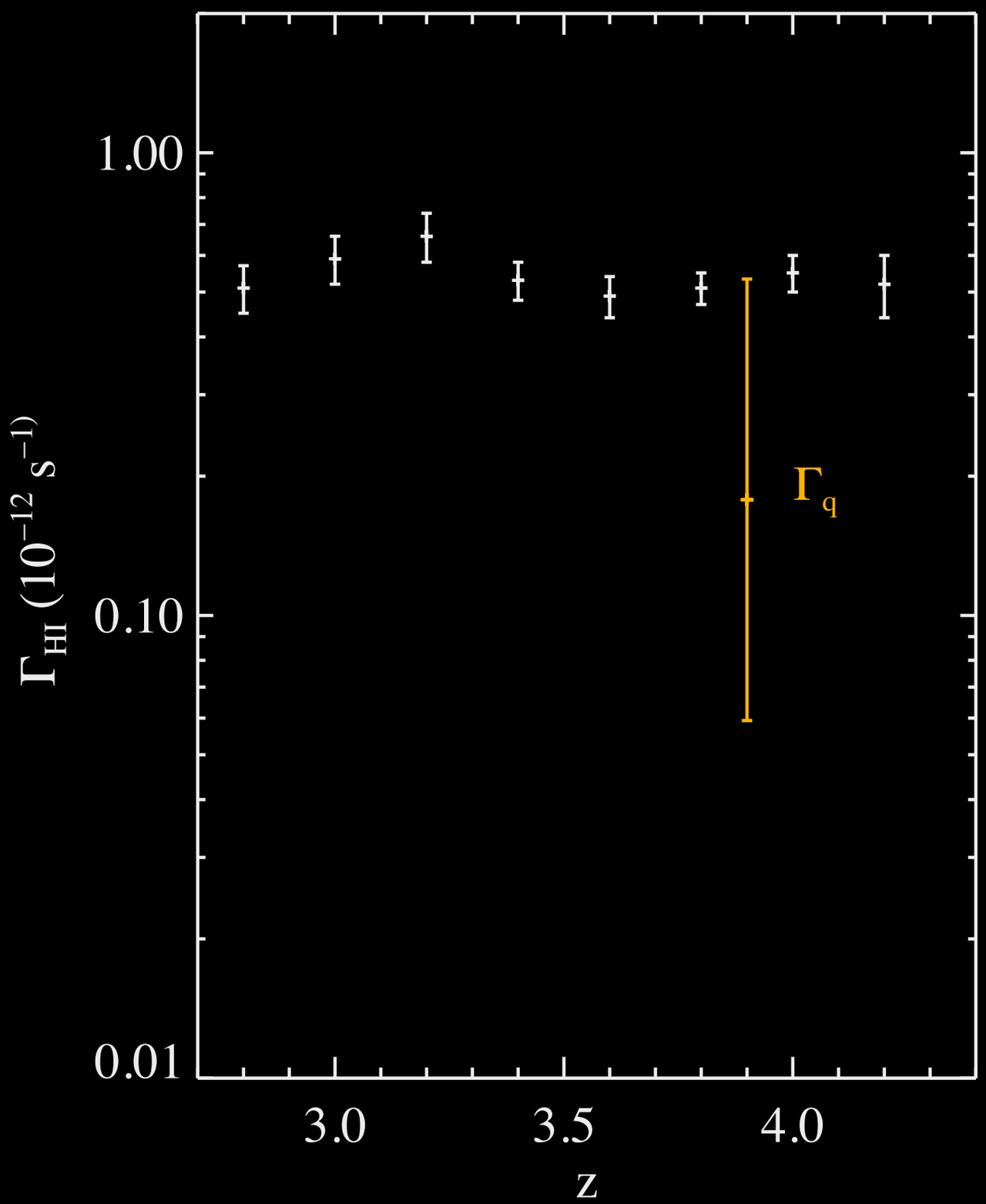
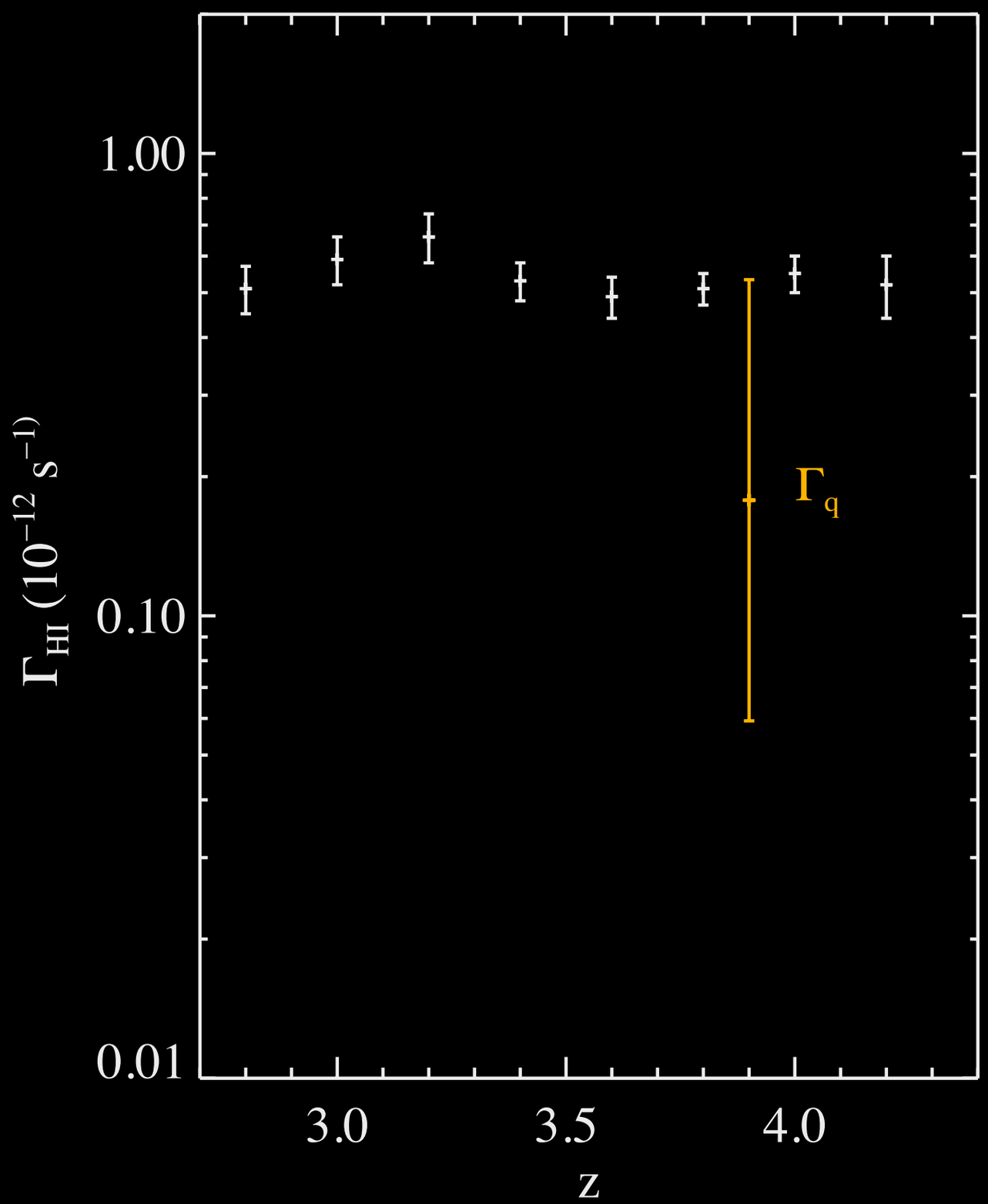


λ_{mfp} Implications: Quasars vs. Stars



λ_{mfp} Implications: Quasars vs. Stars

- z=4
  - Possible to match $\Gamma_{HI} \sim \Gamma_q$
    - Factor of 3 uncertainty in Γ_{HI} and ε_q
  - Stars need not dominate



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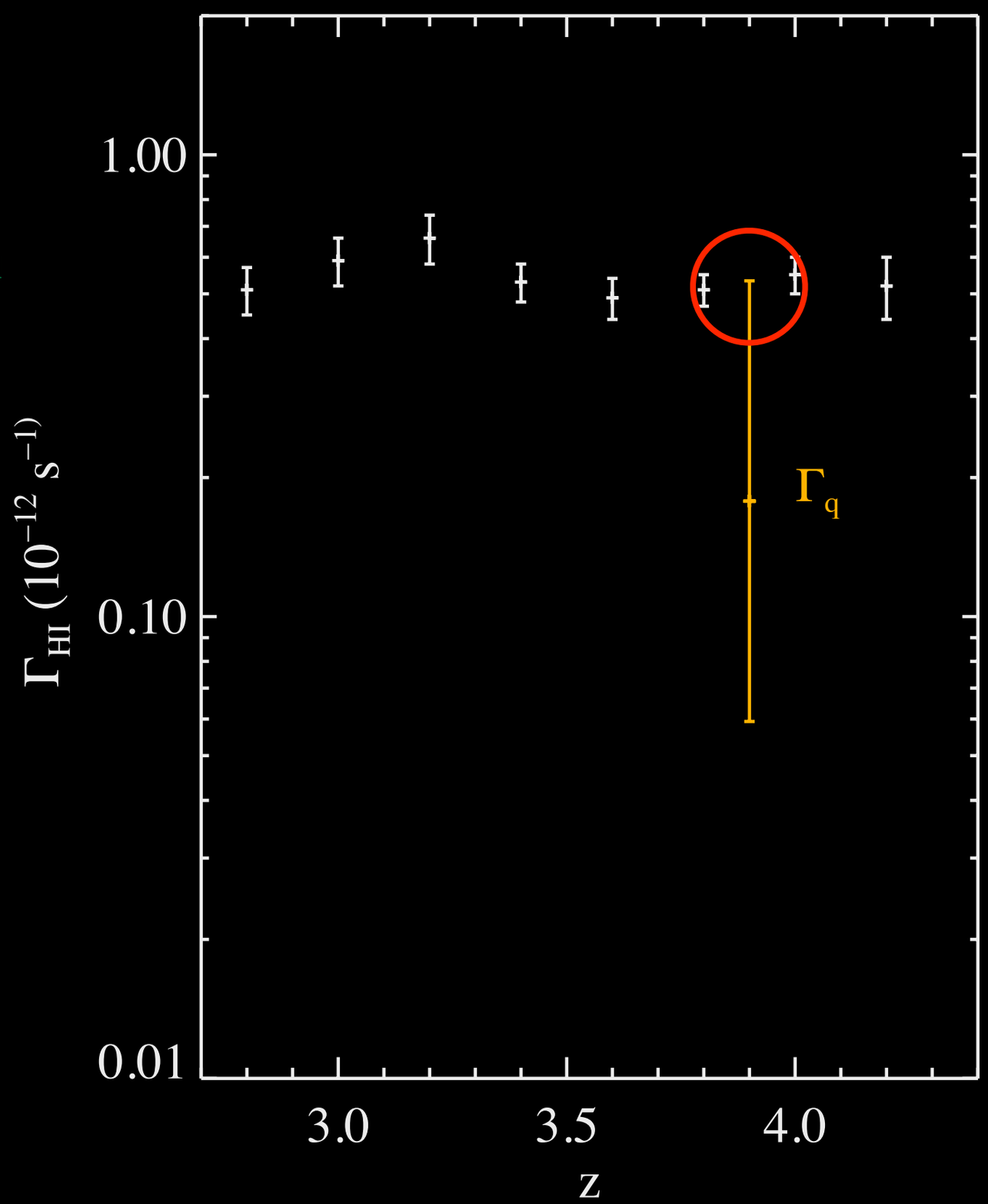
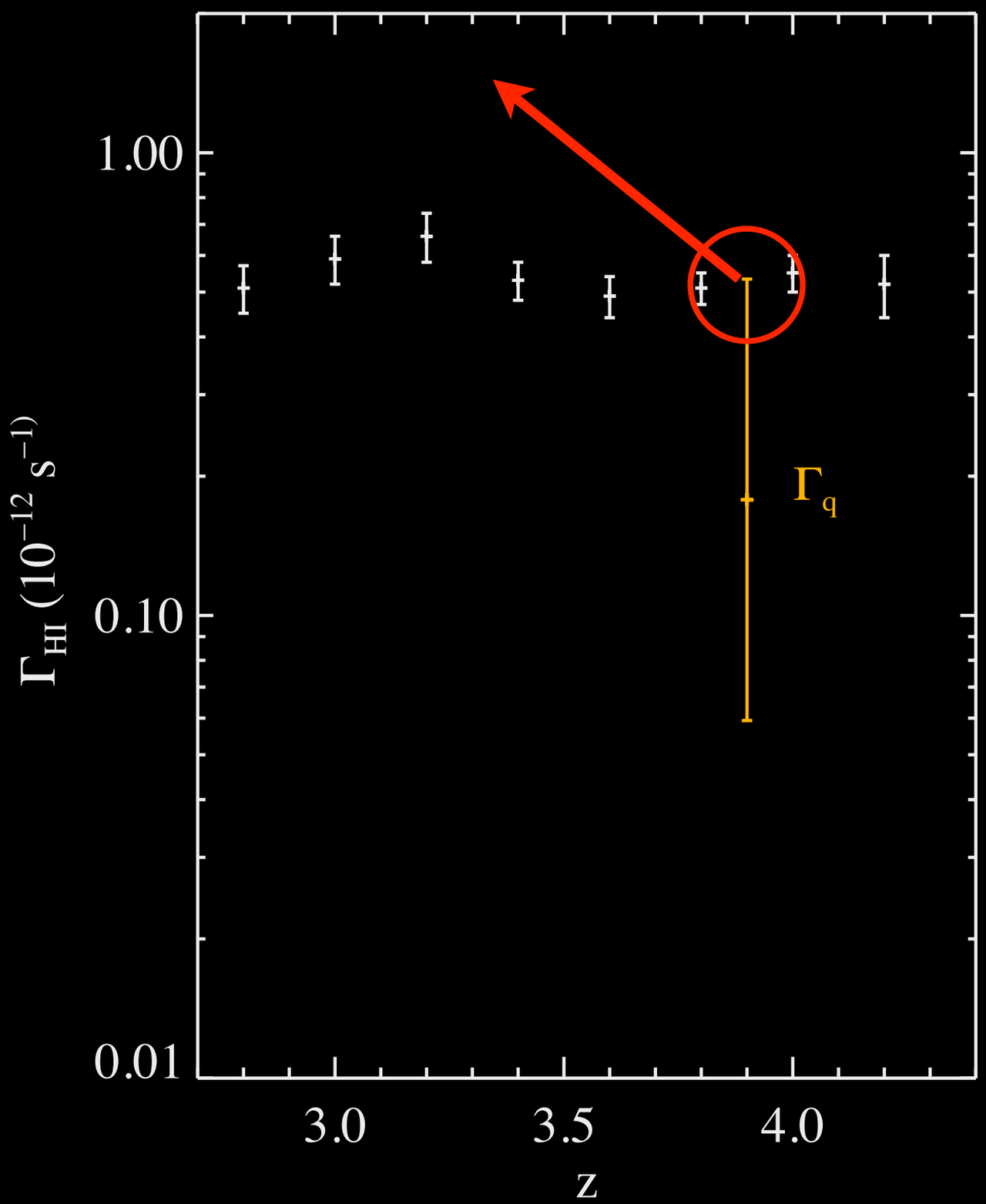


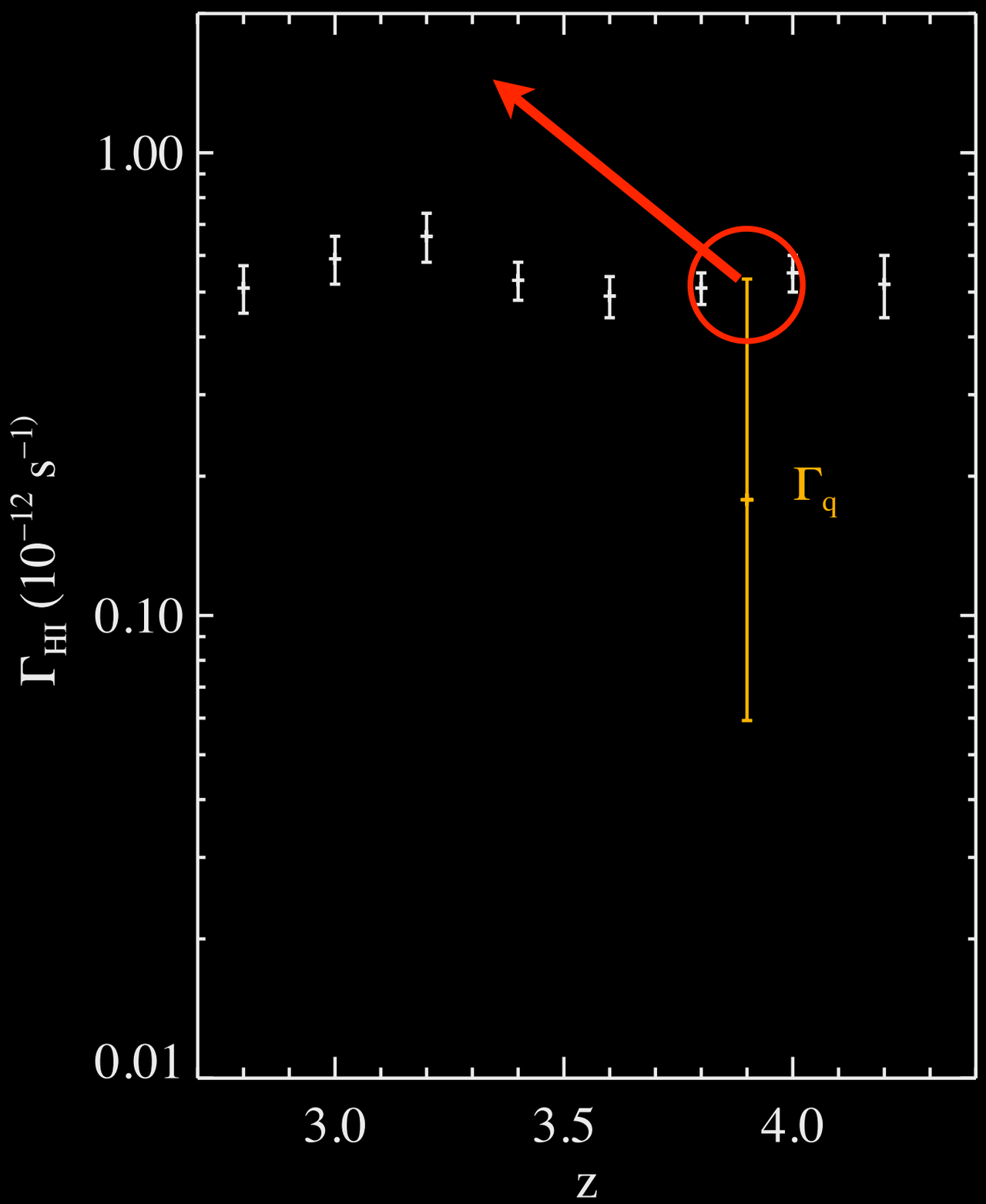
λ_{mfp} Implications: Quasars vs. Stars

- z=4
  - Possible to match $\Gamma_{HI} \sim \Gamma_q$
    - Factor of 3 uncertainty in Γ_{HI} and ε_q
  - Stars need not dominate
- z<4
  - Γ_q increases
    - λ_{mfp} increases
    - ε_q increases
  - Overpredict Γ_{HI} by z~3

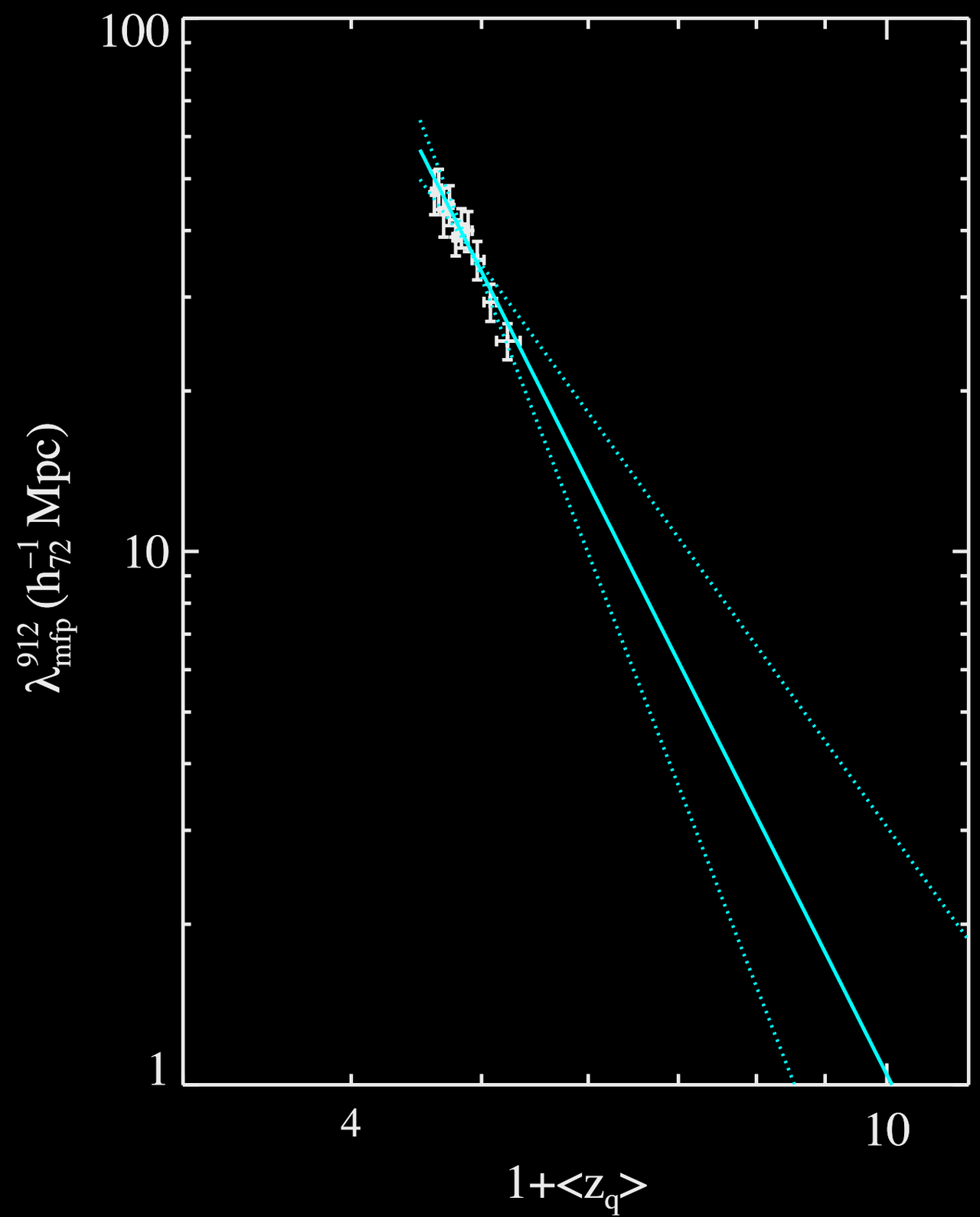


λ_{mfp} Implications: Quasars vs. Stars

- z=4
  - Possible to match $\Gamma_{HI} \sim \Gamma_q$
    - Factor of 3 uncertainty in Γ_{HI} and ε_q
  - Stars need not dominate
- z<4
  - Γ_q increases
    - λ_{mfp} increases
    - ε_q increases
  - Overpredict Γ_{HI} by z~3
- Best inferences
  - Quasars dominate at z~3
  - Stars dominate at z~4
  - This hinges on a flat Γ_{HI}

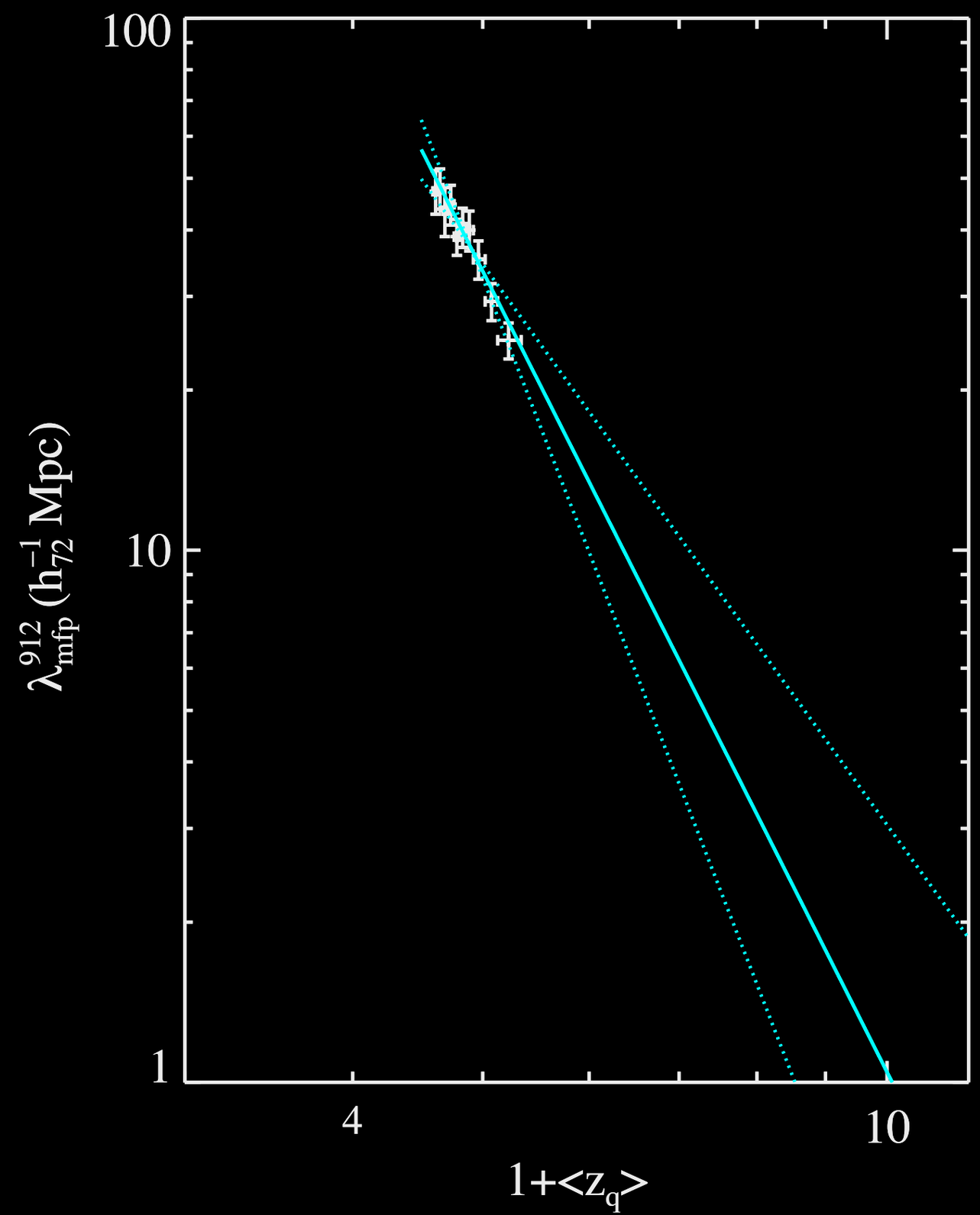


λ_{mfp} Implications: Reionization



λ_{mfp} Implications: Reionization

- Ansatz
  - Demand $\lambda_{mfp} \sim (1+z)^{\gamma}$
    - Physically motivated
- Extrapolate to z>4
  - $z_{reion} > 7.5$
  - $z_{reion} < 20$



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- Extrapolate to z>4
  - $z_{reion} > 7.5$
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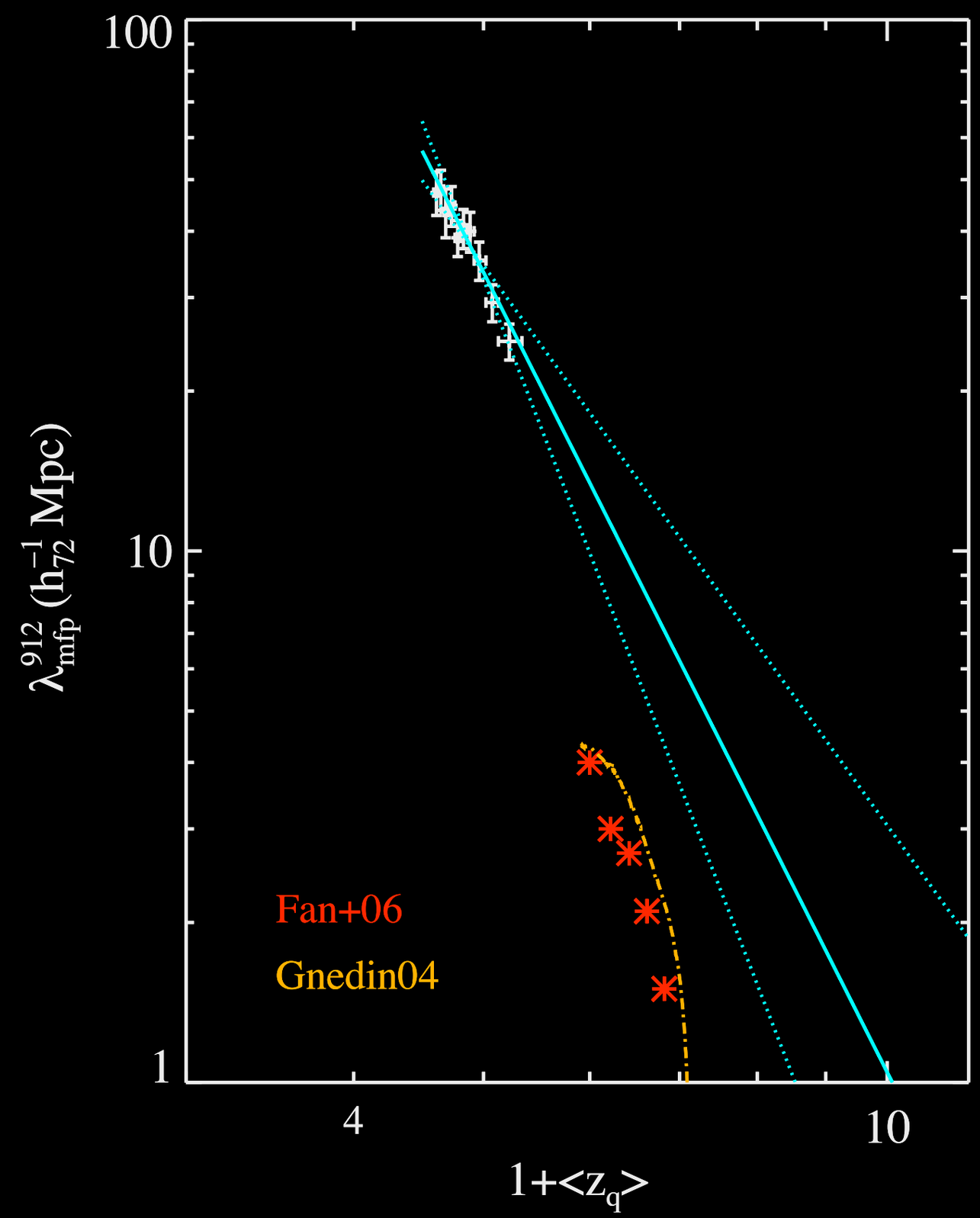
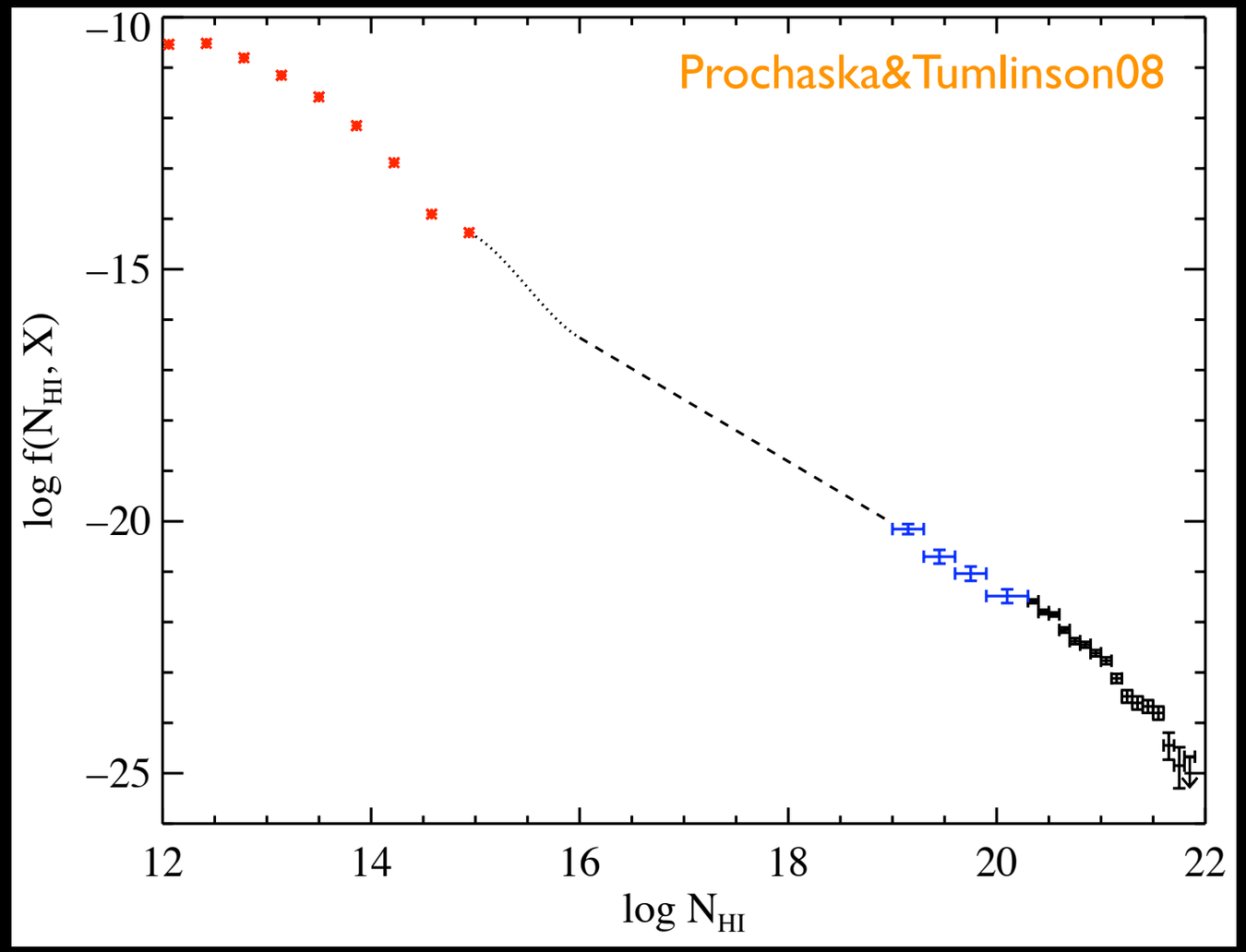
- Comparisons
  - Guesstimates from Lyα
  - Theory 'predictions'

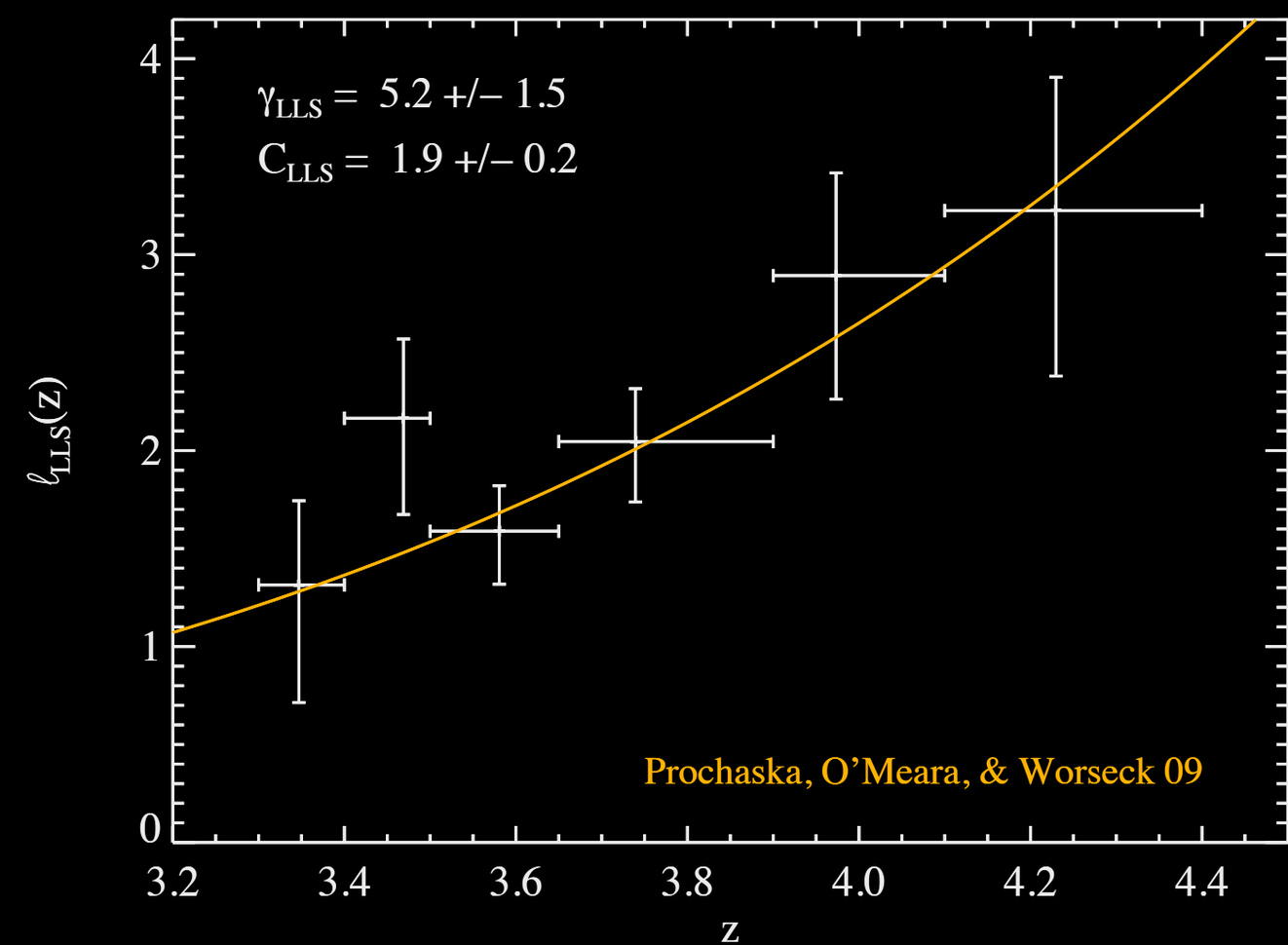


λ_{mfp} Implications: $f(N_{HI})$



λ_{mfp} Implications: $f(N_{HI})$

- SDSS LLS survey
  - DR7
  - Subtle systematic errors



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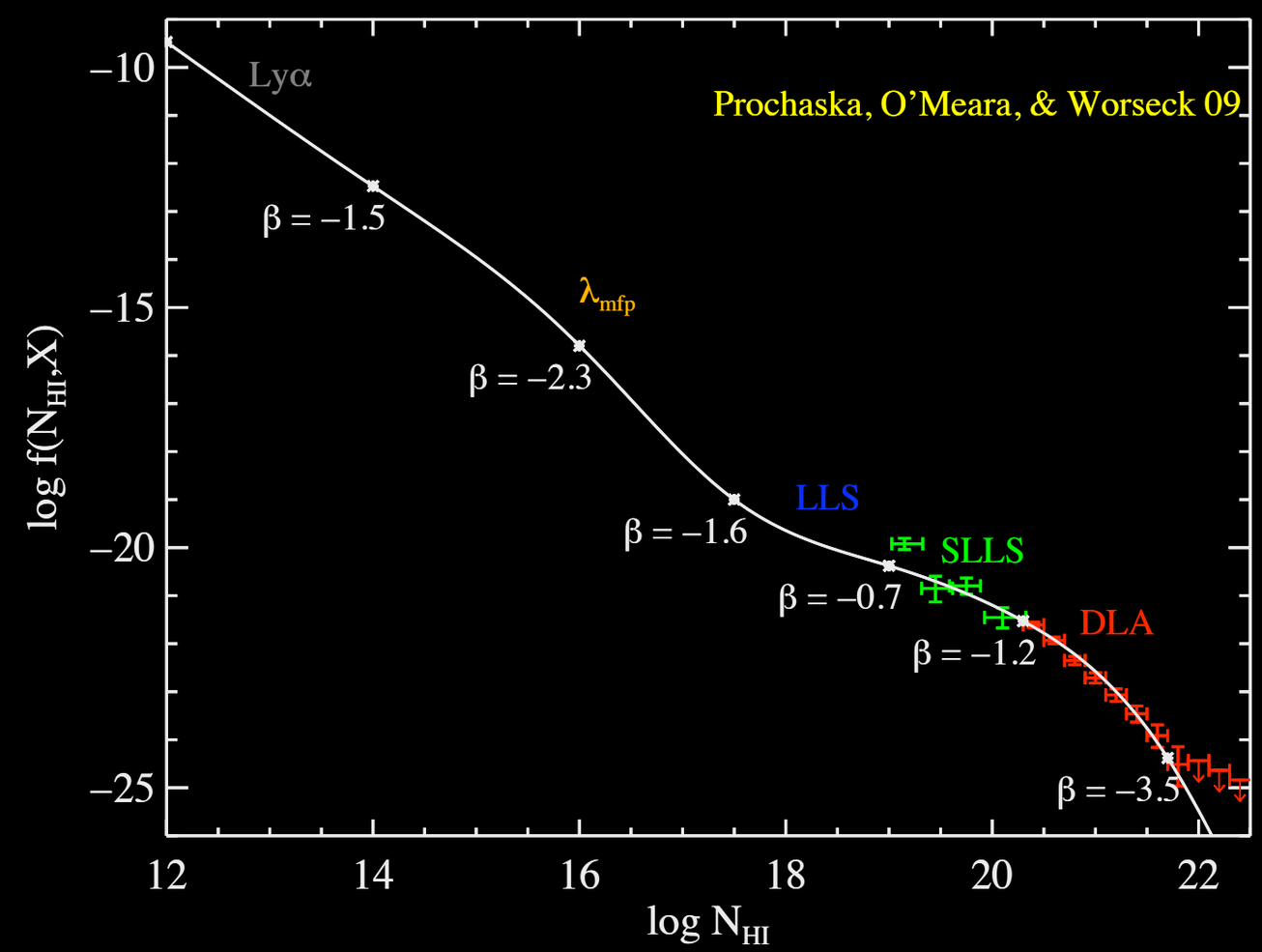
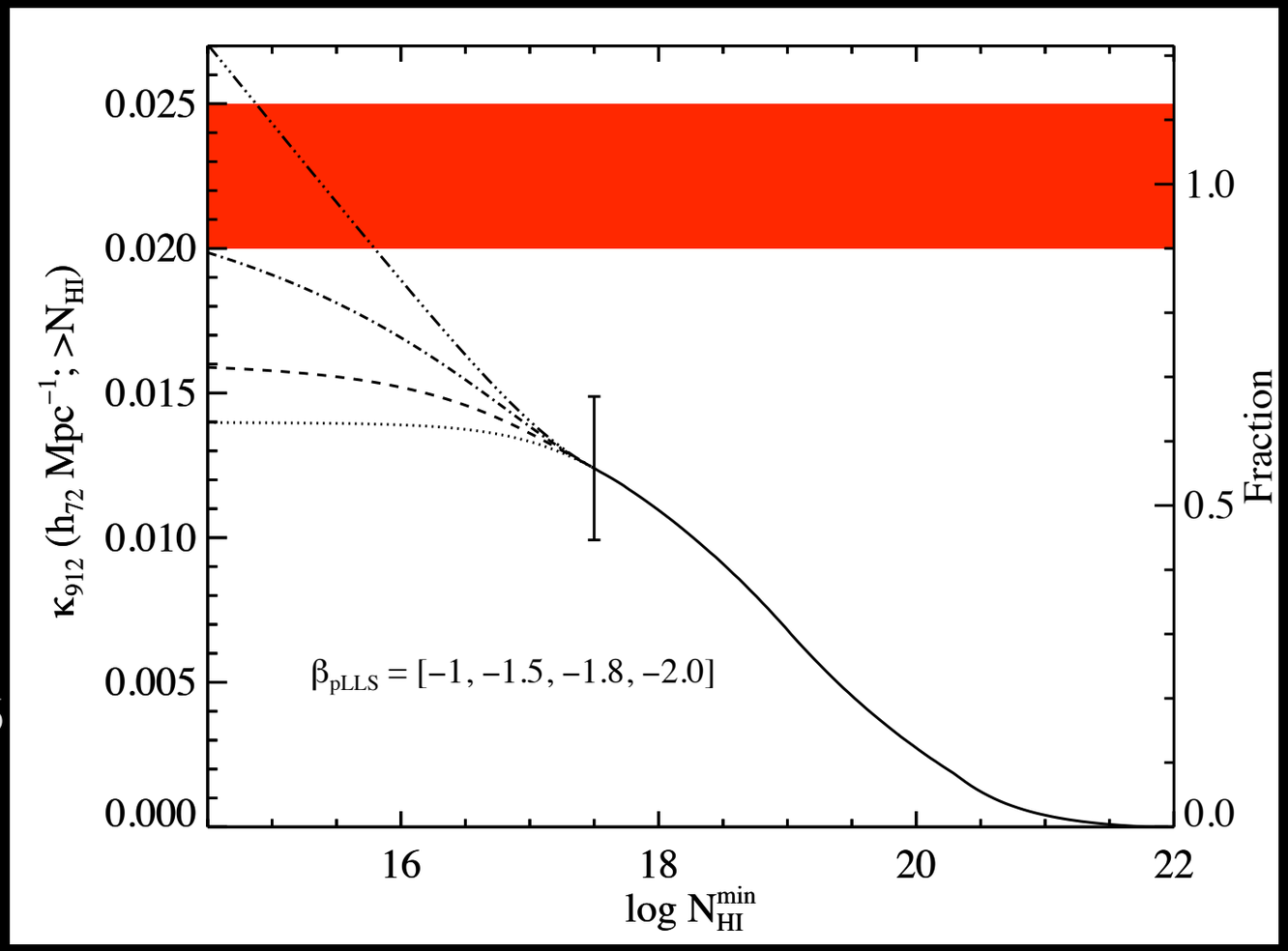
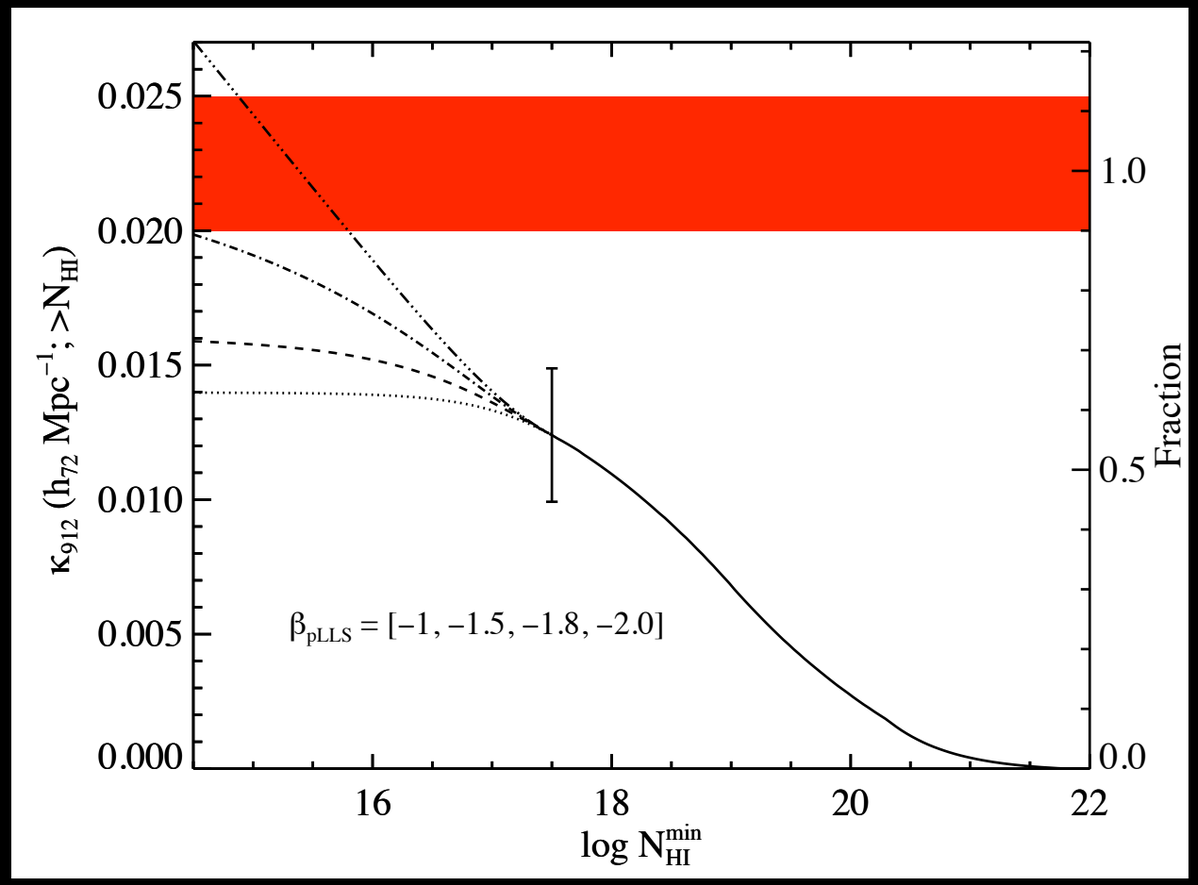


λ_{mfp} Implications: $f(N_{HI})$

- SDSS LLS survey
  - DR7
  - Subtle systematic errors
- Combine $f(N_{HI})$ constraints
  - $z \sim 3.7$
  - DLAs, SLLS, LLS, Lyα, λ_{mfp}
- Results
  - f(N) flattens to > -1 at $N_{HI} \sim 10^{18}$
  - f(N) steepens to < -2 at $N_{HI} \sim 10^{16}$
  - LLS dominate λ_{mfp} at z>3.5



λ_{mfp} Implications: What is its origin?



λ_{mfp} Implications: What is its origin?

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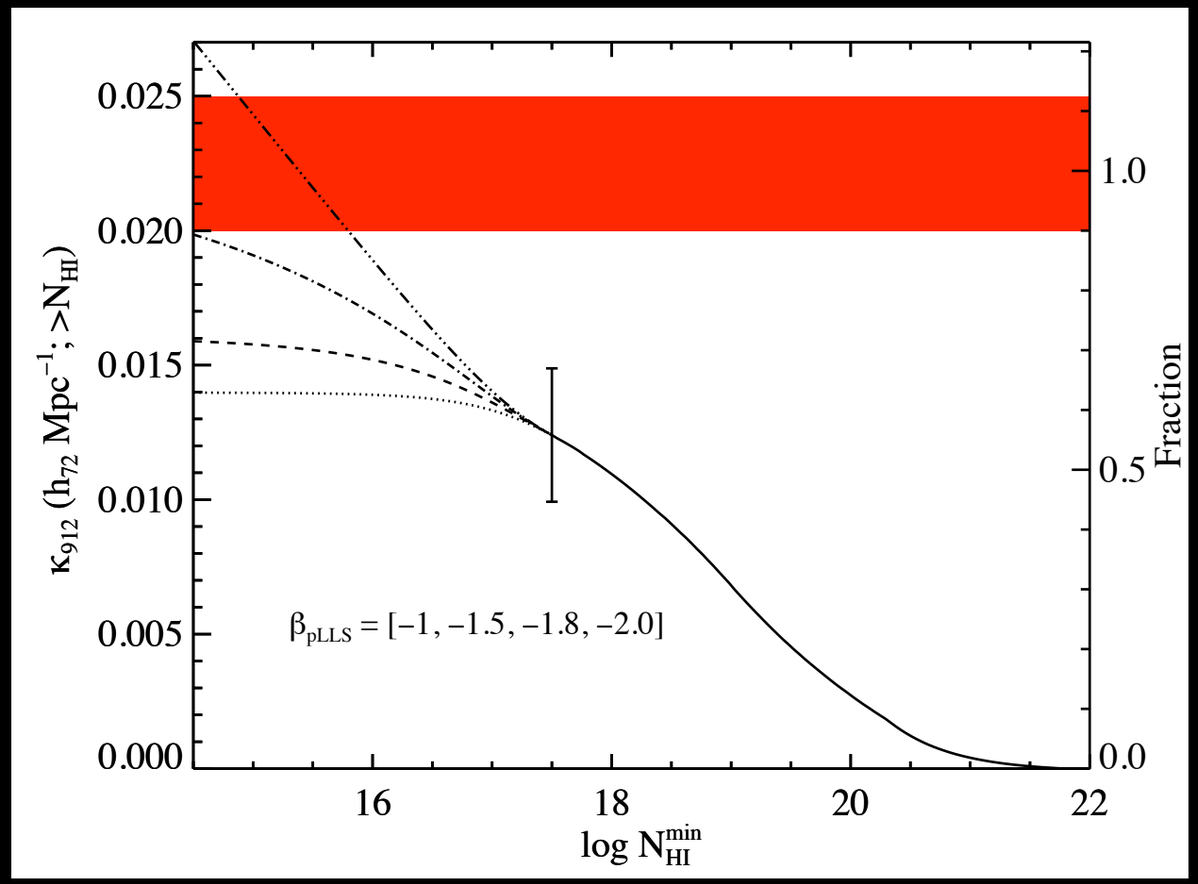
  - Gas with $\tau_{LL} \sim 1$
  - $\log N_{HI} \sim 17$



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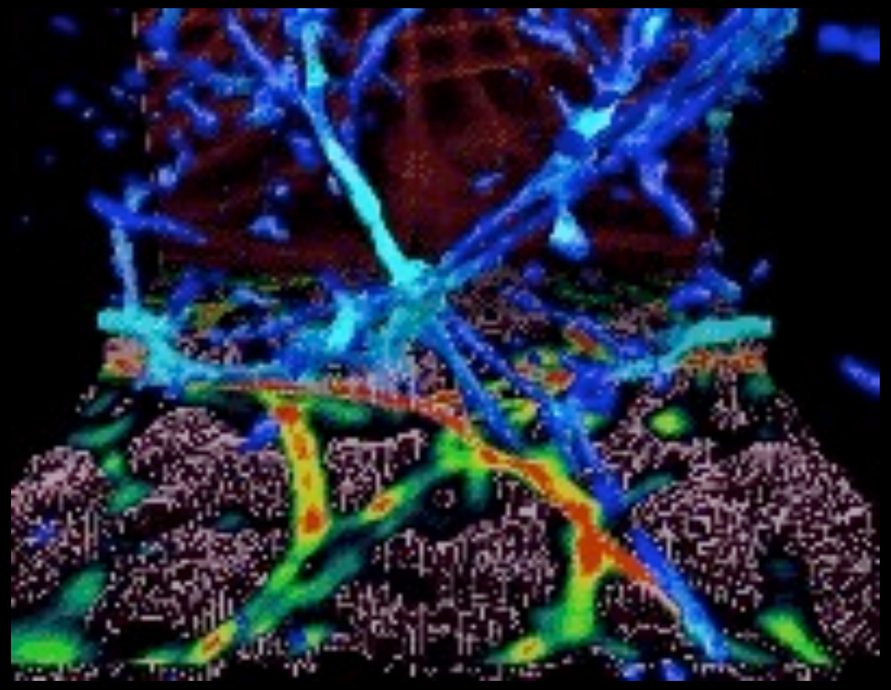

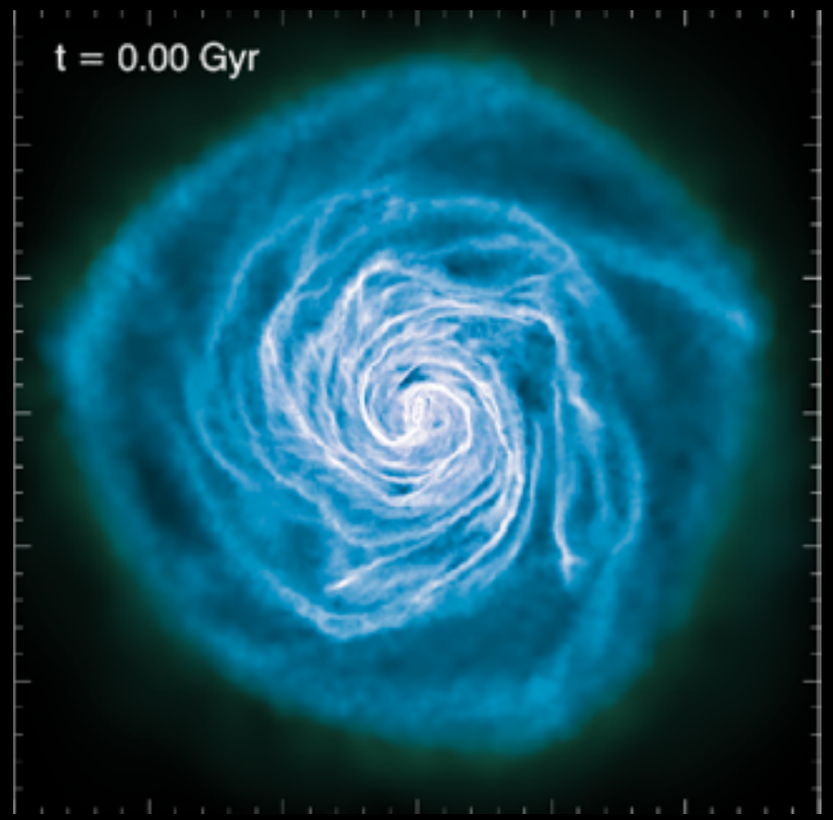

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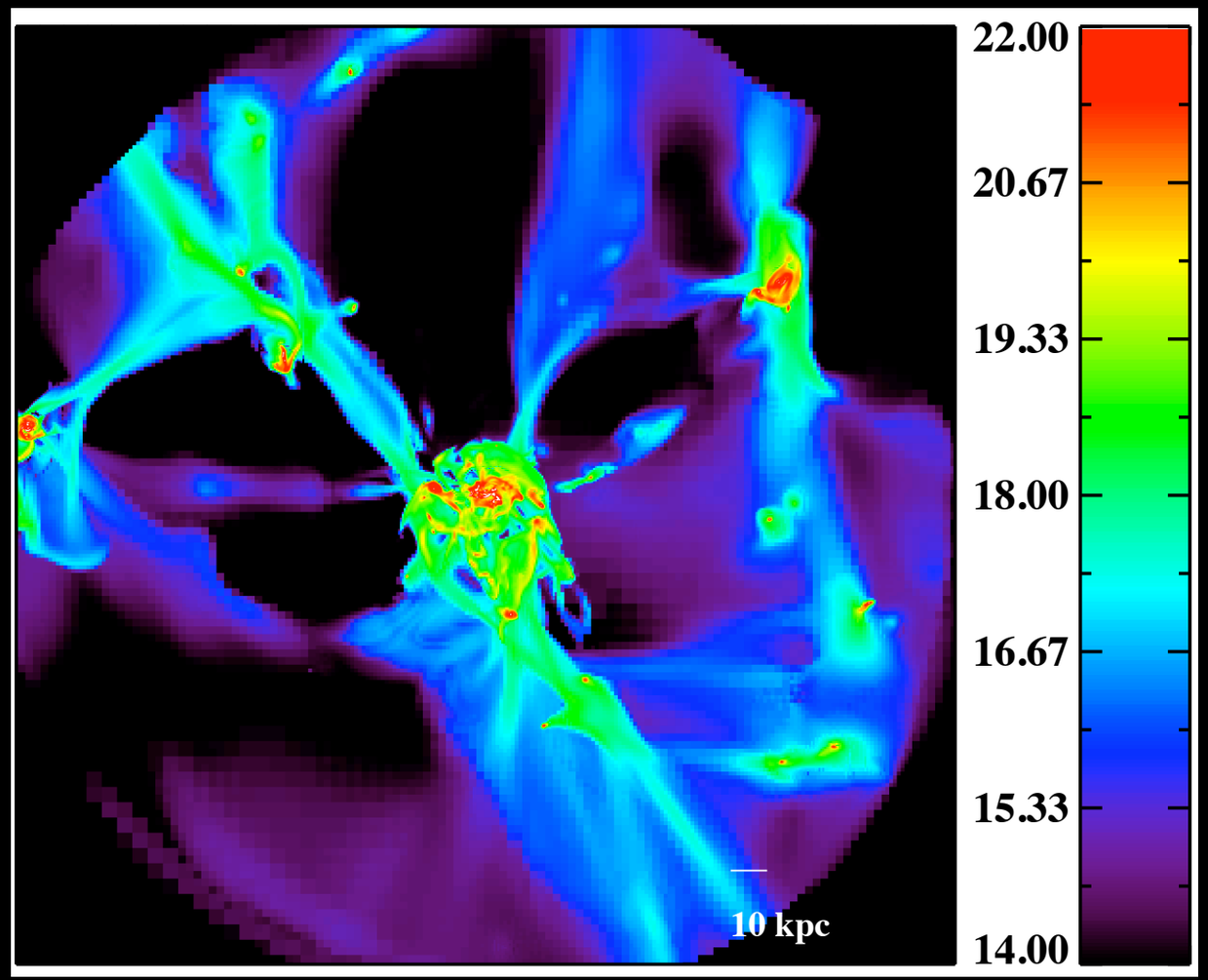
  - First results…
    - "Cold streams"
    - Do they extend beyond galactic halos?



Fumagalli+ 2010

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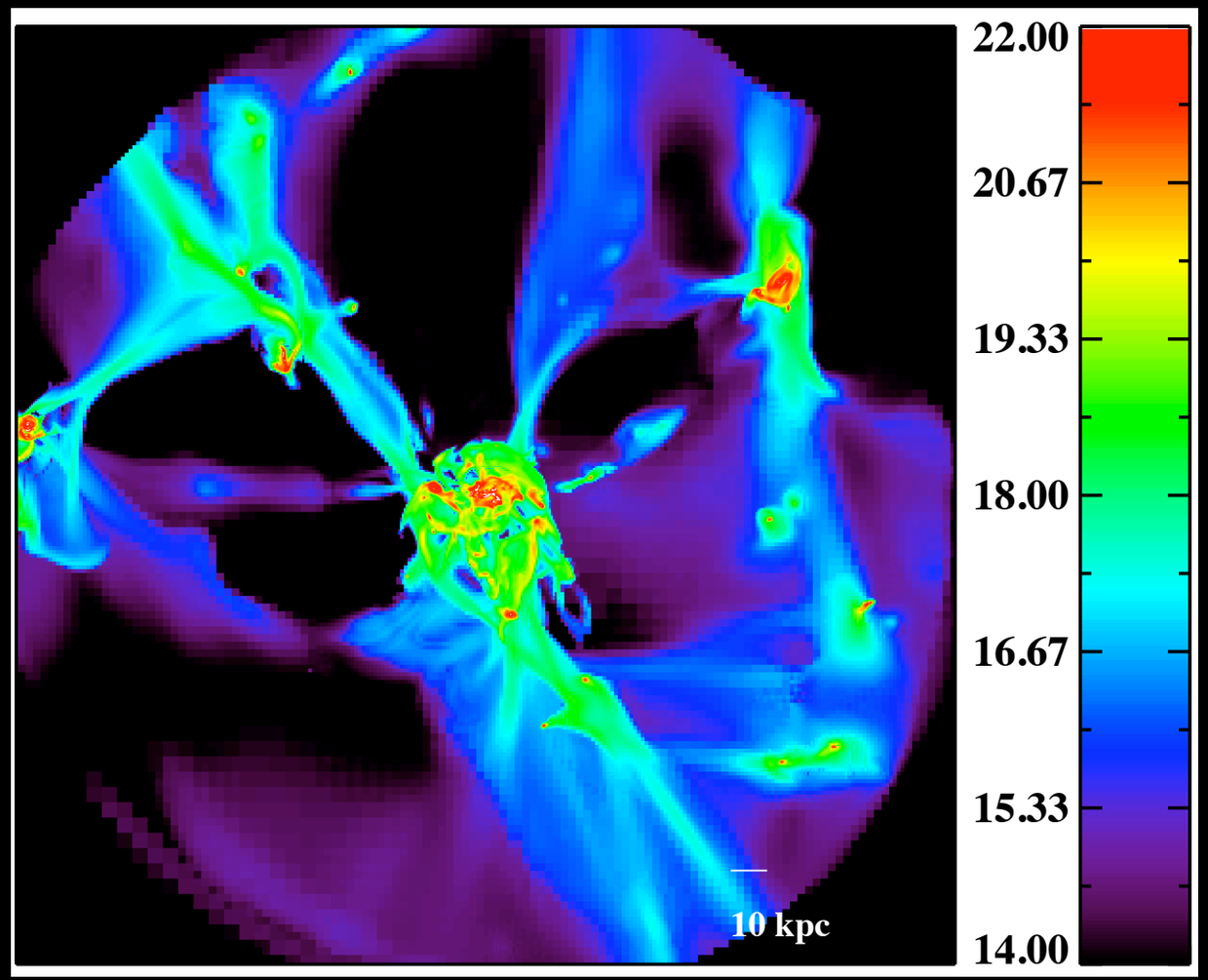
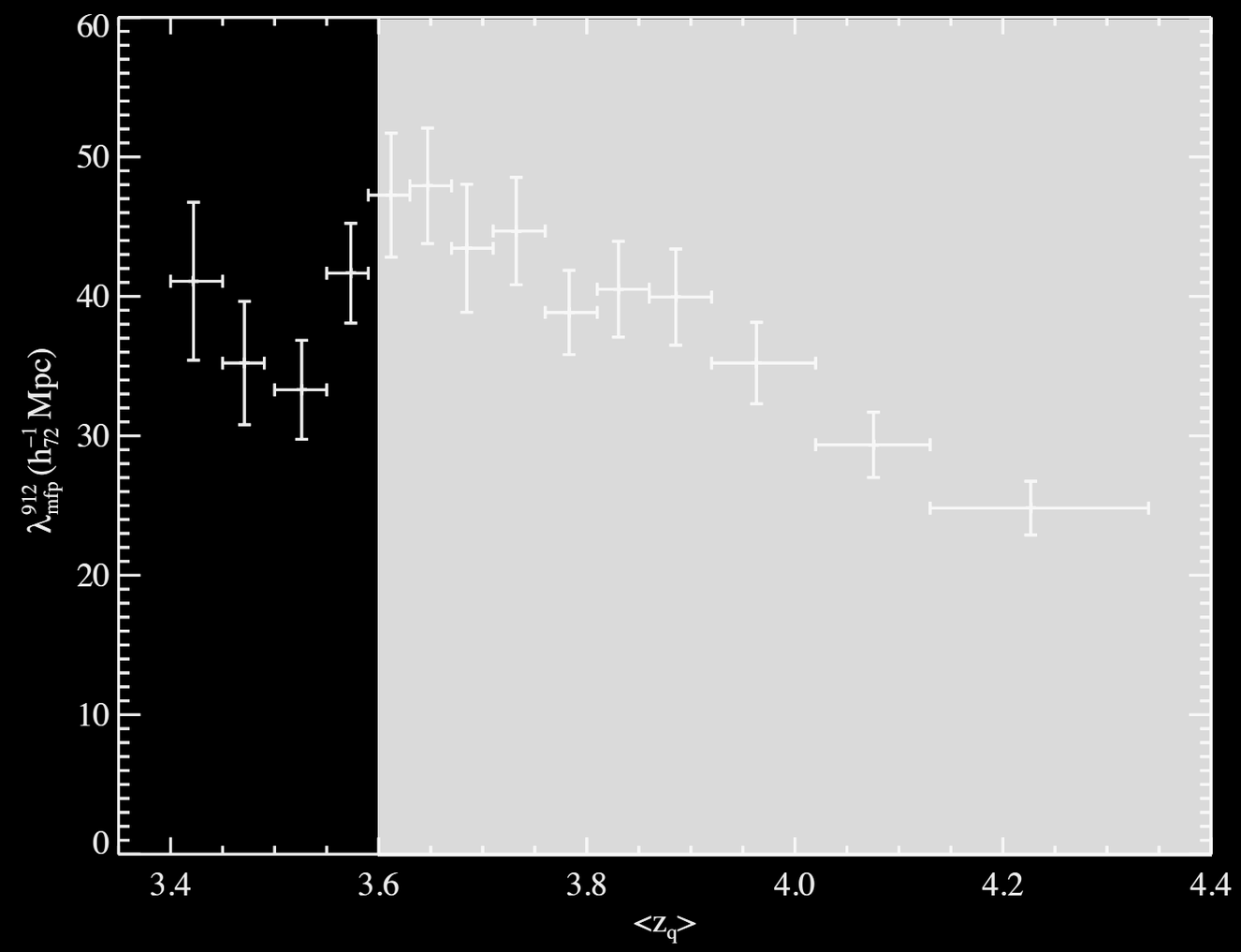
- Why does λ_{mfp} evolve with z?



Fumagalli+ 2010

λ_{mfp}: SDSS Measurements (z<3.6)



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- Unphysical decrease with z
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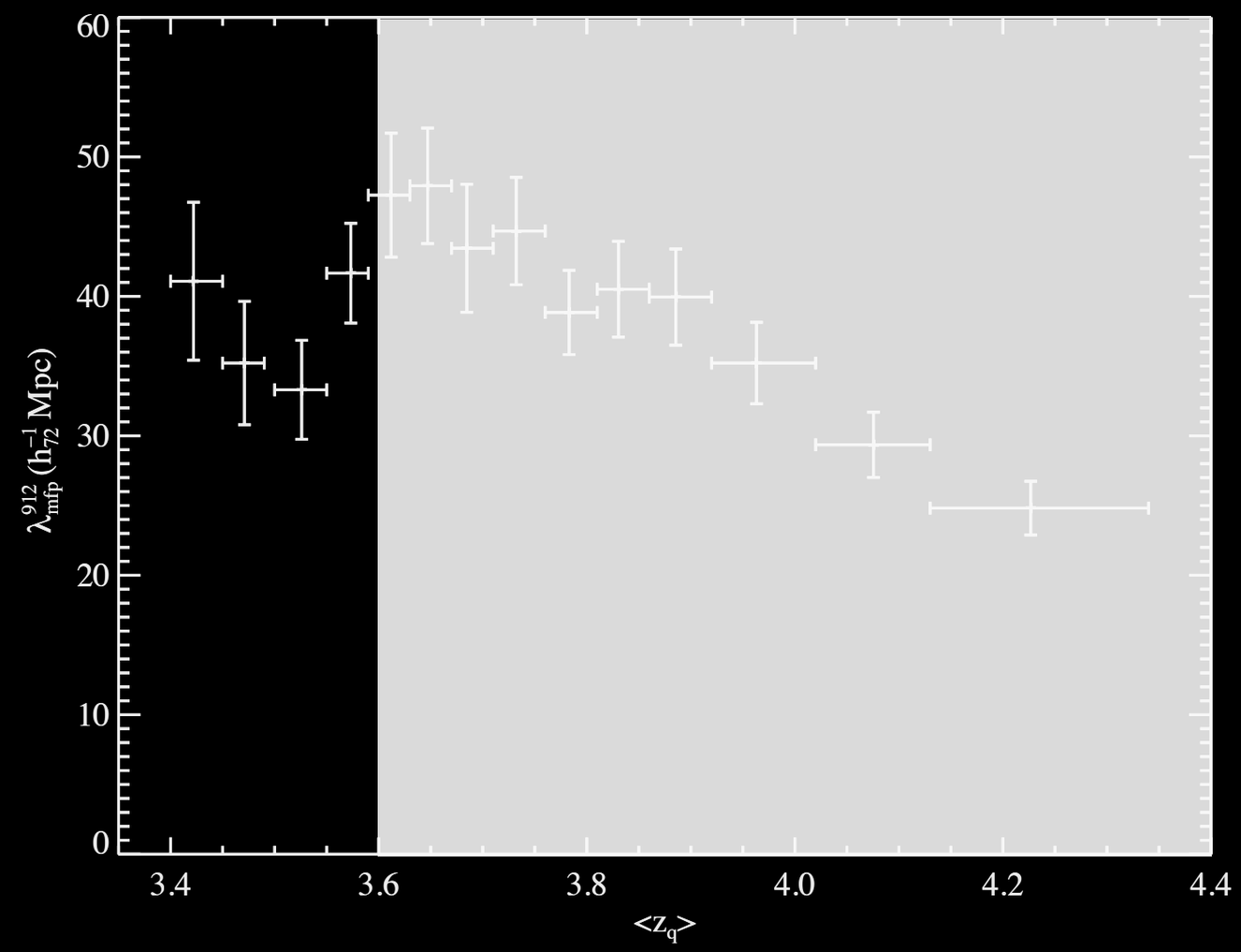

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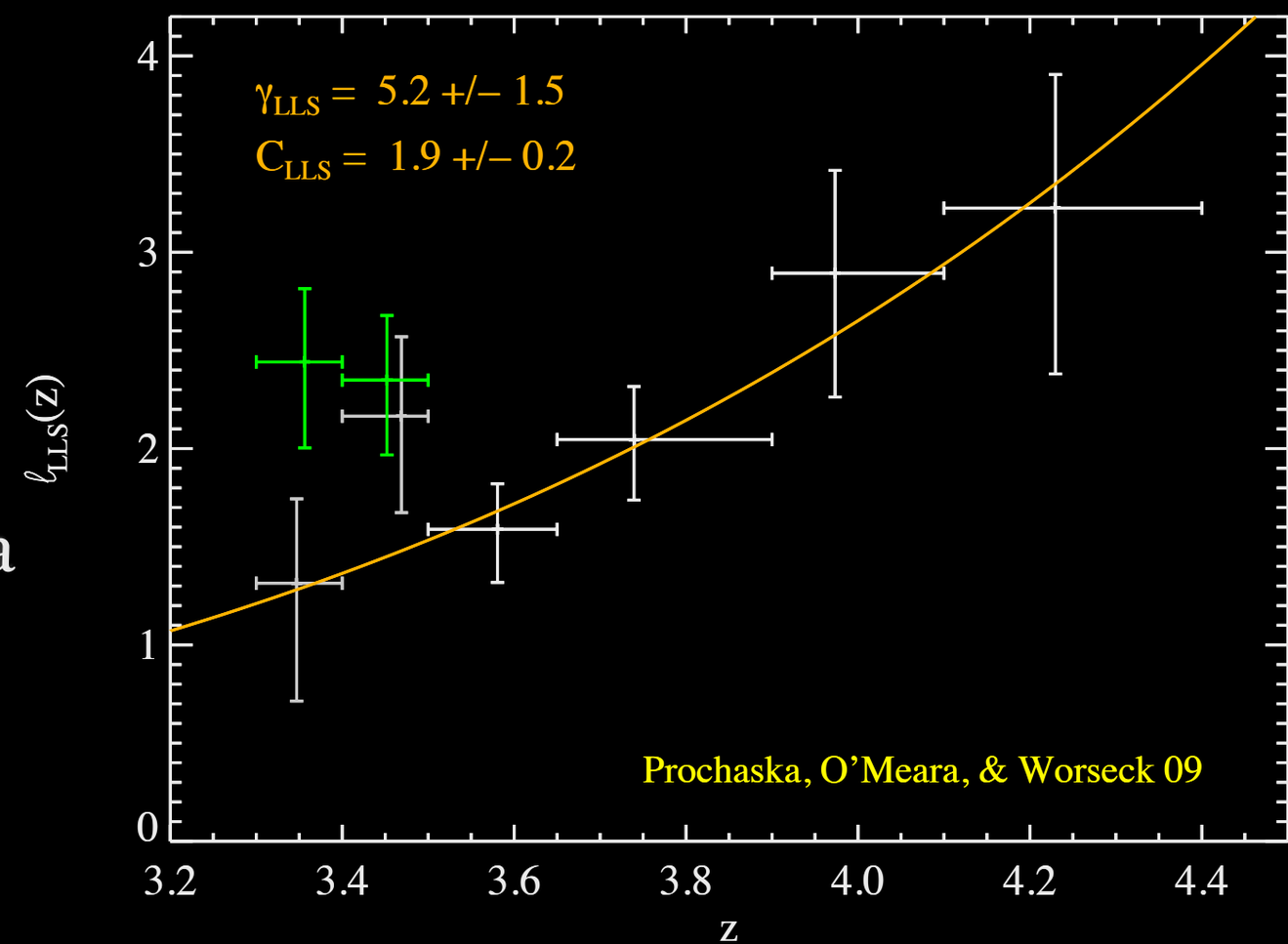

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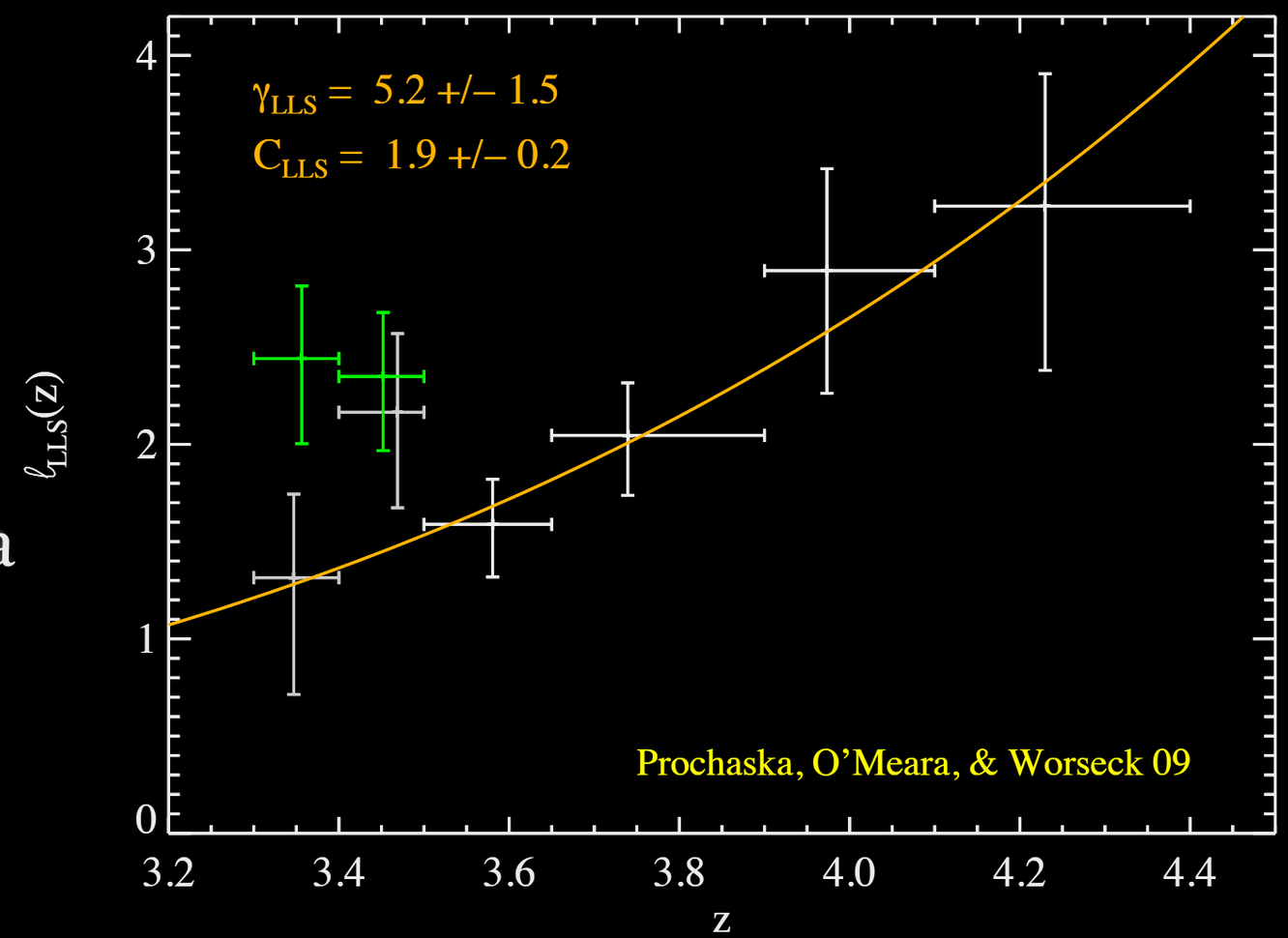
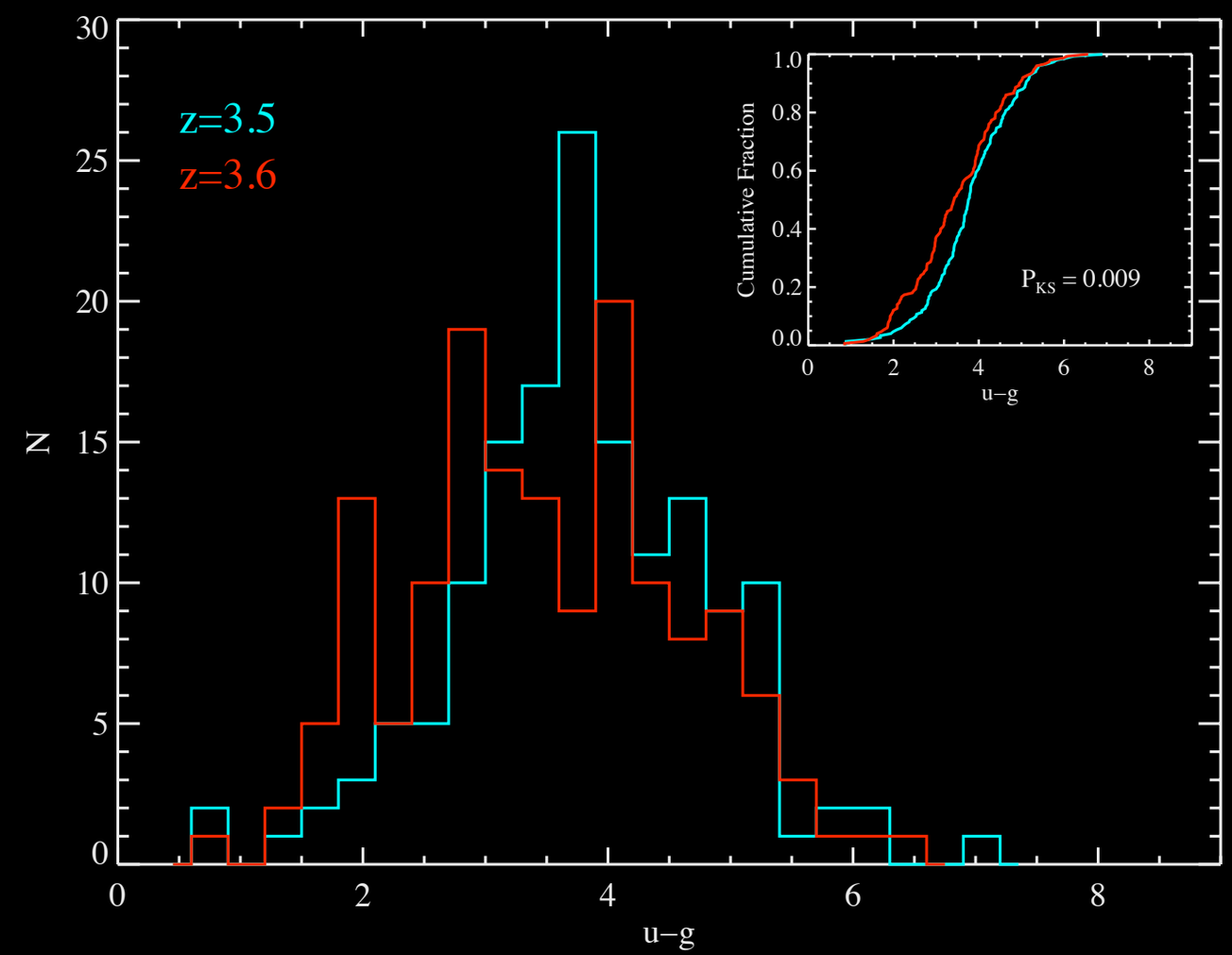
- Implies:
  - Bluer (u-g) quasars at z=3.6 than z=3.5
    - Opposite to expected evolution



λ_{mfp} Implications: SDSS Bias



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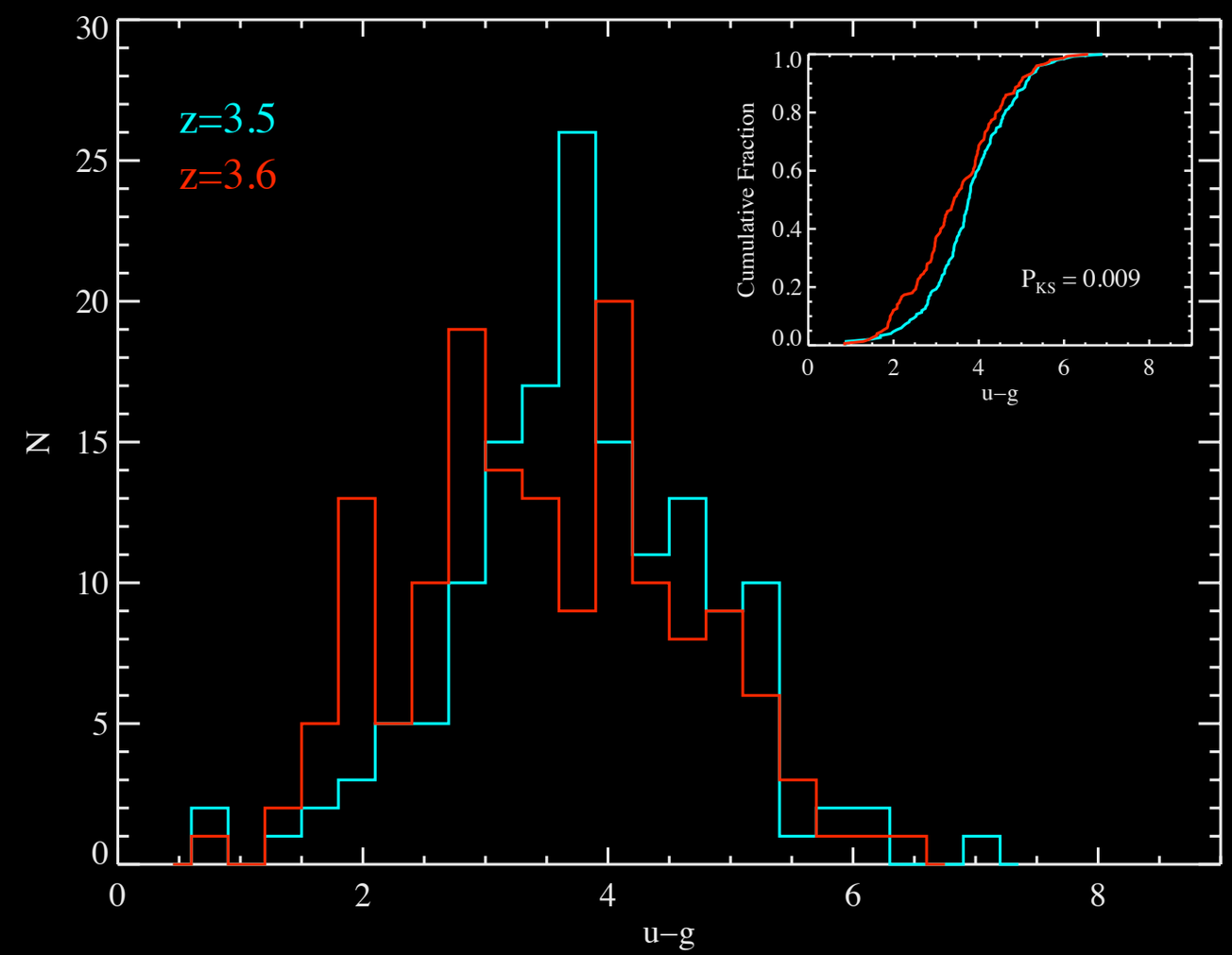
    - True for radio selected quasars too



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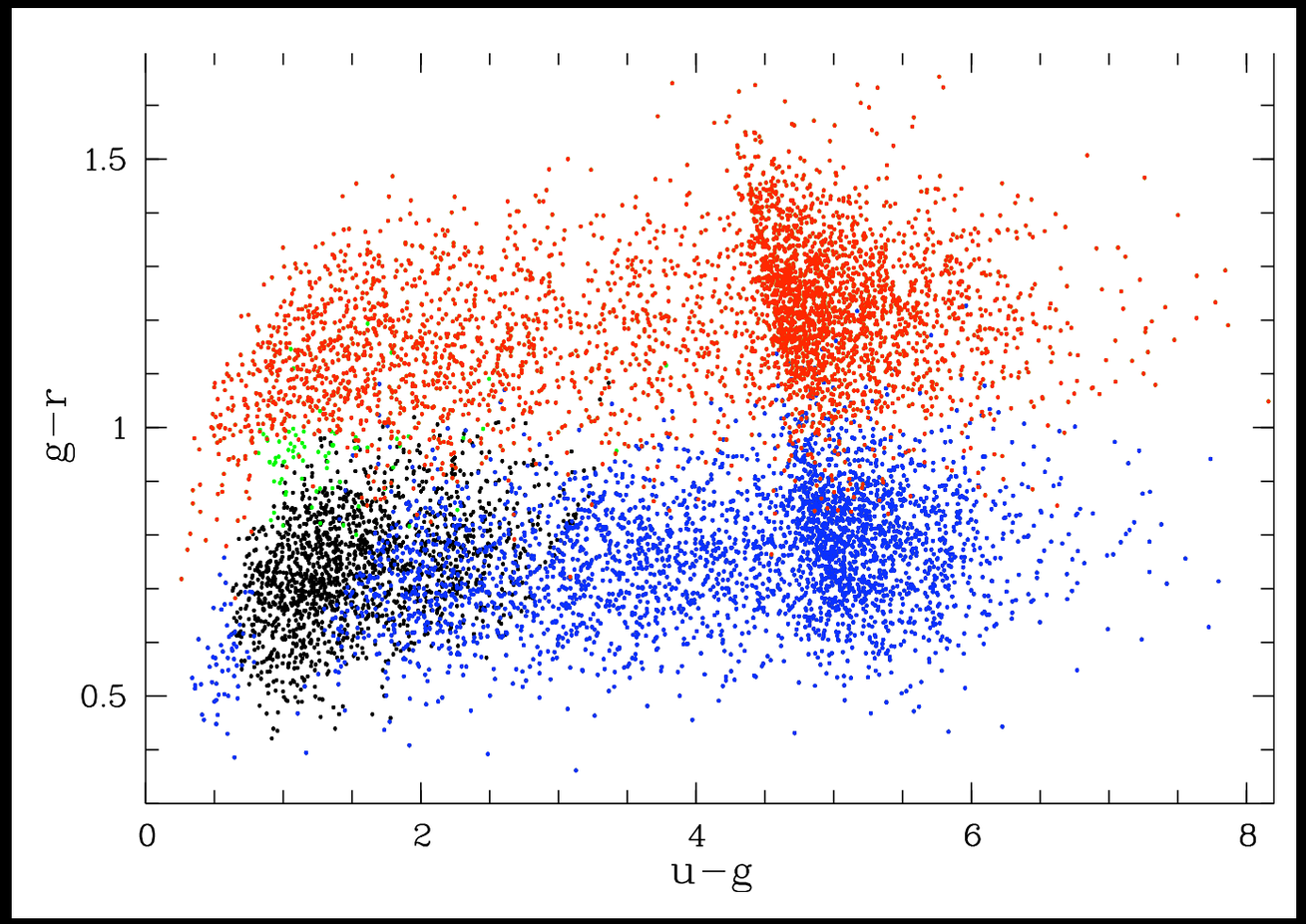

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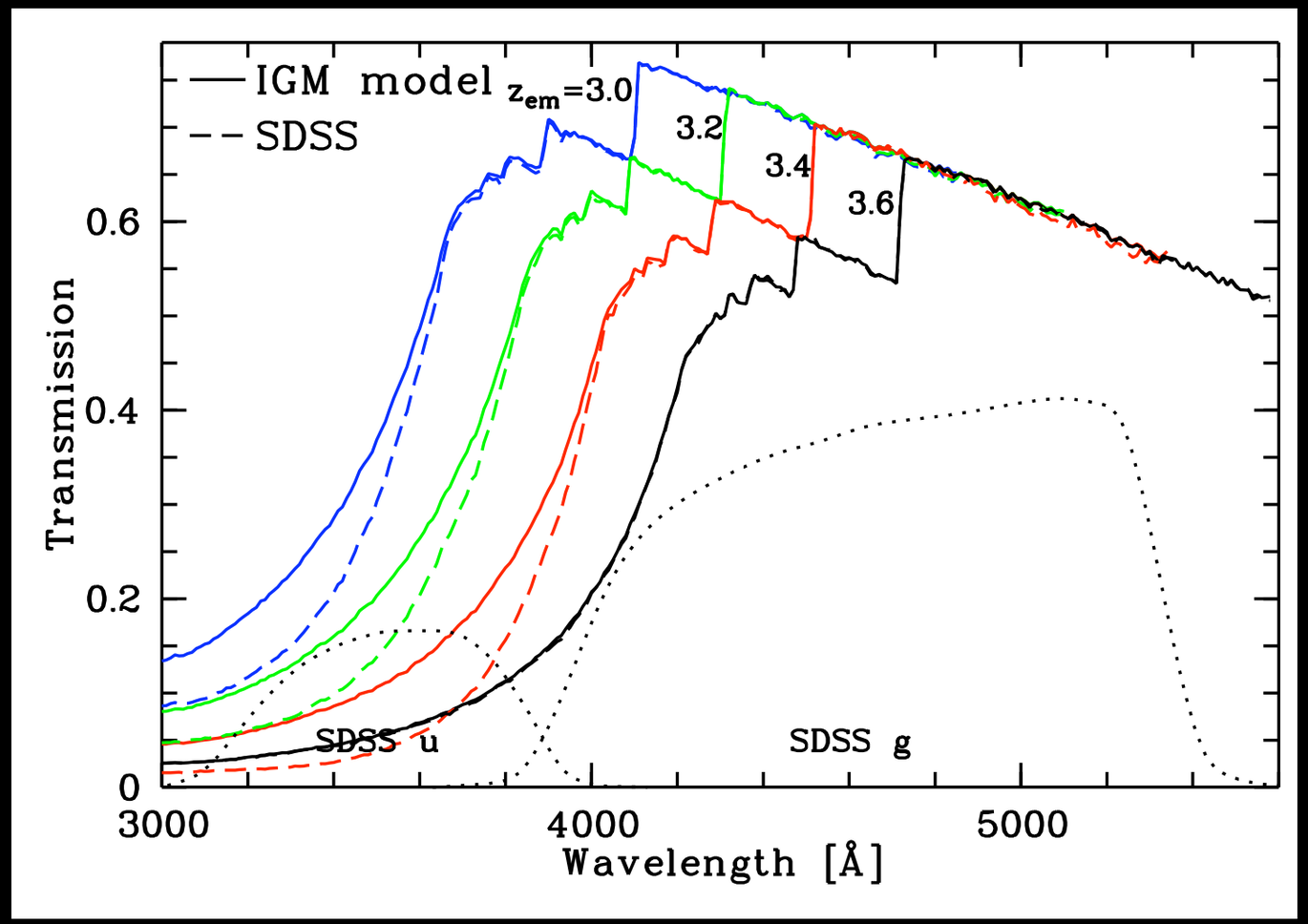
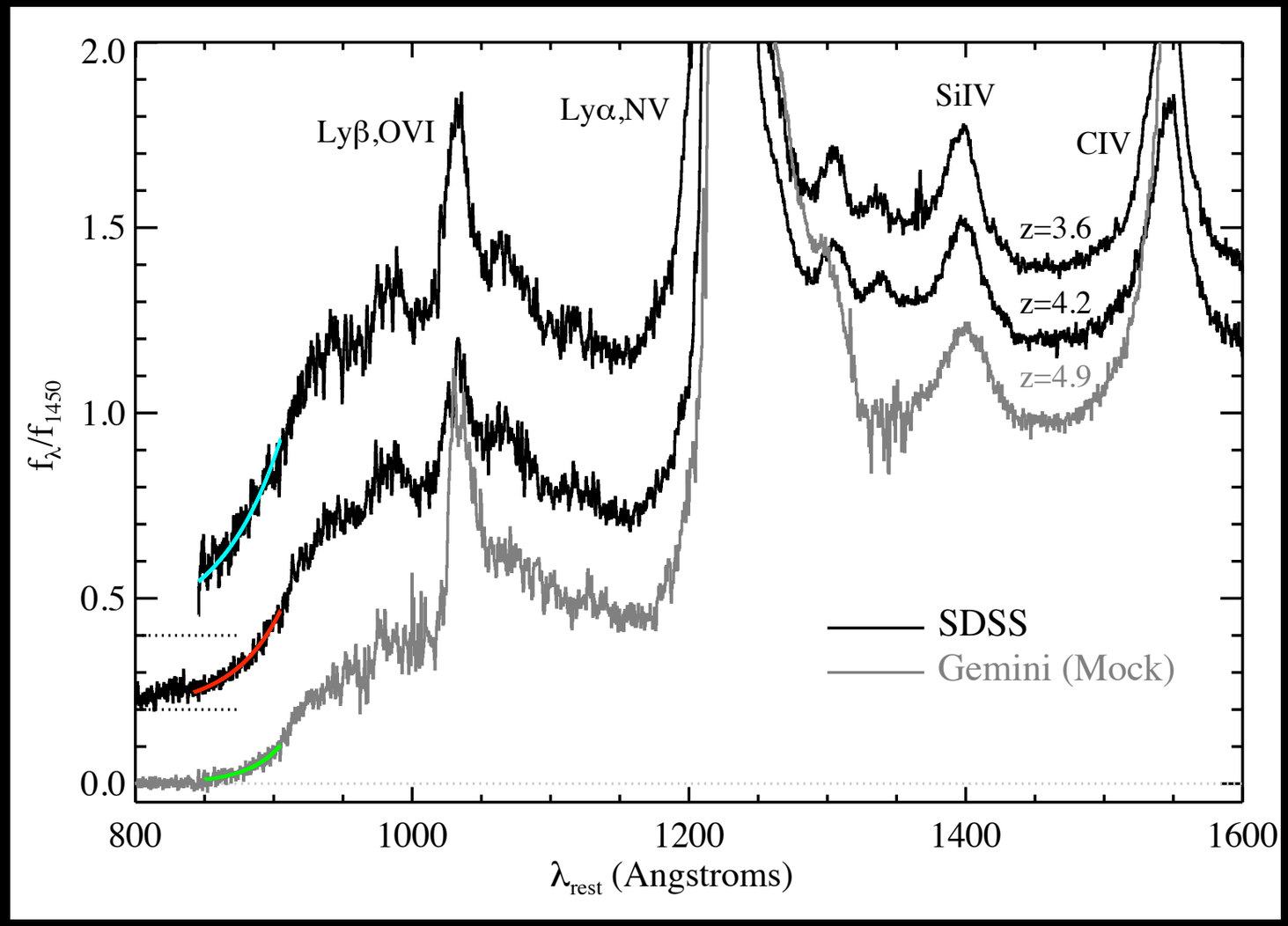
  - 'Perfect storm' of errors
- Implications:
  - Biased toward quasars with LLS
  - Biased against quasars that are useful for HeII studies
  - IGM studies at z~3 from SDSS are suspect



Future Work: λ_{mfp} at z>4

- SDSS
  - S/N too poor at z>4
  - But, the quasars exist
- Approved Gemini/GMOS
  - ~200 quasars at z>4.4
  - IGM studies
  - Collaboration
    - PI: Worseck
    - Multi-national effort



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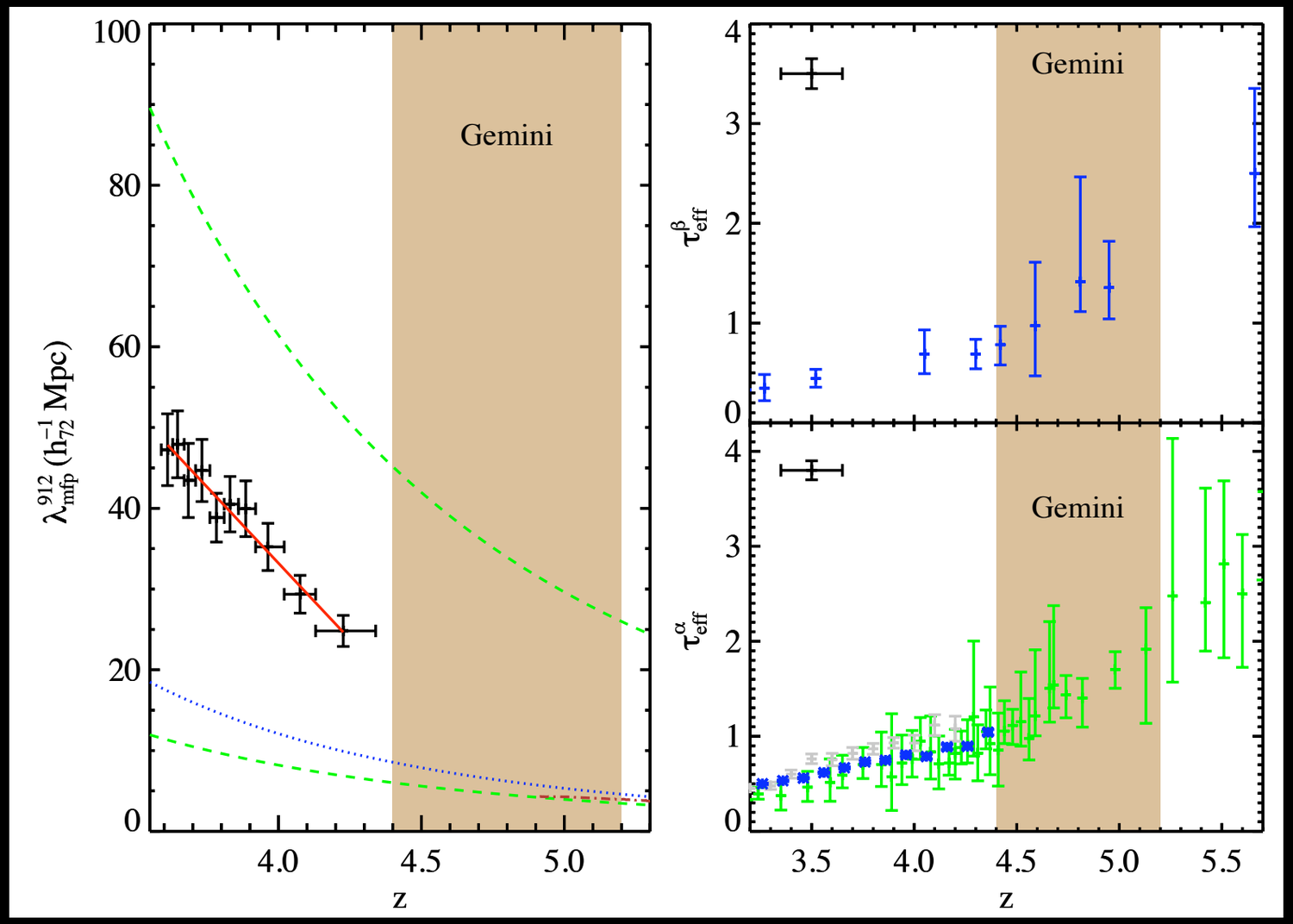
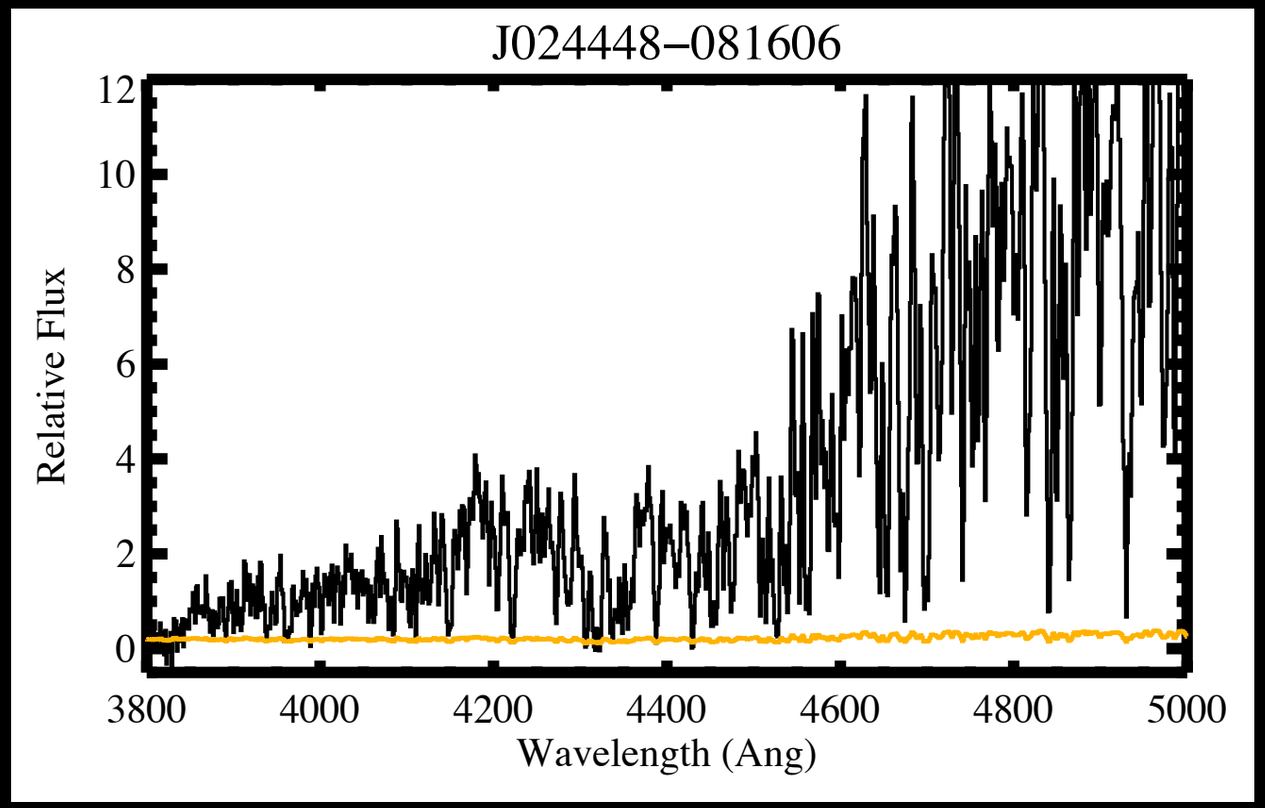
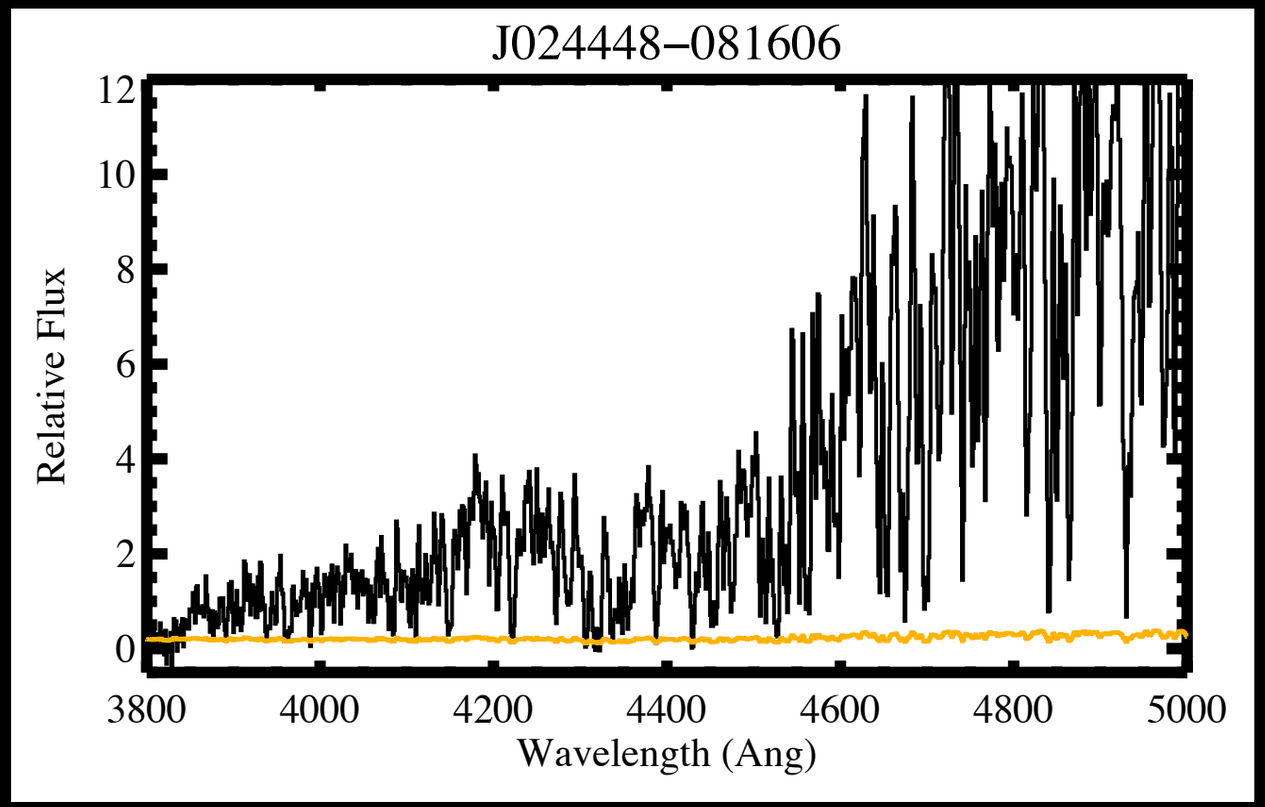


Future Work: λ_{mfp} at z~3

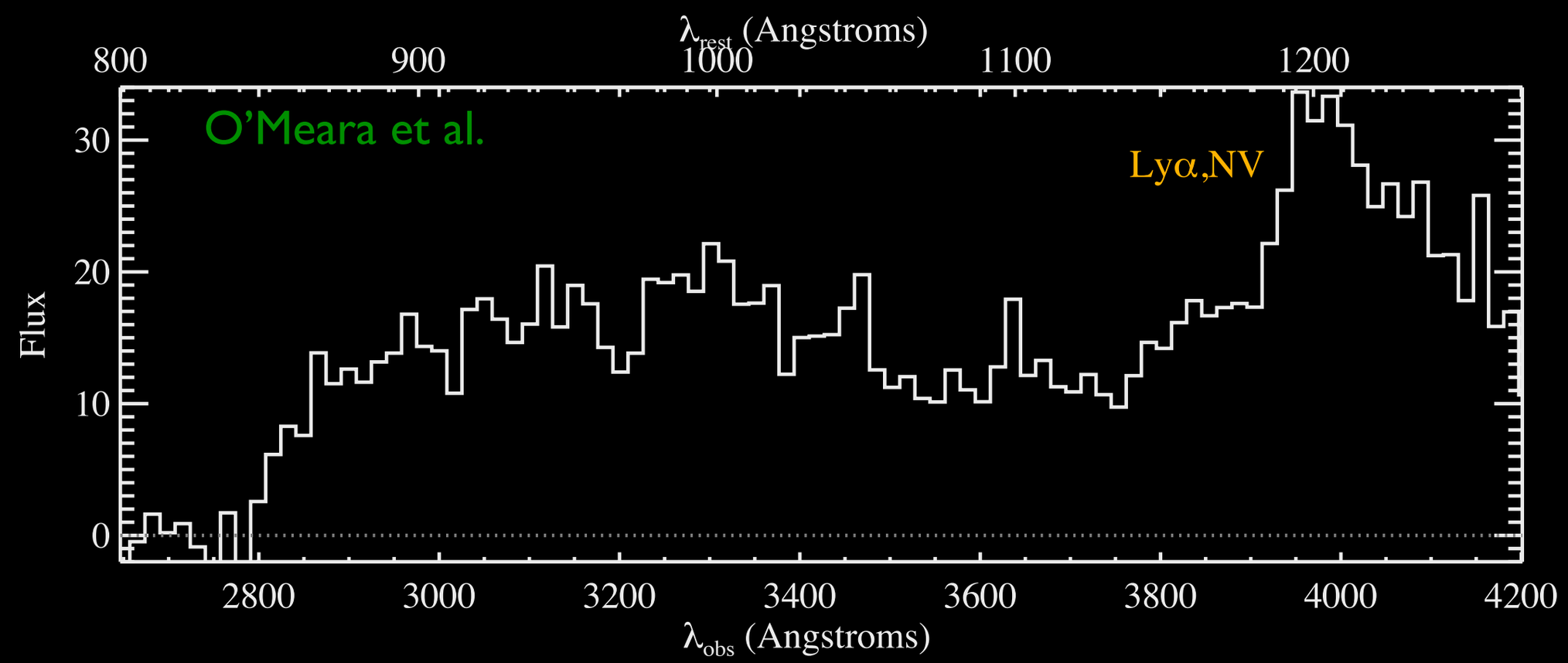


Future Work: λ_{mfp} at z~3

- SDSS
  - Spectral coverage limits to z>3.3
  - Quasar bias kills z~3.4
- Path forward?
  - Focus on quasars discovered without color-selection
    - Radio
    - X-ray
    - Spectroscopic
  - Ongoing program with Keck/LRIS



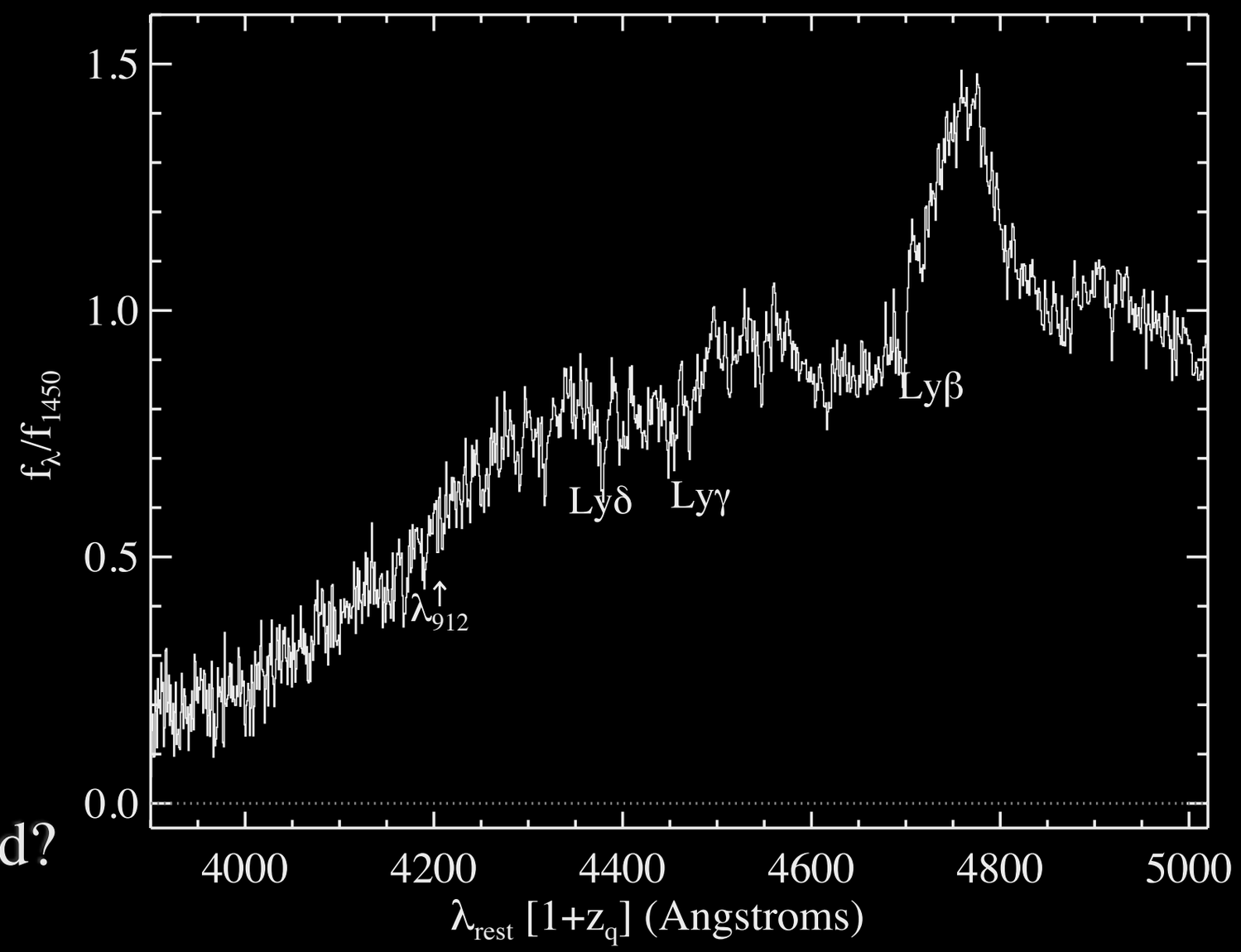
Future Work: λ_{mfp} at z<2.5



- λ_{LL} < 3000Ang
  - Space-based UV observations
  - ACS Prism program
    - Cycle 16 (PI: O'Meara)
    - Obtained ~15 spectra
- New sample (Cycle 17)
  - WFC3 grism
  - 35 observed to date
  - Stay tuned
- Planned (Cycle 18)
  - COS snapshot survey z~1

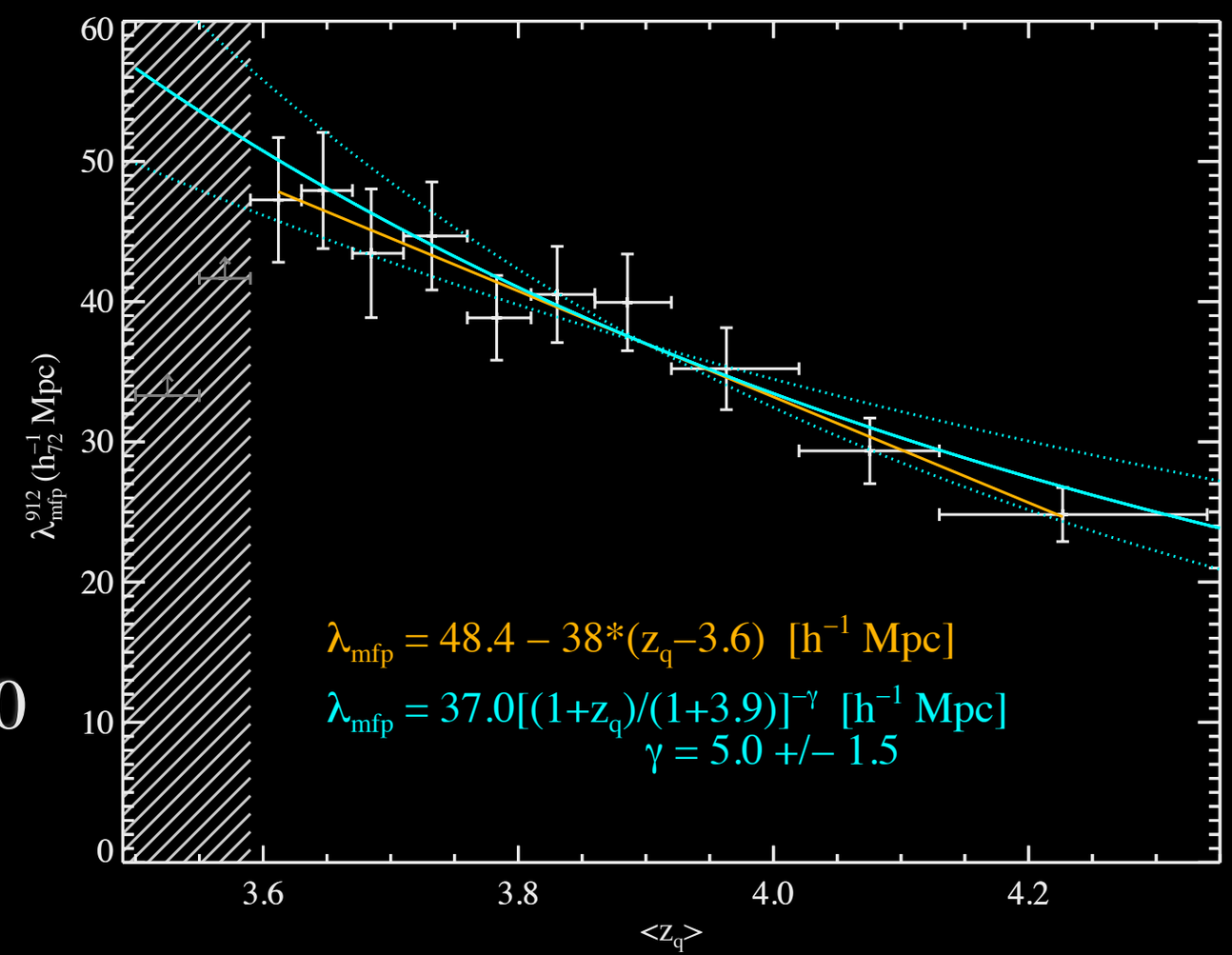
Future Work: Stacked Spectrum

- D_A
  - More work to be done
  - Is the dip real?
- D_B, D_G, ...
  - Model at high precision
  - Constrain $f(N_{HI})$ at $N_{HI} \sim 10^{15}$ to 10^{16}
    - Independent constraint from MFP
- Quasar SED
  - What is the shape below 1Ryd?



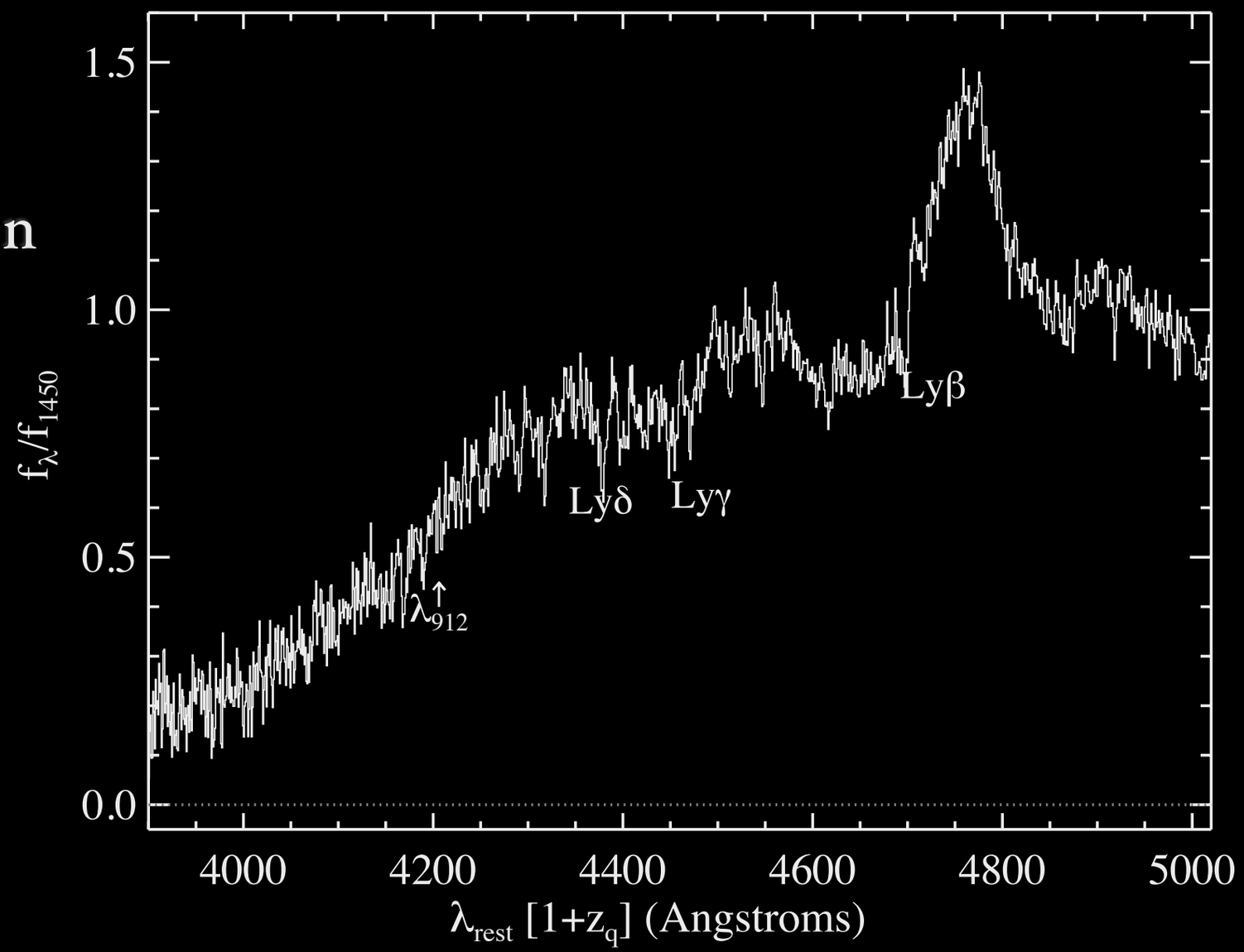
Summary

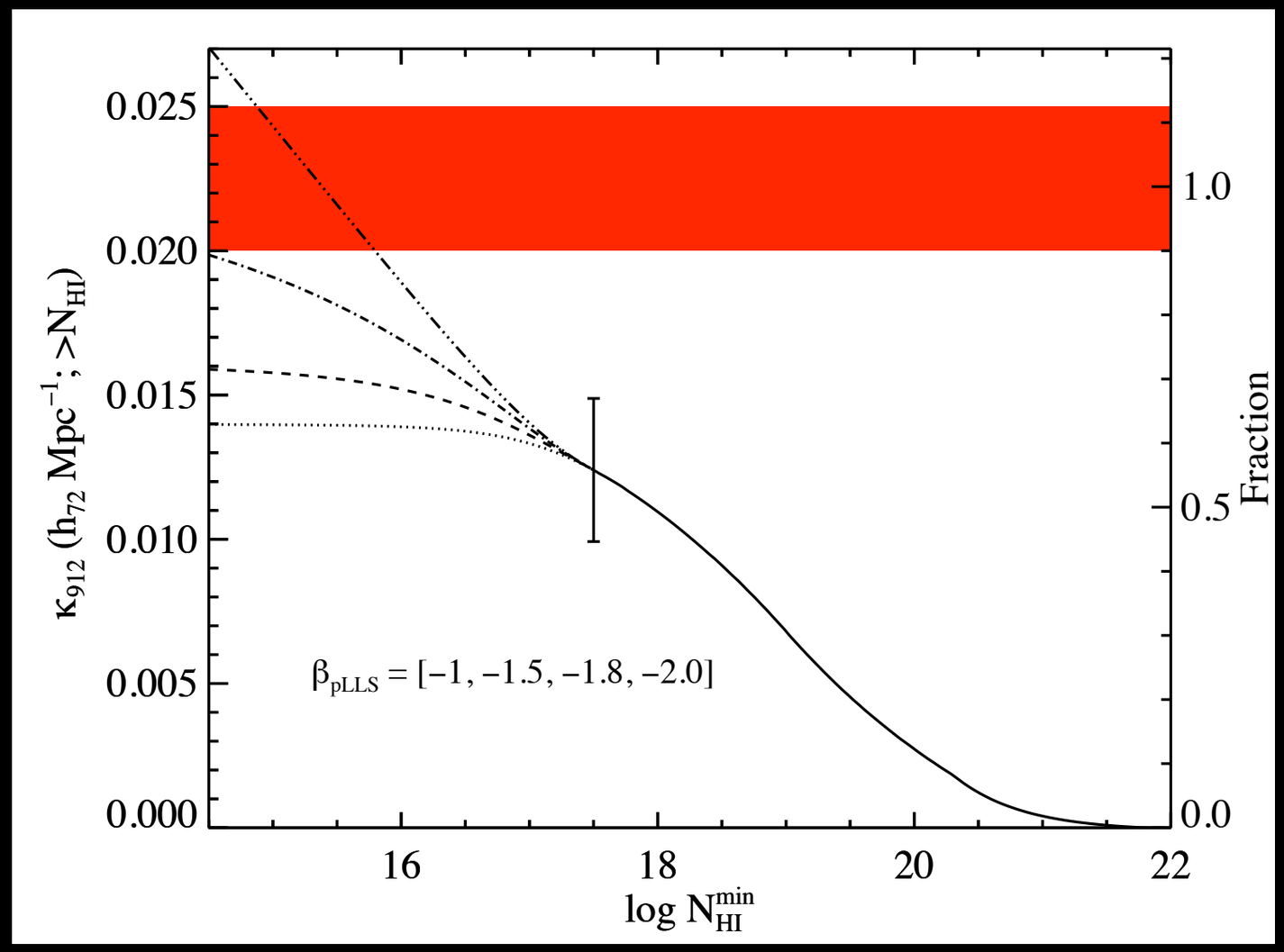
- Most precise measurement of λ_{mfp} to date
  - Stacked quasar spectrum
    - ~10x improvement over previous work
  - λ_{mfp} = 48.4 - 38 (z-3.6) [h^{-1} Mpc]
- Implications
  - Quasars may dominate at z~3
    - But unlikely at z~4
  - Reionization occurred at 7.5<z<20
  - LLS + λ_{mfp}
    - Well constrained $f(N_{HI})$ at z~3.7
- SDSS Quasar spectra
  - Biased toward LLS at z~3.4
  - Be careful with the IGM at z~3

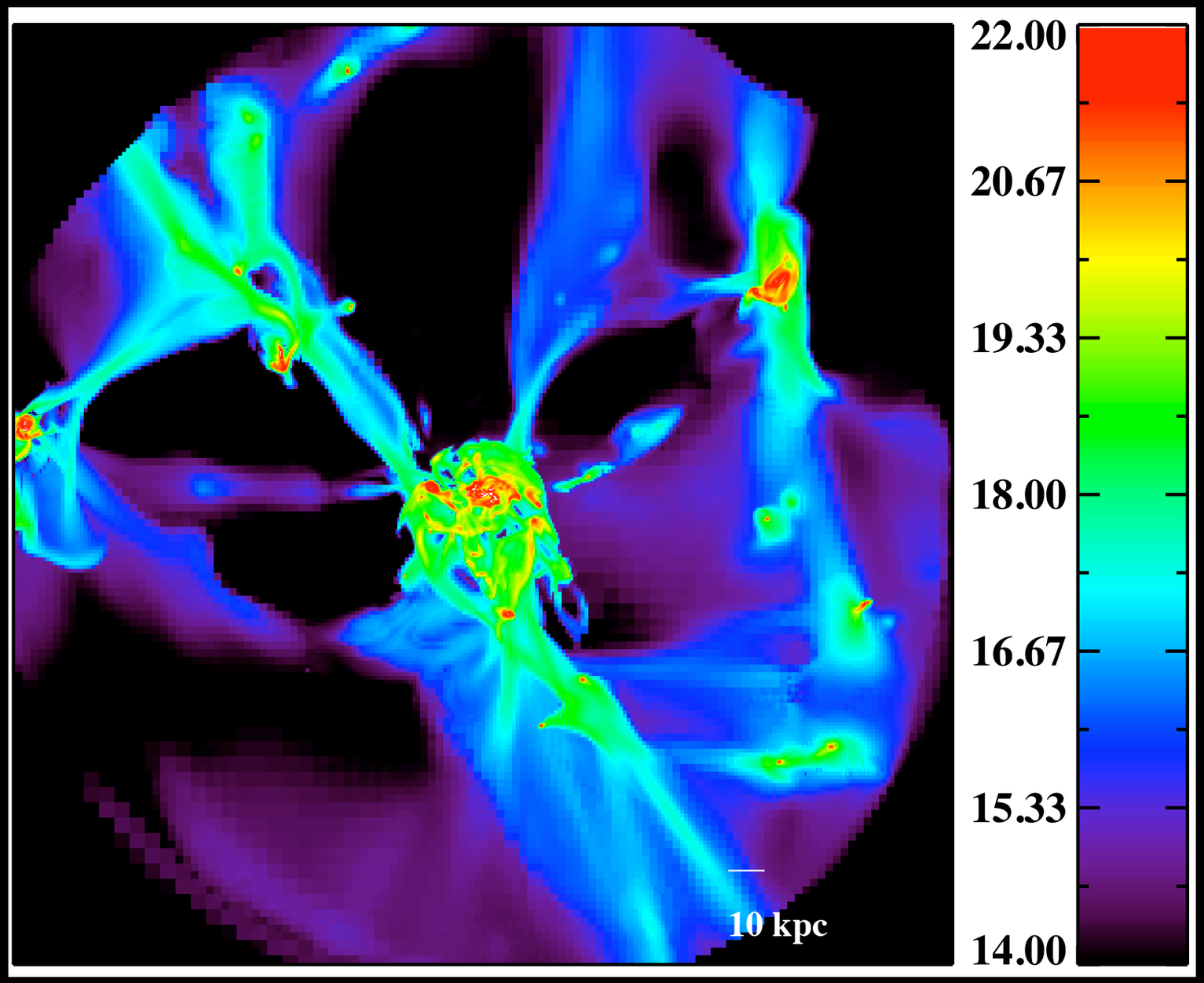


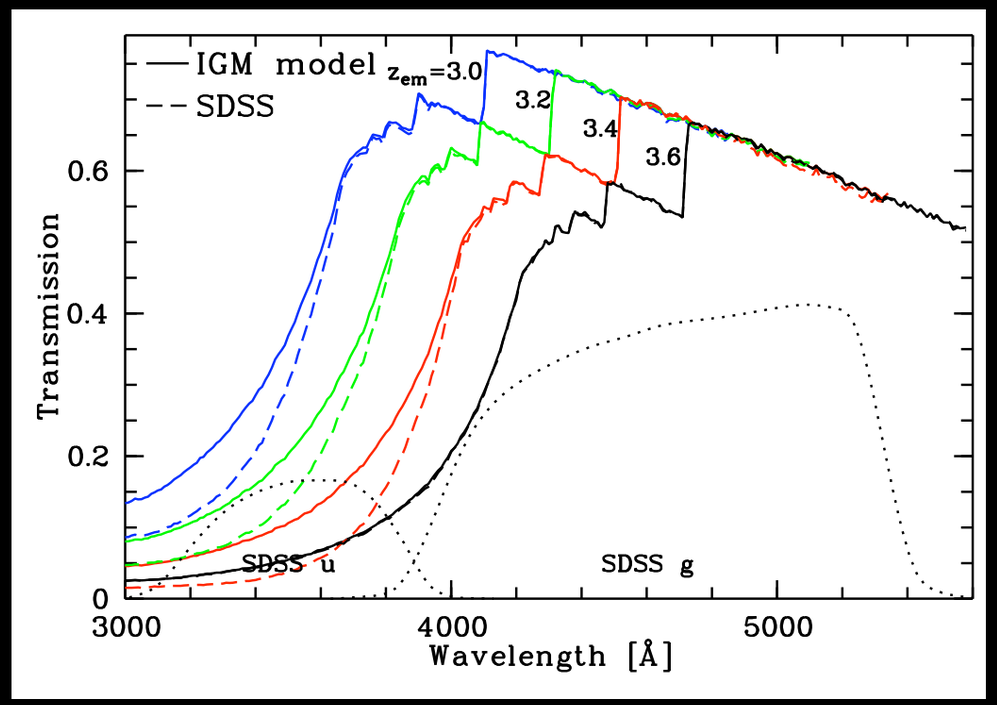
Looking under the rug...

- Ignore over 850-900Ang
  - QSO SED
  - Lya forest redshift evolution
  - Metals
  - Evolution in the MFP
  - Proximity region
- Counter-arguments
  - Exponentials always win
  - Δz is small (~0.3)
  - It is desirable to include the proximity region




0.025
0.020
0.015
0.010
0.005
0.000
κ_{912} (h_{72} Mpc^{-1}; >N_{HI})
1.0
0.5
0.0
Fraction
β_{pLLS} = [−1, −1.5, −1.8, −2.0]
16
18
20
22
log N_{HI}^{min}


22.00
20.67
19.33
18.00
16.67
15.33
14.00
10 kpc


IGM model
SDSS
z_{em}=3.0
3.2
3.4
3.6
SDSS u
SDSS g
Transmission
0
0.2
0.4
0.6
3000
4000
5000
Wavelength [Å]