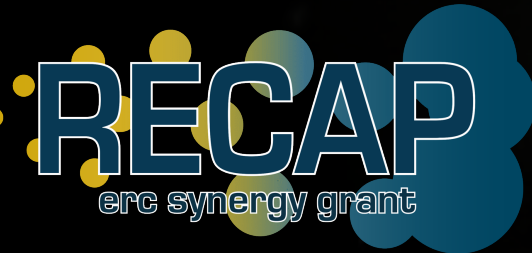


# Galaxy-Absorbers Cross Correlation Function in the EIGER Survey

Christian Piscitelli, PhD Student @INAF OATs

Supervisors: Valentina d'Odorico,  
Collaborators: Manuela Bischetti, Marta Galbiati



# The Circumgalactic Medium at high redshift

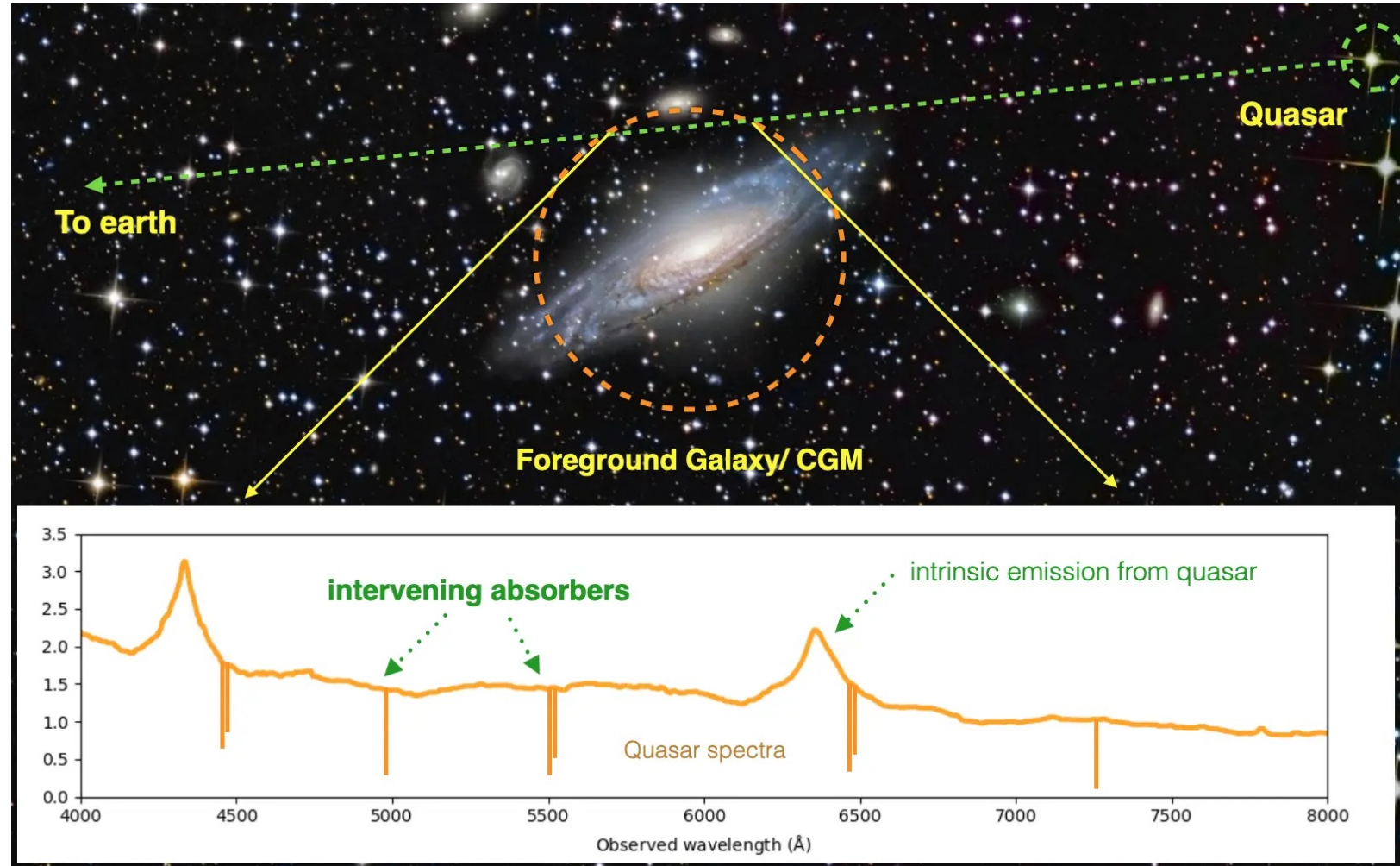
Intervening absorbers in quasar spectra trace the gas along the LoS.

Important physical properties:

- I. Column density ( $N$ )
- II. Doppler parameter ( $b$ )
- III. Redshift ( $z$ )

Key Questions:

- I. Gas distribution: what is the **covering fraction of different ions?**
- II. Spatial connection: what does the **cross correlation function** reveal?

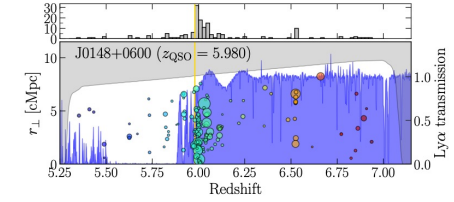
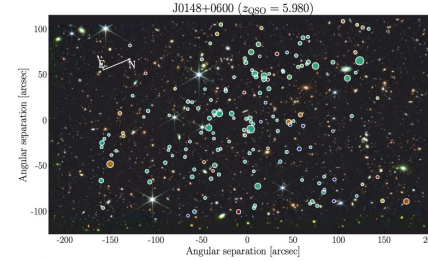
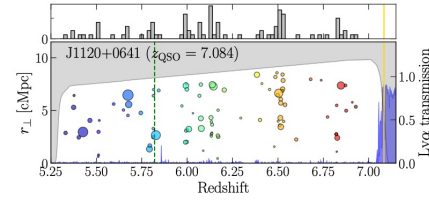
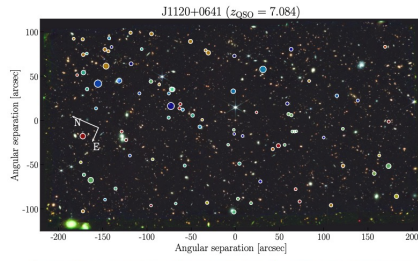
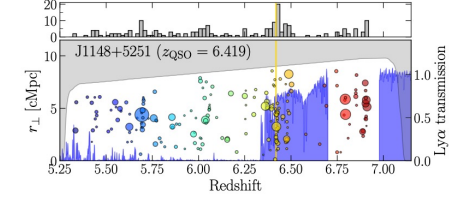
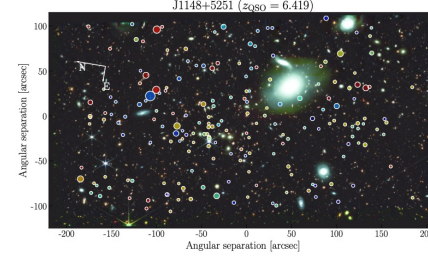
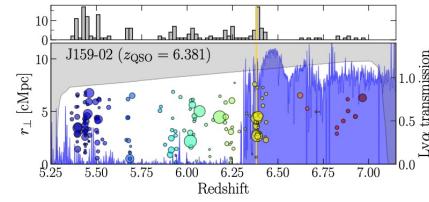
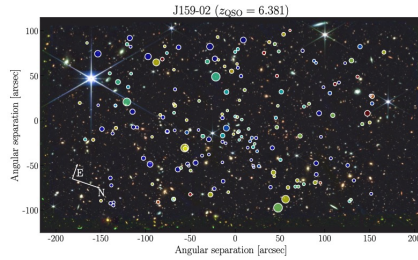
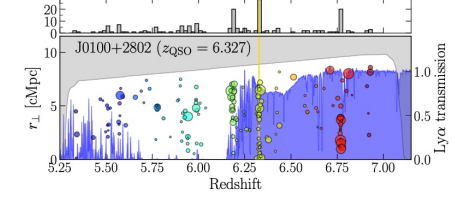
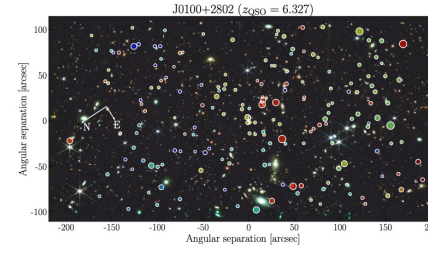
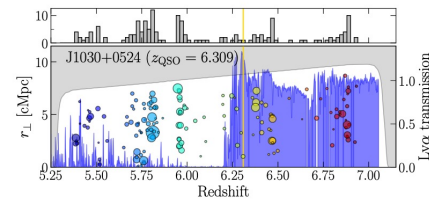
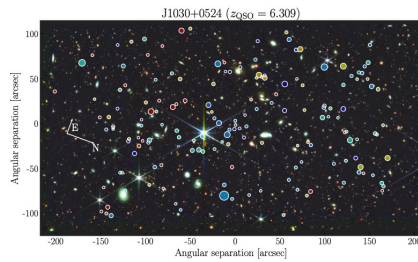


Anand+ 2021

# The EIGER Survey

*EIGER = Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization (Kashino+ 2023)*

- Goal: explore the IGM/CGM at the end of Cosmic Reionization
- Imaging (JWST/NIRCam): 6 quasar fields observed with F115W, F200W, and F356W, identifying [O III]-emitters
- Spectroscopy: deep and high-resolution optical/NIR quasar spectra (VLT/X-Shooter, Keck/Hires, Magellan/FIRE)



# The working sample

For each quasar field we have:

- [O III] emitters in the field of view with Ra, Dec, Z (Kashino+ 2026)
- Absorption systems in the redshift range  $z = [5.2, 7.02]$ , with their column density
  - Absorption systems for J1120 come from Bosman+ 2017
  - Absorption systems for J1148 come from Becker+ 2006

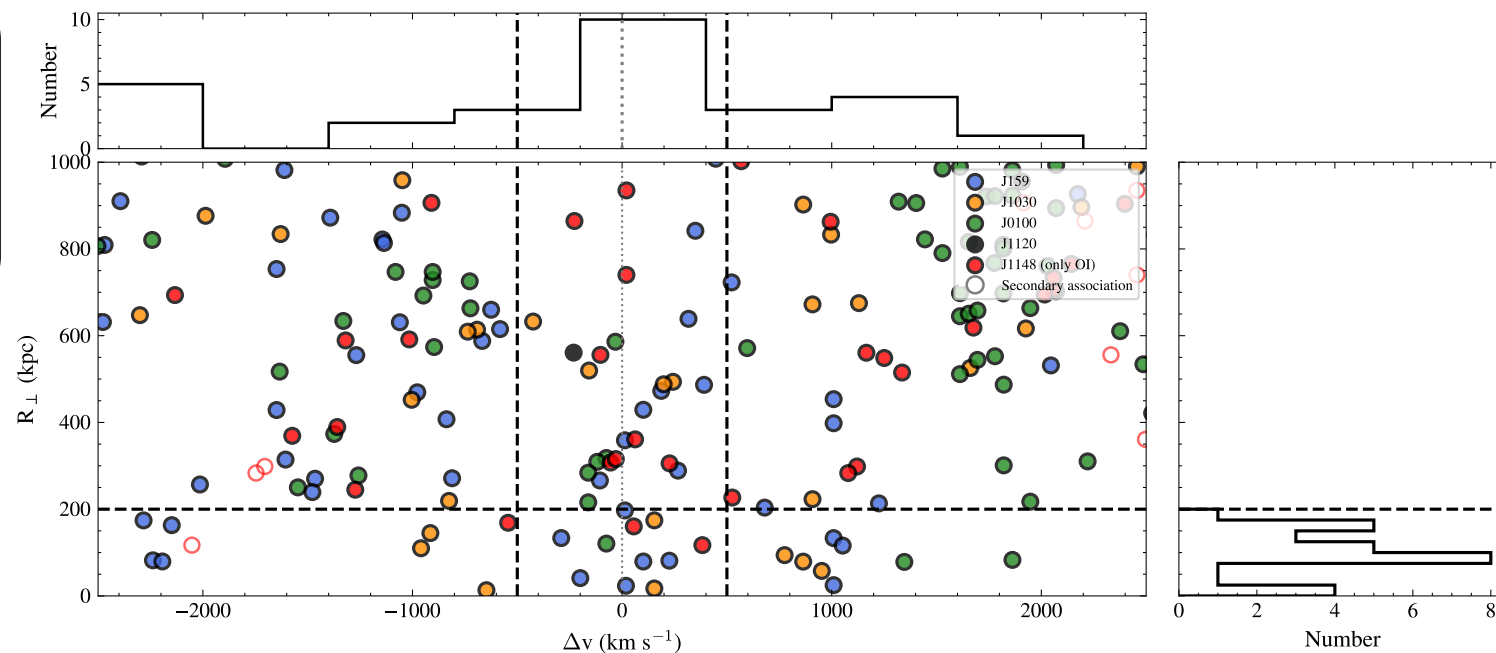
To complete the useful information, we compute:

- Impact parameter ( $R_{\perp}$ )
- Redshift distance in terms of velocity ( $\Delta v$ )

We focused our analysis **only** on **CII** absorption system, with  $\log(N) > 12.0$

$$R_{\perp}(\text{pkpc}) = \theta \cdot D_A(z_{gal})$$

$$\Delta v(\text{km/s}) = c \frac{(1 + z_{abs})^2 - (1 + z_{gal})^2}{(1 + z_{abs})^2 + (1 + z_{gal})^2}$$



# CII Covering Fraction (1)

How far does the neutral gas extend around [O III] emitters?

To answer this question, we compute the CII covering fraction as

$$f_c^{real}(R_{\perp}, \Delta v) = \frac{\sum_{i \in S_{real}(R_{\perp})} 1_i(\Delta v_{max})}{\sum_{i \in S_{real}(R_{\perp})} 1}$$

Where:

- $S_{real}(R_{\perp})$  is the sample of galaxies that fall in the impact parameter bin
- $1_i(\Delta v_{max}) = \begin{cases} 1, & \text{if } \exists \text{ an absorbers with } |\Delta v_i| \leq \Delta v_{max} \\ 0, & \text{otherwise} \end{cases}$

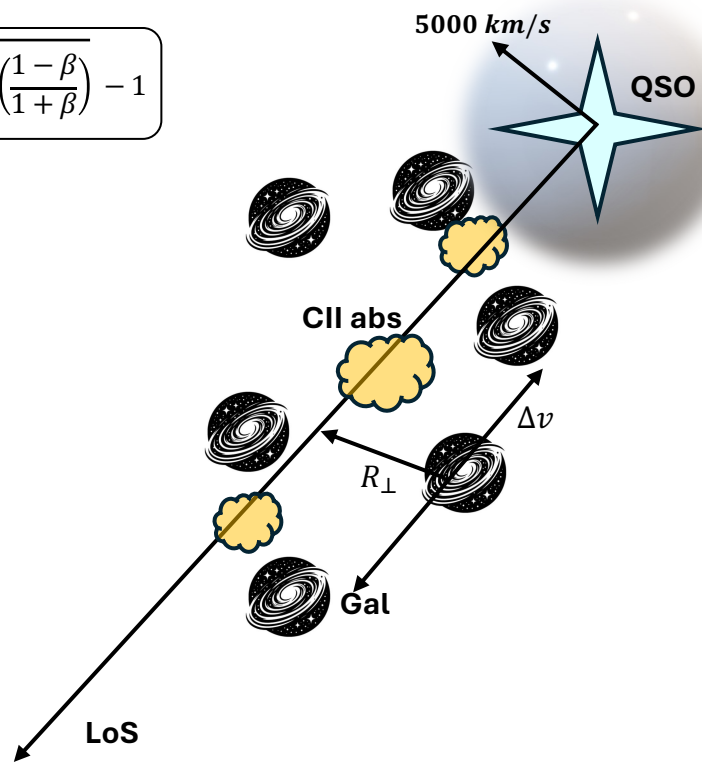
To disentangle the physical association from pure chance, we calculate the expected background using a cross-field shuffling technique.

$$f_c^{bkg}(R_{\perp}, \Delta v) = \frac{\sum_{k=1}^6 \sum_{m \neq k} \sum_{j \in G_k(R_{\perp,m})} 1_j(\Delta v_{max})}{\sum_{k=1}^6 \sum_{m \neq k} \sum_{j \in G_k(R_{\perp,m})} 1}$$

Where:

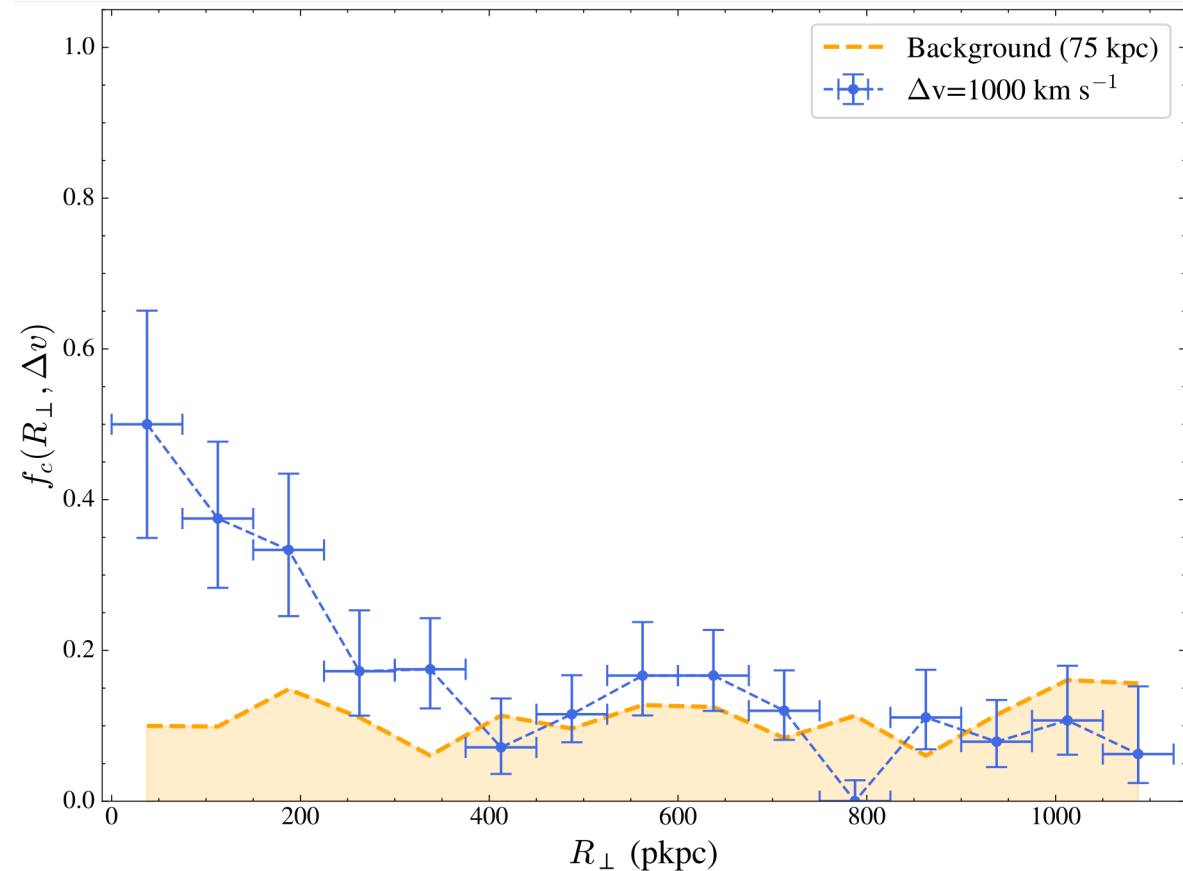
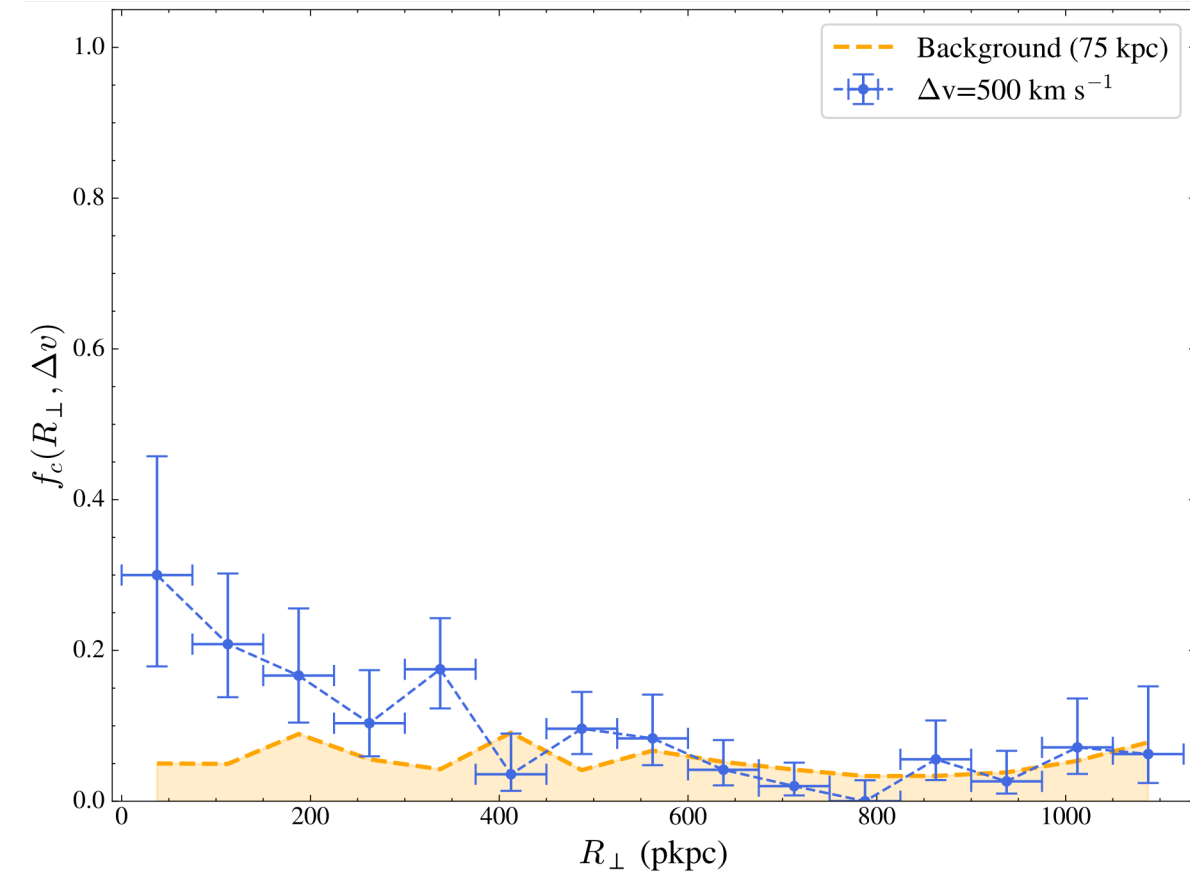
- $G_k$  is the sample of galaxies in the k-th field
- $R_{\perp,m}$  indicates the impact parameter calculated wrt field  $m \neq k$

$$z_{max} = (1 + z_{qso}) \sqrt{\frac{1 - \beta}{1 + \beta}} - 1$$



# CII Covering Fraction (2)

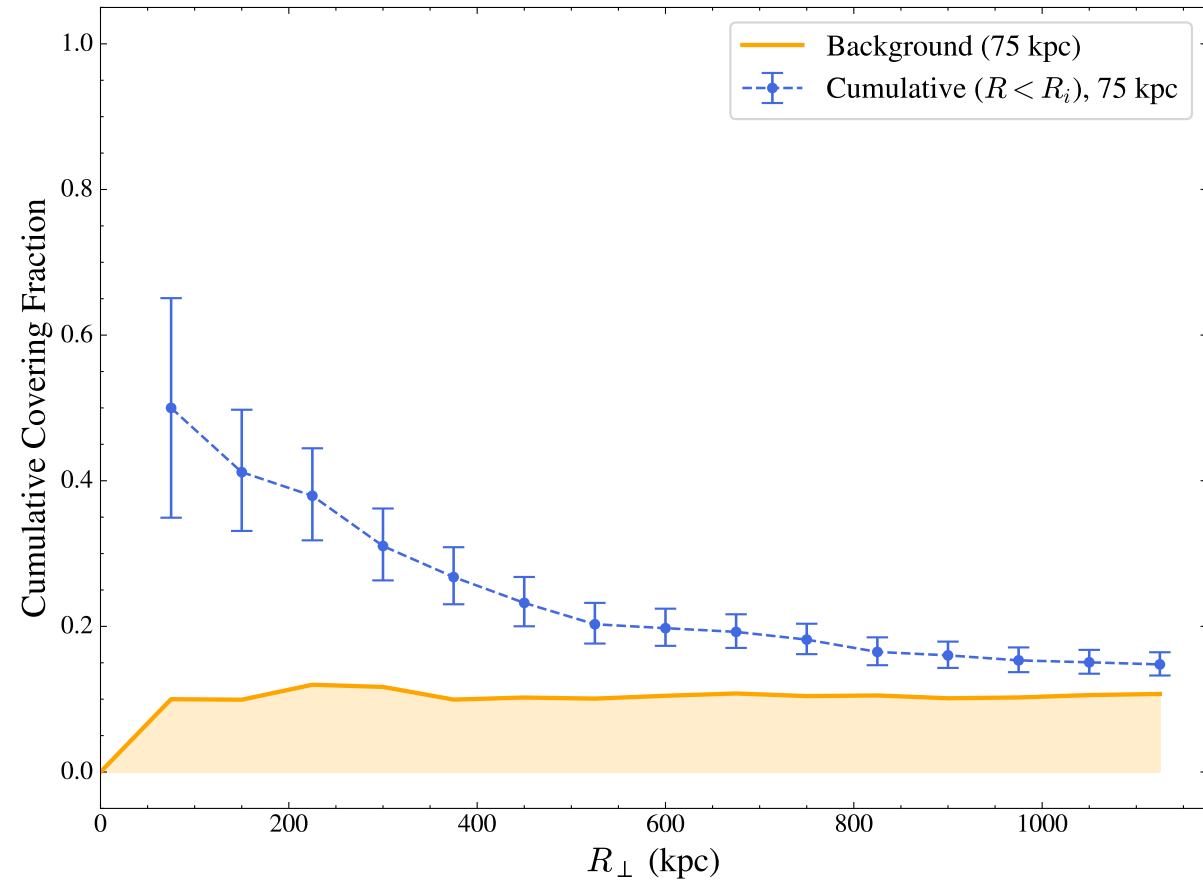
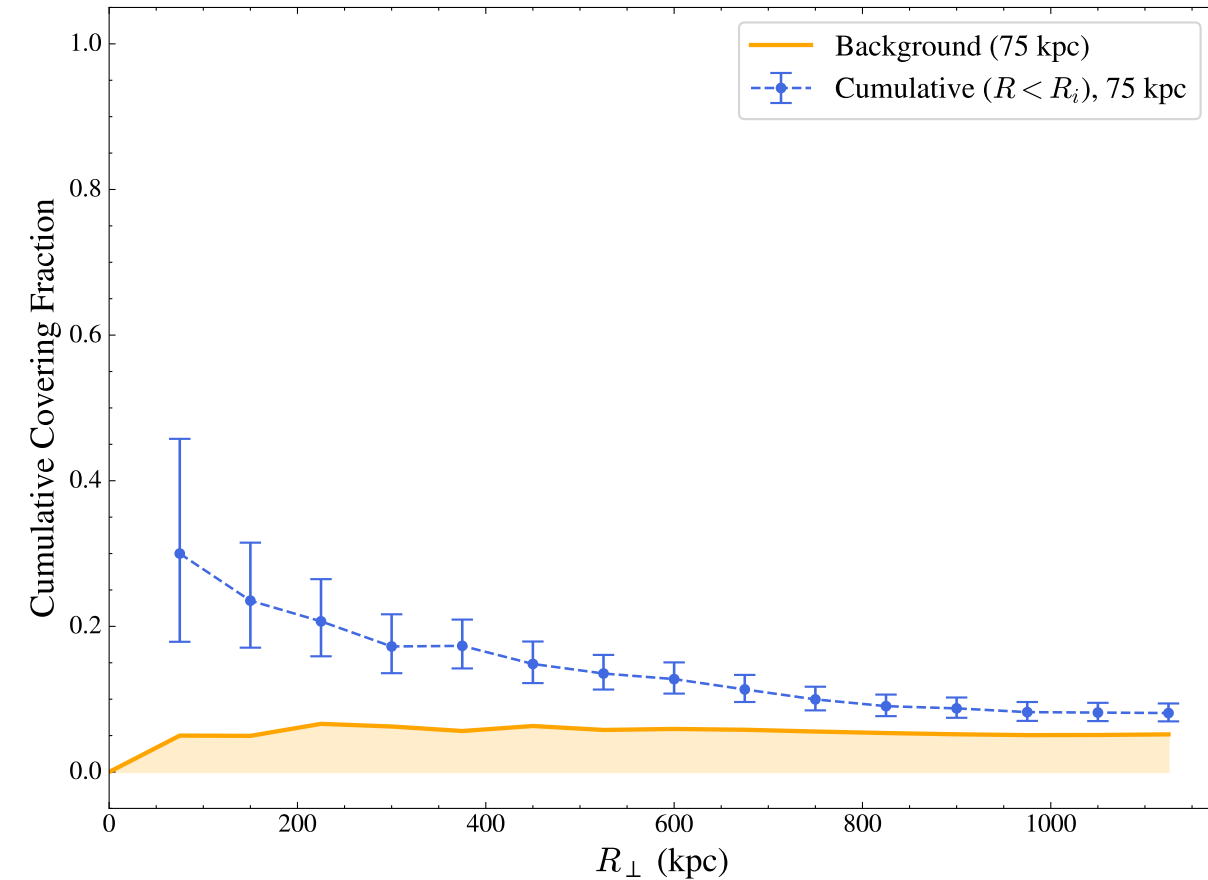
We chose  $R_{\perp} = 75 \text{ kpc}$  and  $\Delta v = 500, 1000 \text{ km/s}$



The vertical error bars account for the  $1\sigma = 68\%$  Wilson-score confidence intervals, while the horizontal bars reproduce the width of each radial interval.

# CII Covering Fraction (3)

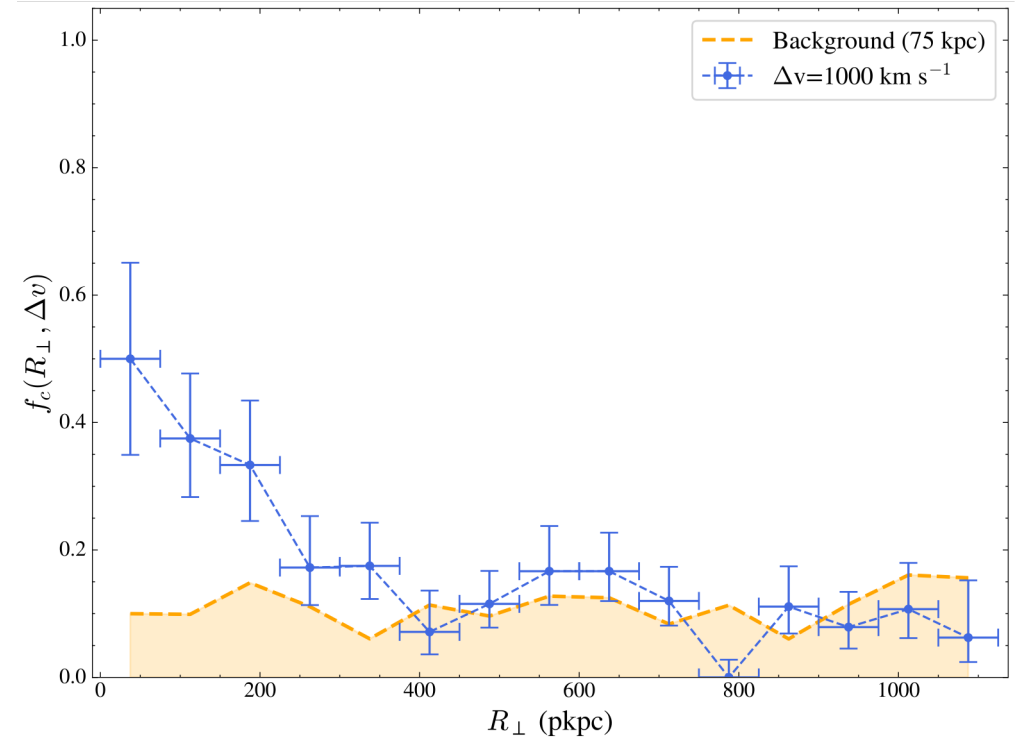
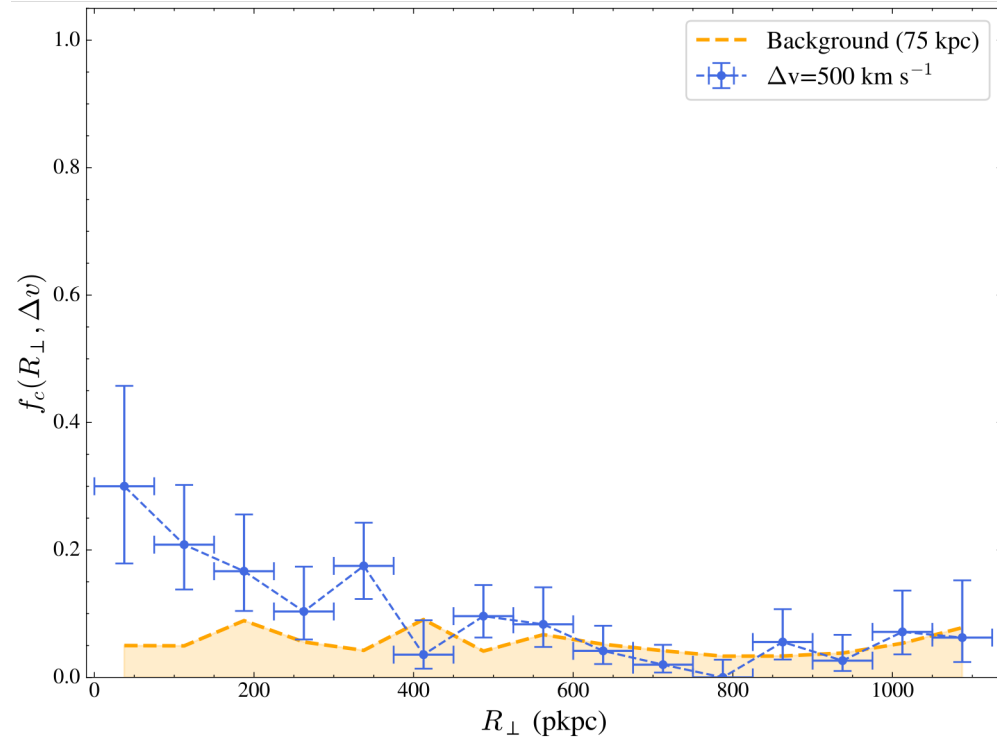
We chose  $R_{\perp} = 75$  kpc and  $\Delta v = 500, 1000$  km/s



The vertical error bars account for the  $1\sigma = 68\%$  Wilson-score confidence intervals.

# CII Covering Fraction – CII mass

We chose  $R_{\perp} = 75 \text{ kpc}$  and  $\Delta v = 500, 1000 \text{ km/s}$



We estimate the CII ion mass in an annulus through  $M_{CII} = \frac{1}{f_{ion}} f_c \pi (R_{out}^2 - R_{in}^2) \langle N_{CII} \rangle m_{CII}$  where:

- $f_{ion}$  is the ionization fraction, assumed equal to 1 → lower limit
- $f_c$  is the covering fraction in that annulus
- $\langle N_{CII} \rangle$  is the mean CII column density in the annulus
- $m_{CII} = 12 m_p$  is the mass of carbon atom

$$M_{CII}(0 - 100 \text{ kpc}) \approx 1.49 \cdot 10^5 M_{\odot}$$

$$M_{CII}(100 - 300 \text{ kpc}) \approx 6.04 \cdot 10^5 M_{\odot}$$

$$M_{CII}(0 - 300 \text{ kpc}) \approx 7.53 \cdot 10^5 M_{\odot}$$

# 3D Cross-Correlation Function (1)

Now, we want to quantify the spatial correlation between [O III] emitters and [C II] absorbers.

To estimate this correlation we define the 3D Cross-Correlation Function  $\xi(\Delta r)$  as the excess of real pairs over random ones, following these steps:

1. Exact 3D galaxy-absorber distance  $\Delta r$  given by

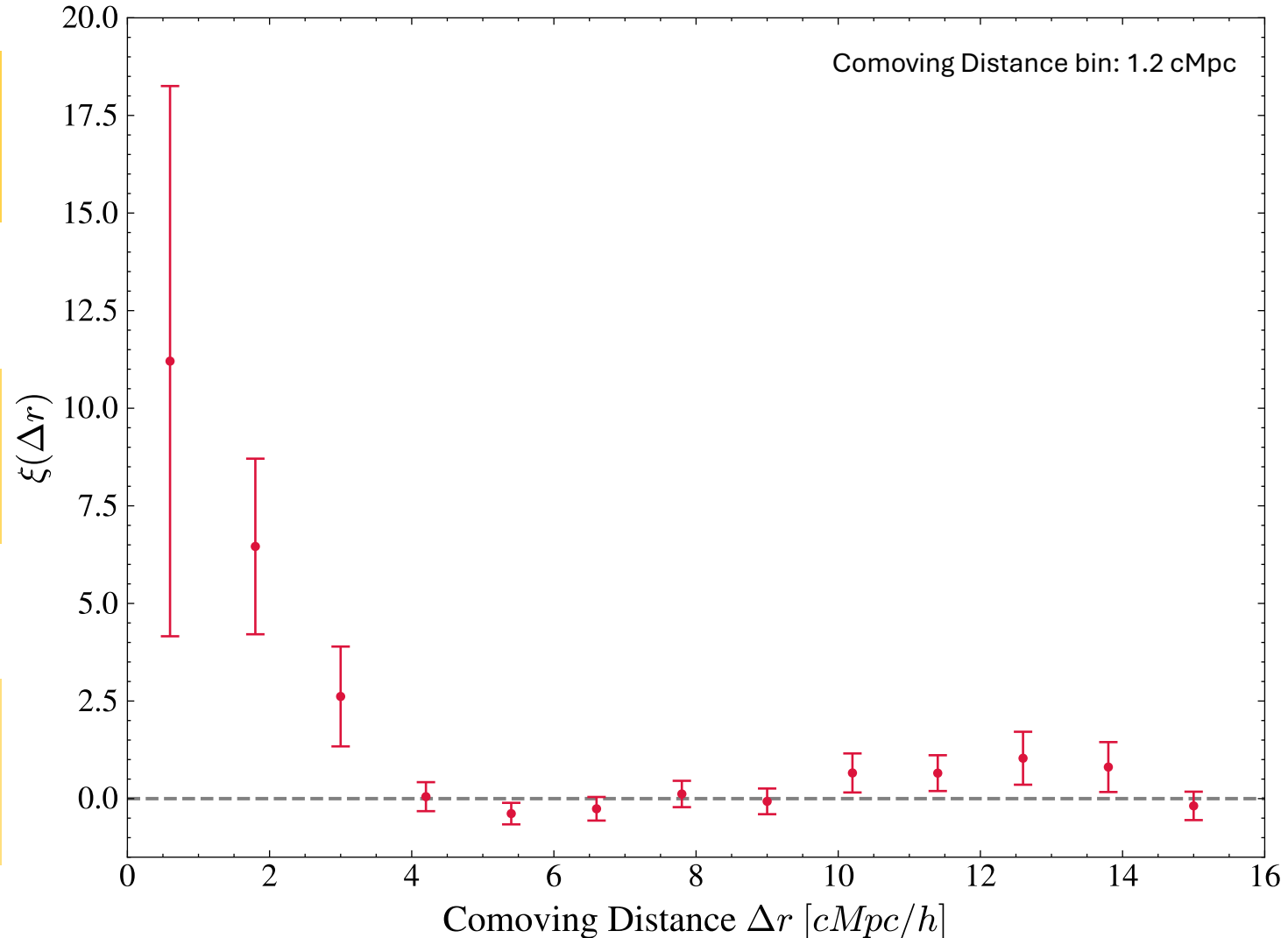
$$\Delta r = \sqrt{r_{1,\parallel}^2 + r_{2,\parallel}^2 - 2r_{1,\parallel}r_{2,\parallel} \cos \Delta\theta}$$

2. Peebles estimator:

$$\xi(\Delta r) = \frac{DD(\Delta r)}{RR(\Delta r)} \left( \frac{N_{RR}}{N_{DD}} \right) - 1$$

3. Errors estimated with Poisson statistics:

$$\delta\xi(\Delta r) = \frac{1 + \xi}{\sqrt{DD(\Delta r)}}$$



# 3D Cross-Correlation Function (2)

Now, we want to quantify the spatial correlation between [O III] emitters and [C II] absorbers.

To estimate this correlation we define the 3D Cross-Correlation Function  $\xi(\Delta r)$  as the excess of real pairs over random ones, following these steps:

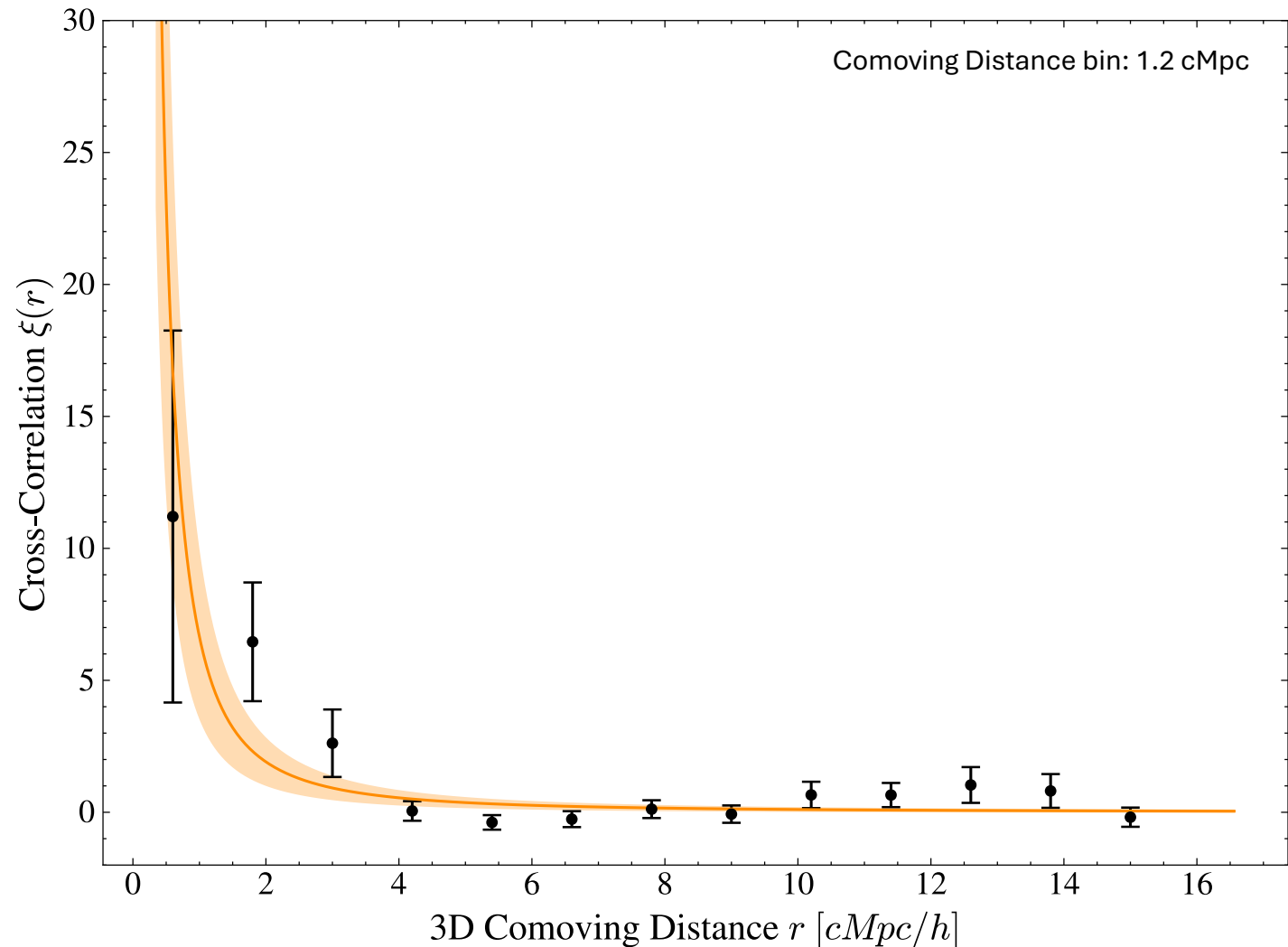
4. Power-law fit to find correlation length

$$\xi(\Delta r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

Due to degeneracy between  $r_0$  and  $\gamma$ , we fixed  $\gamma$

$$r_0 = 2.865 \pm 0.675 \text{ cMpc } h^{-1}$$

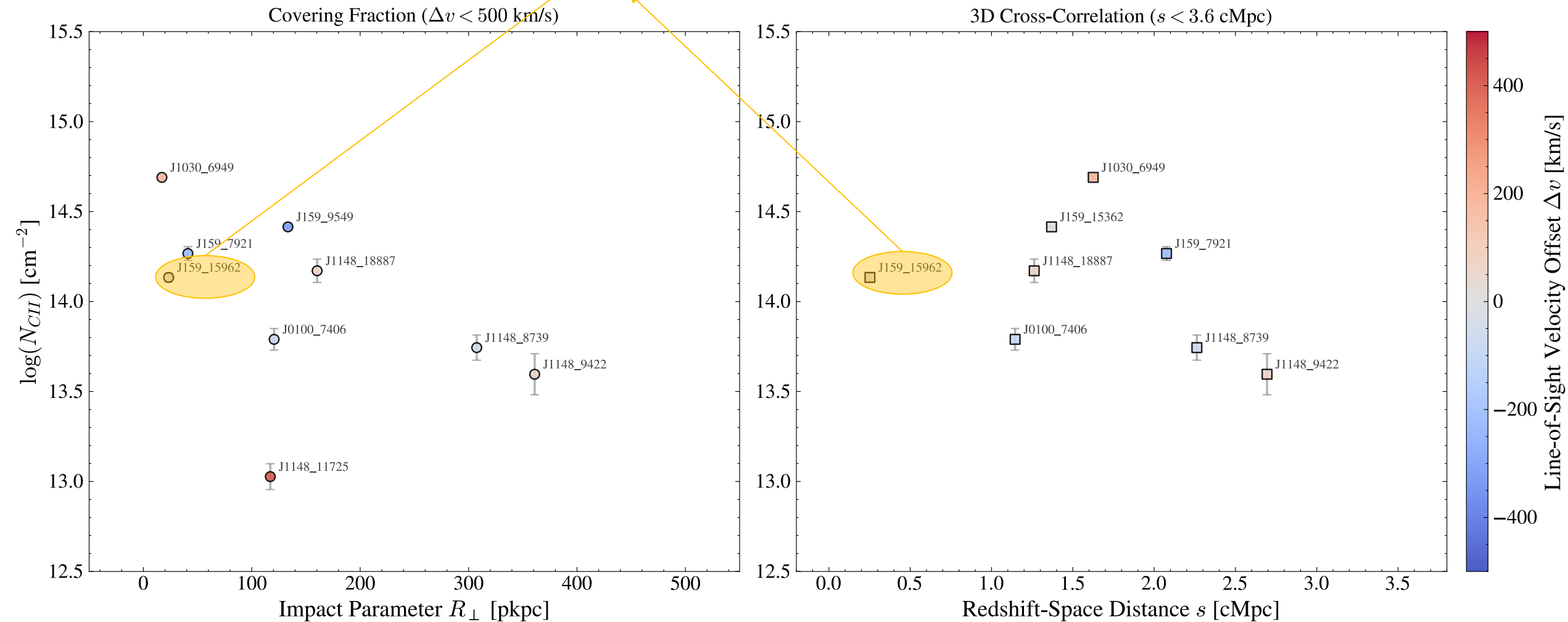
$$\gamma = 1.8$$



# CII log(N) profile

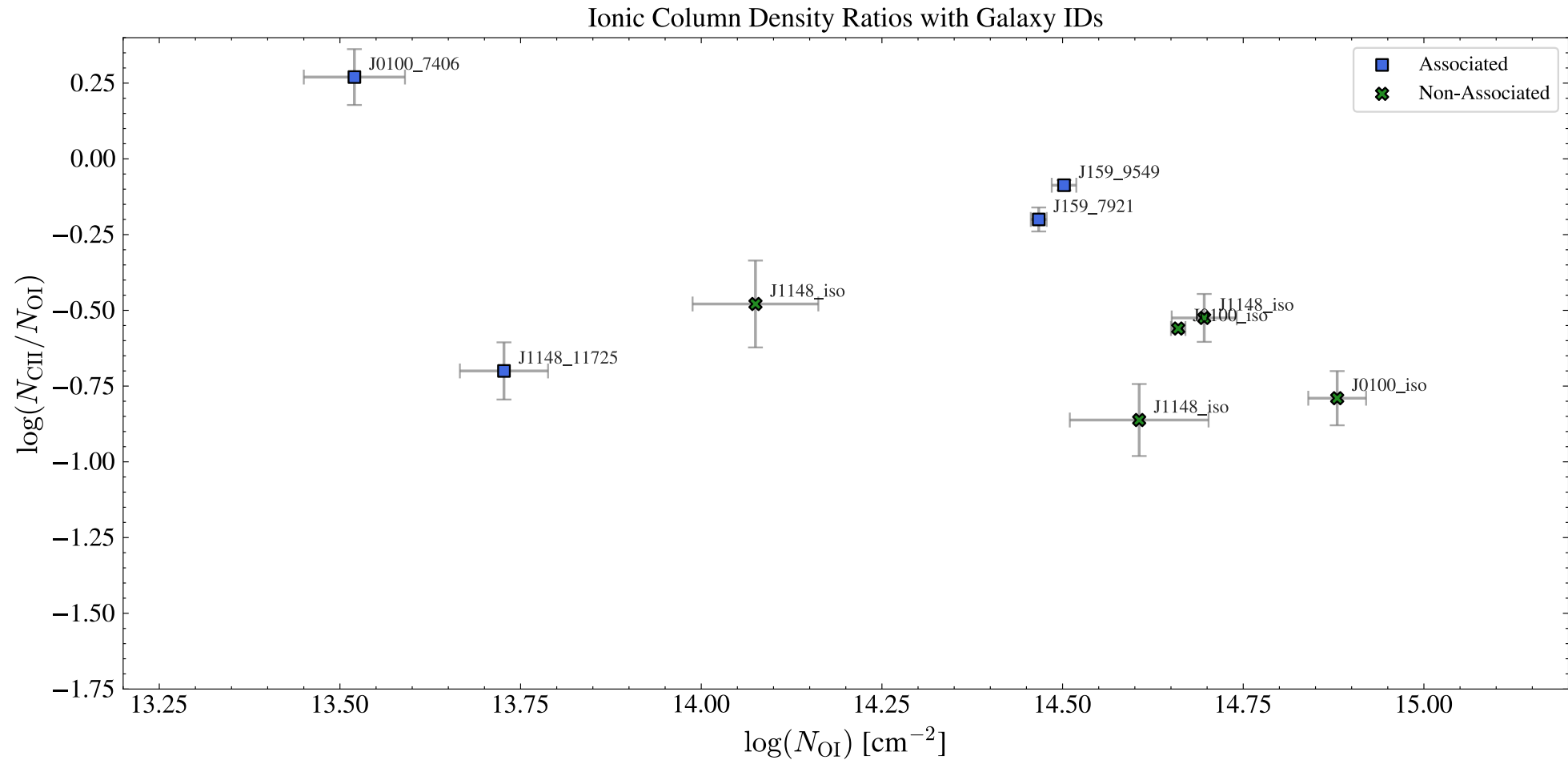
J159 | Gal ID: 15962 ( $z_{gal} = 6.2390$ )  $\rightarrow$  CII ( $z_{abs} = 6.2386$ ) |  $R_{\perp} = 23.4$  pkpc |  $\Delta v = 18.4$  km/s

J159 | Gal ID: 15962 ( $z_{gal} = 6.2390$ )  $\rightarrow$  CII ( $z_{abs} = 6.2386$ ) |  $s_{3D} = 0.25$  cMpc |  $\Delta v = 18.4$  km/s

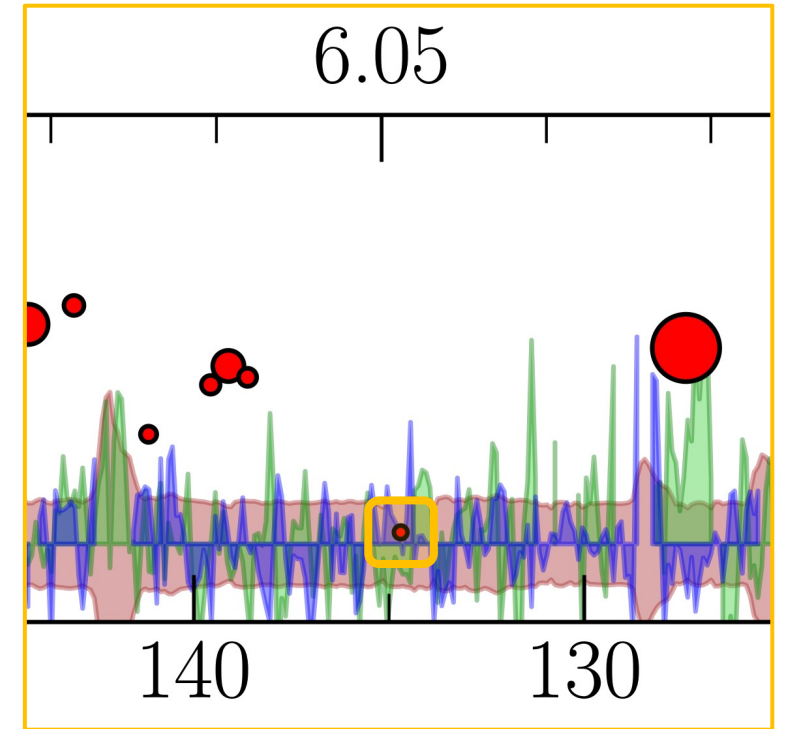
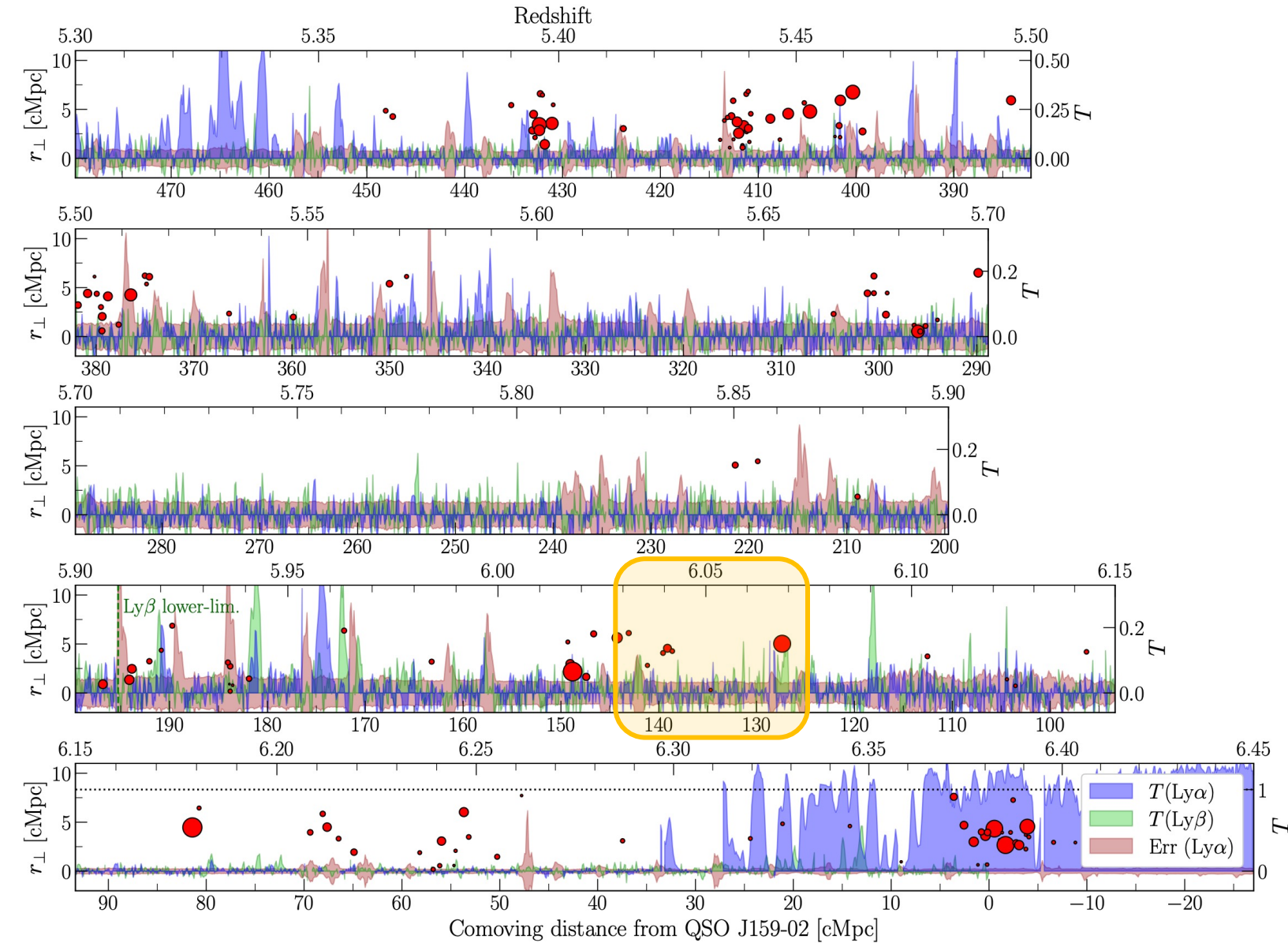


# Backup Slide

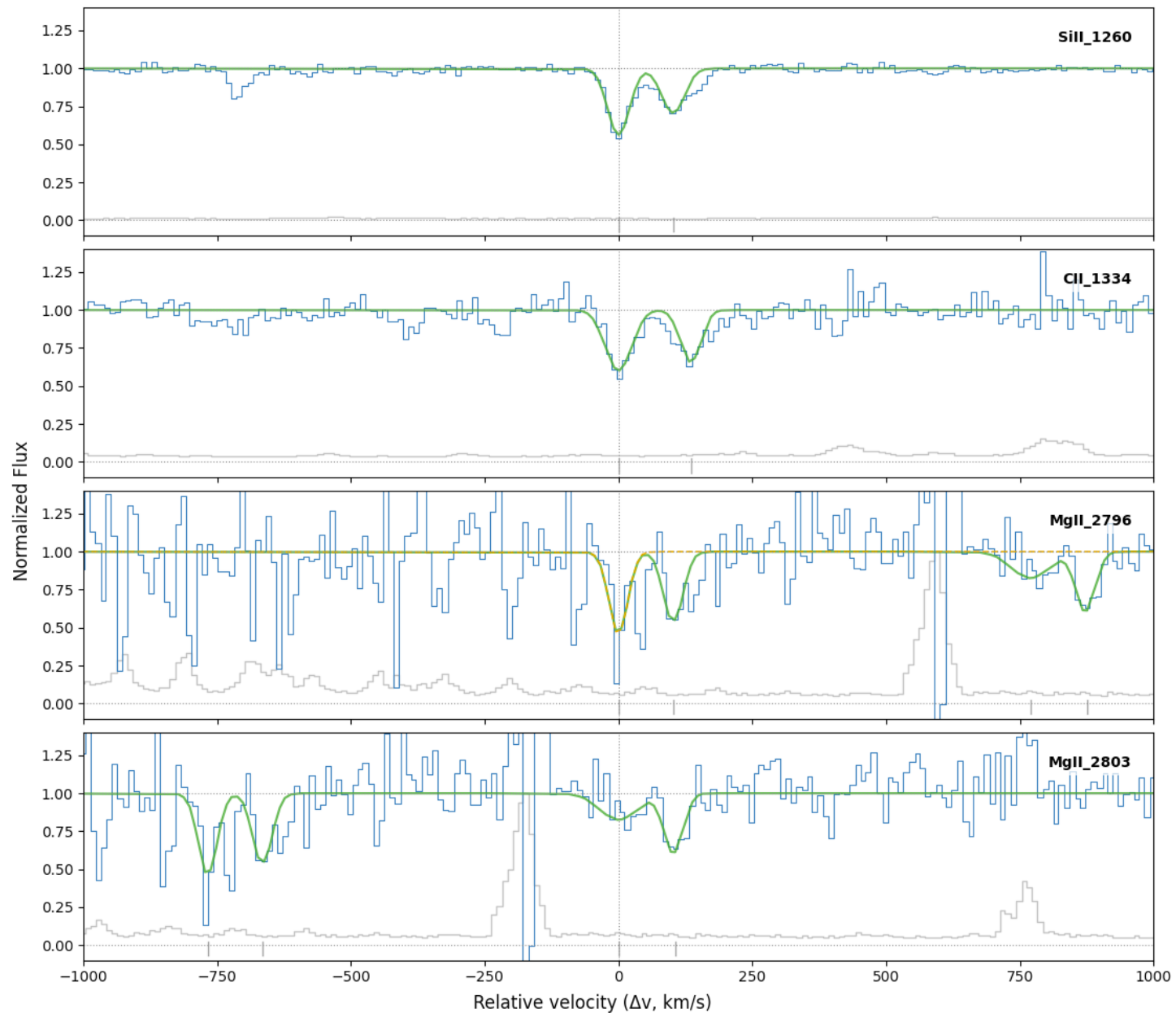
# Metal abundances



# Intervening absorbers in J159-02 spectrum (2)

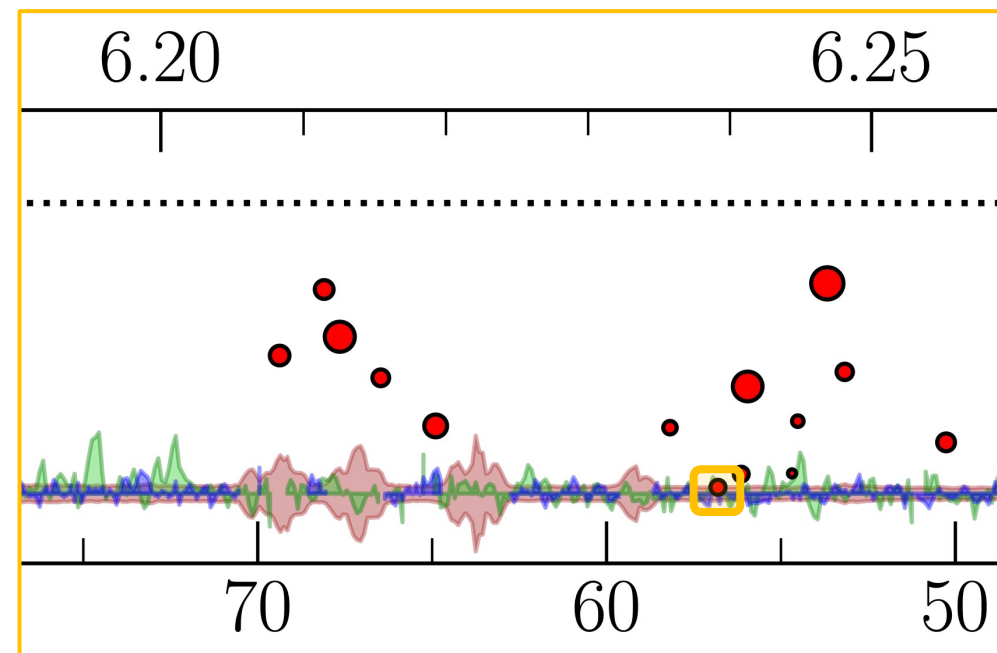
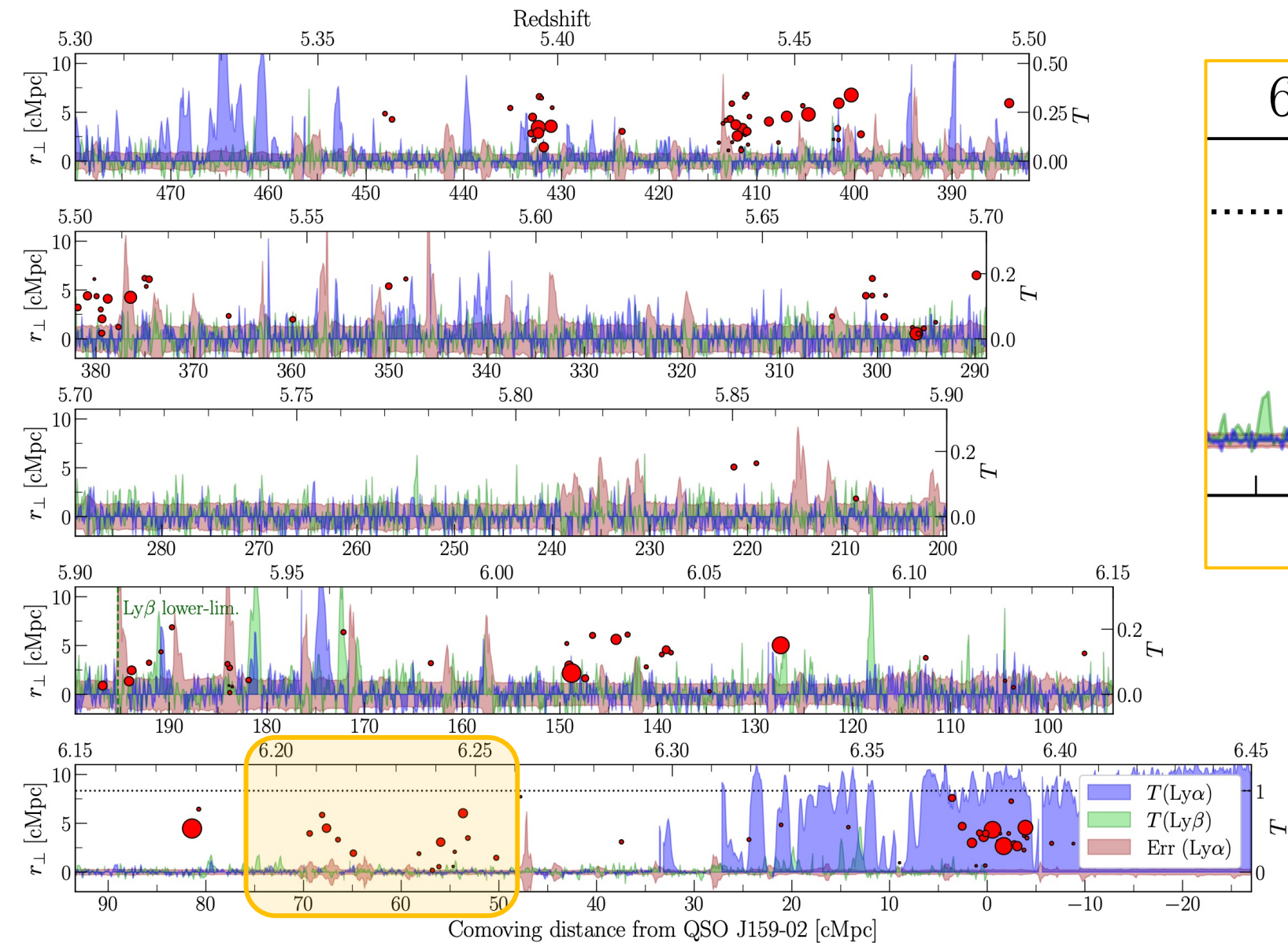


# Intervening absorbers in J159-02 spectrum (3)

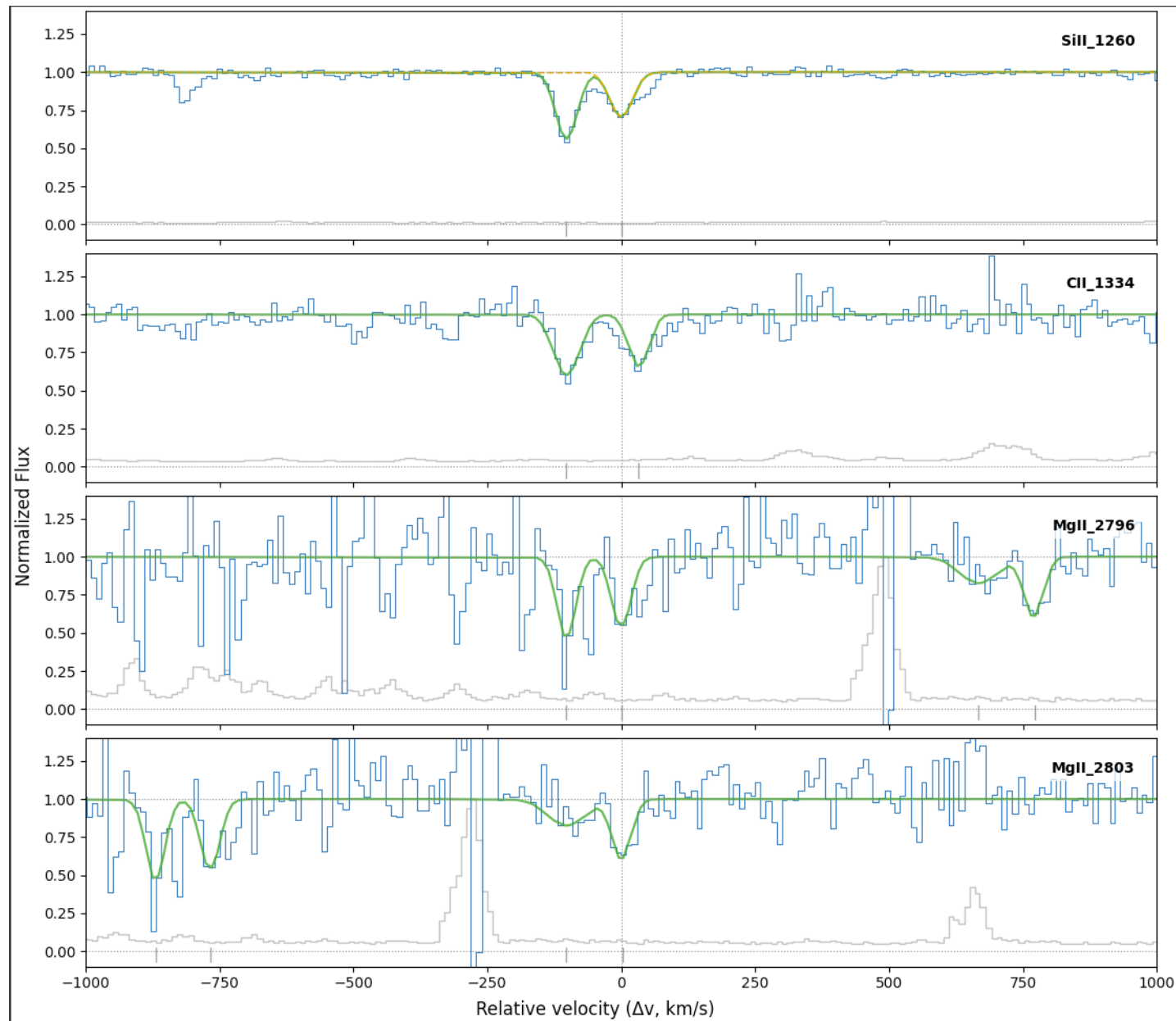


Absorption system at  $z \sim 6.23694$

# Intervening absorbers in J159-02 spectrum (3)

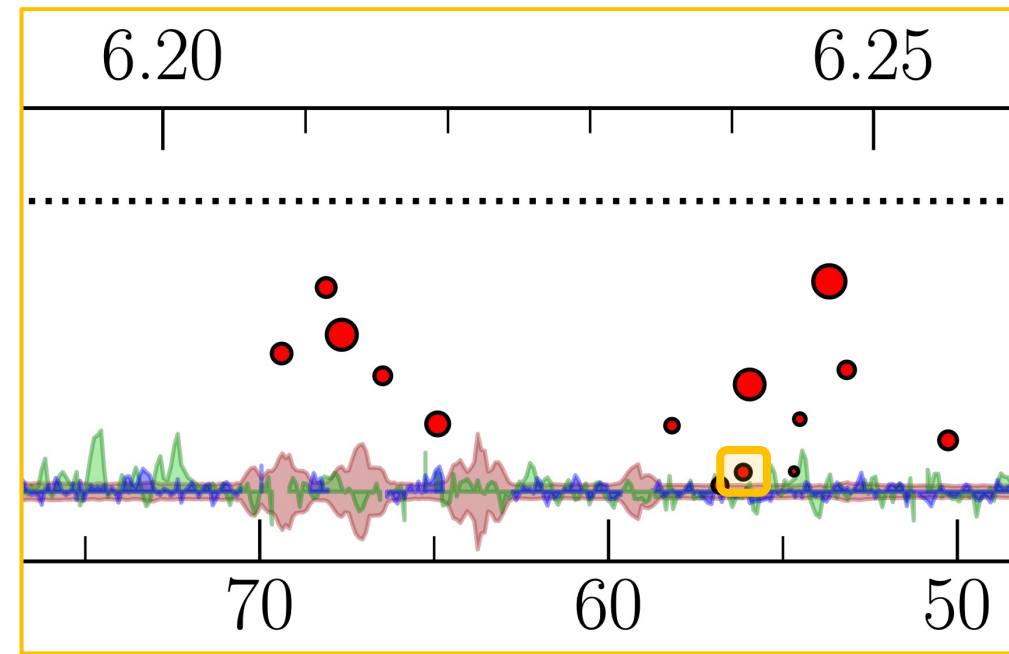
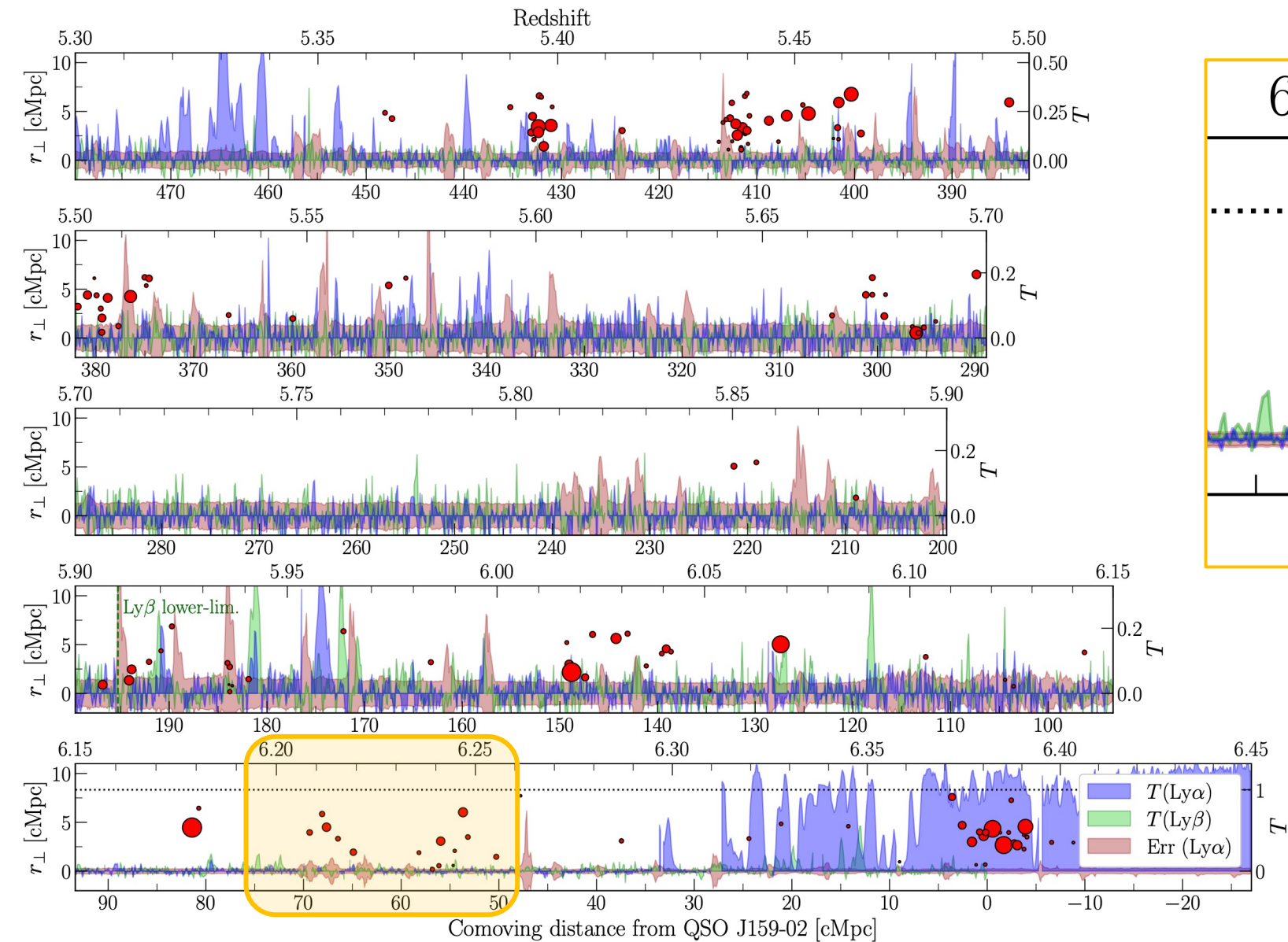


# Intervening absorbers in J159-02 spectrum (4)



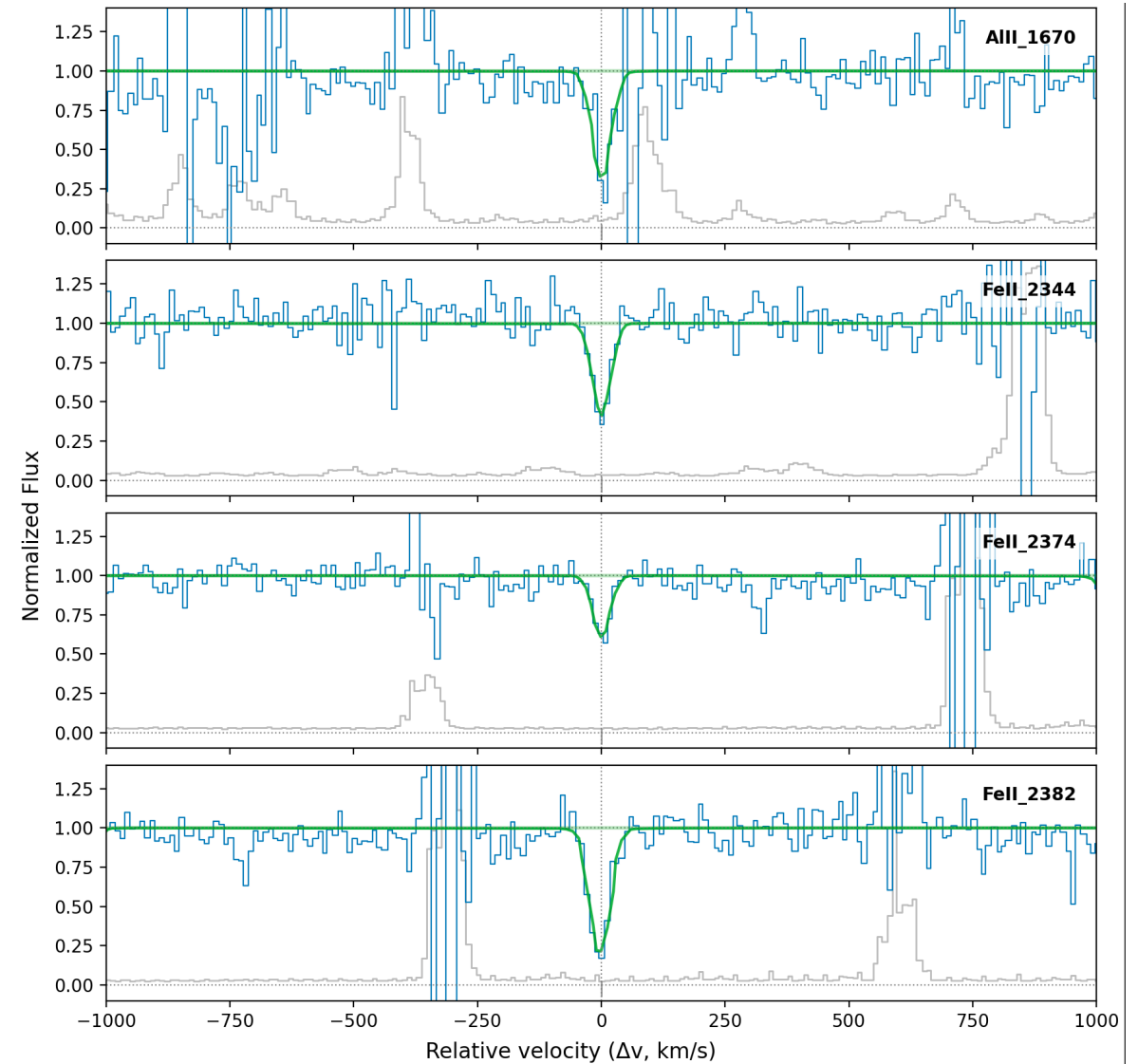
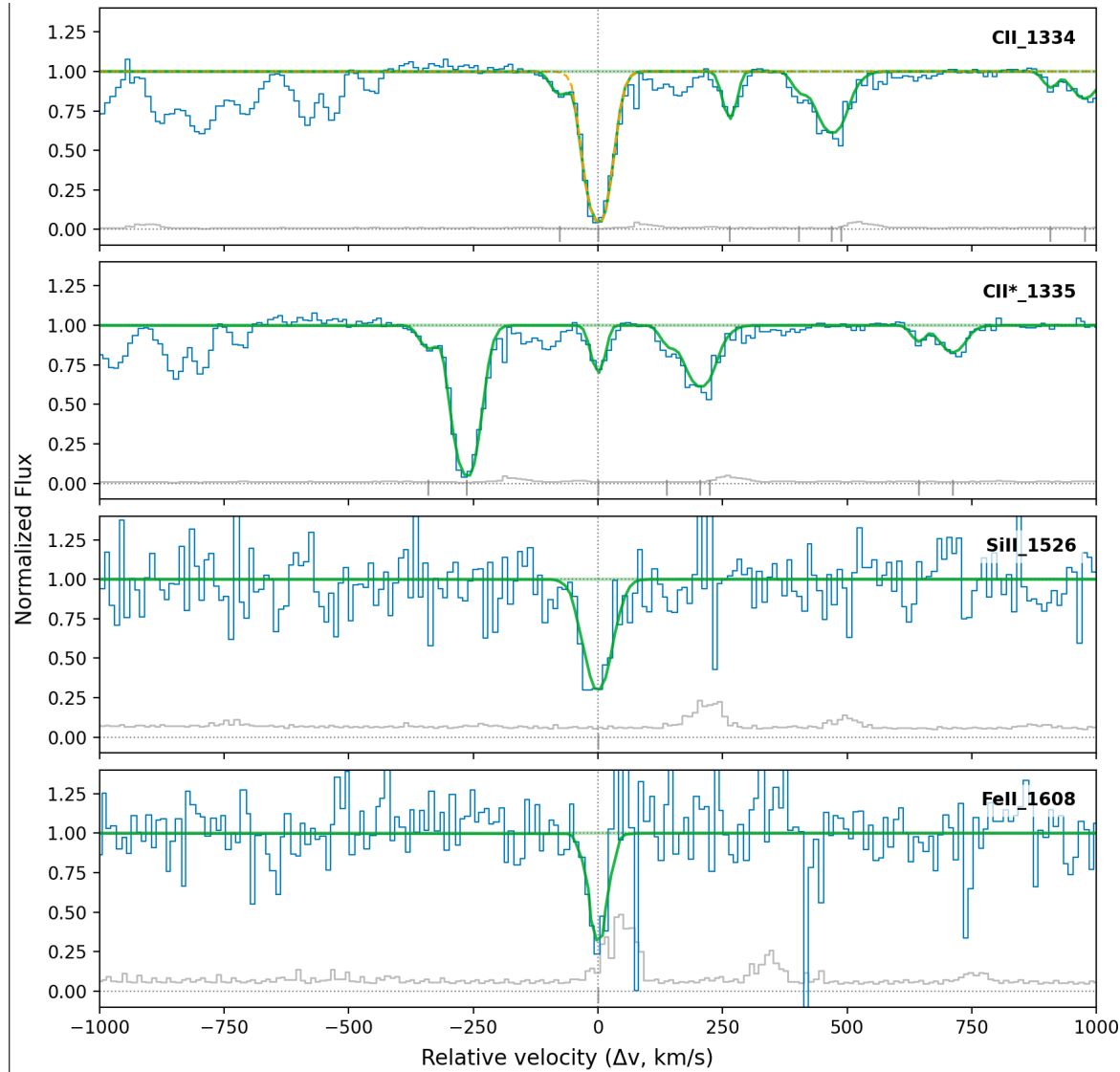
Absorption system at  $z \sim 6.23941$

# Intervening absorbers in J159-02 spectrum (4)

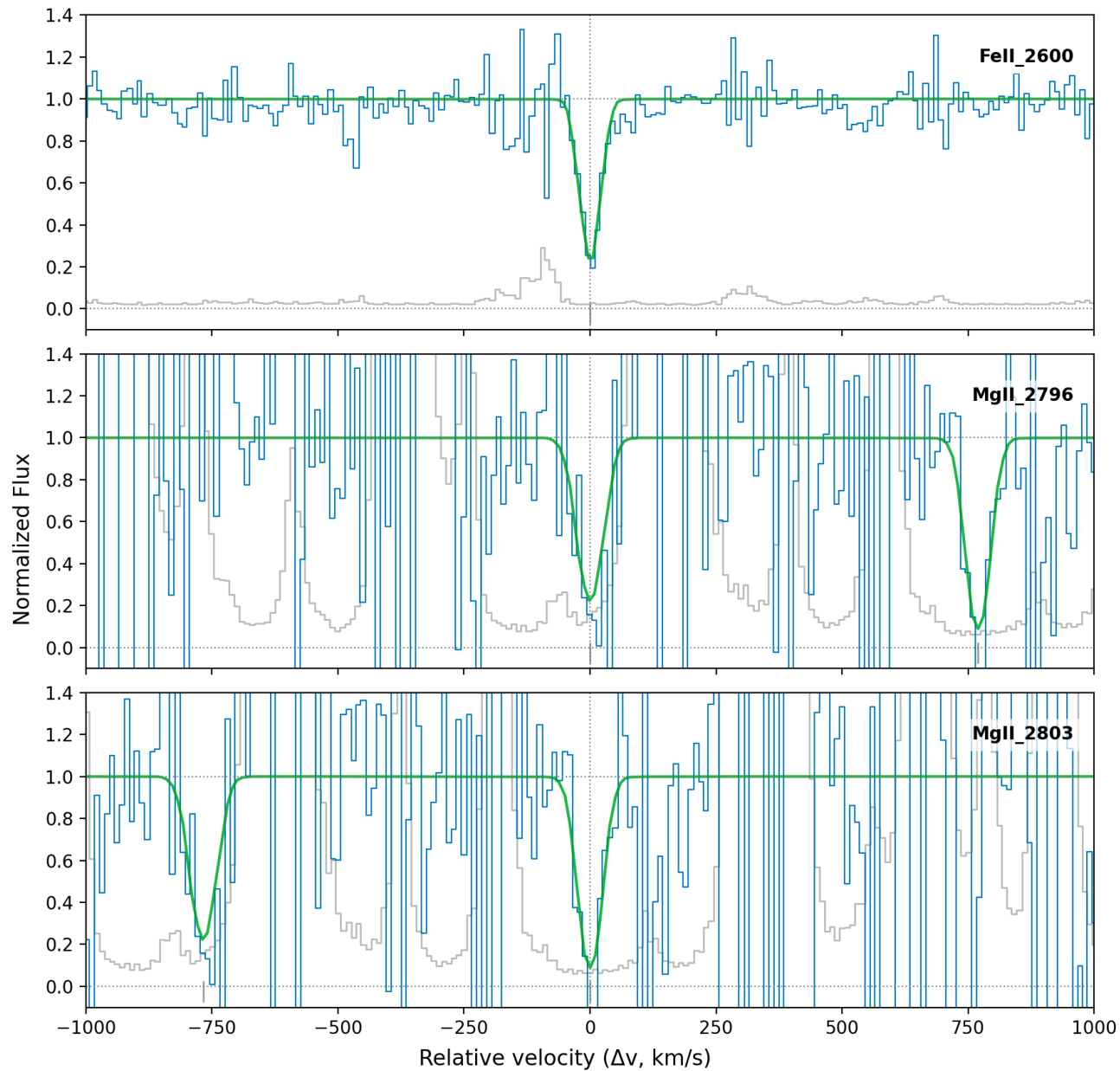


# Intervening absorbers in J159-02 spectrum (5)

Absorption system at  $z \sim 5.73491$

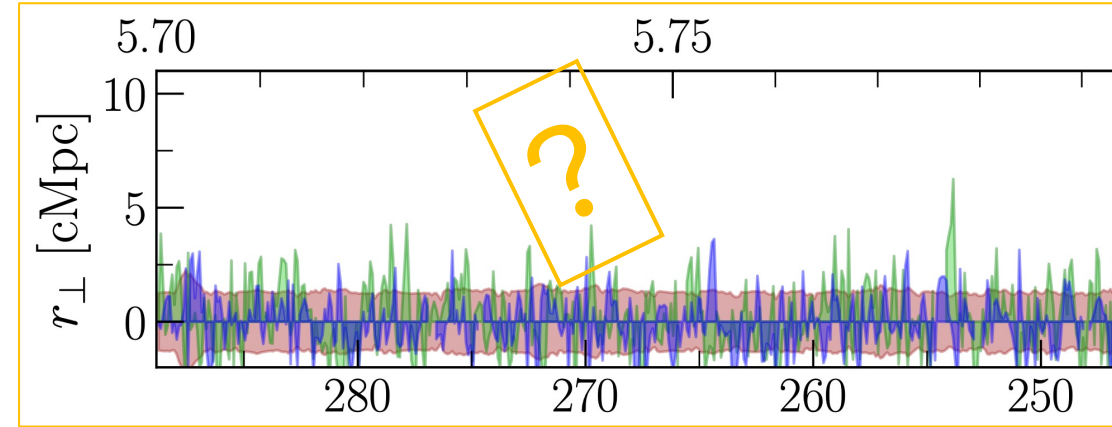
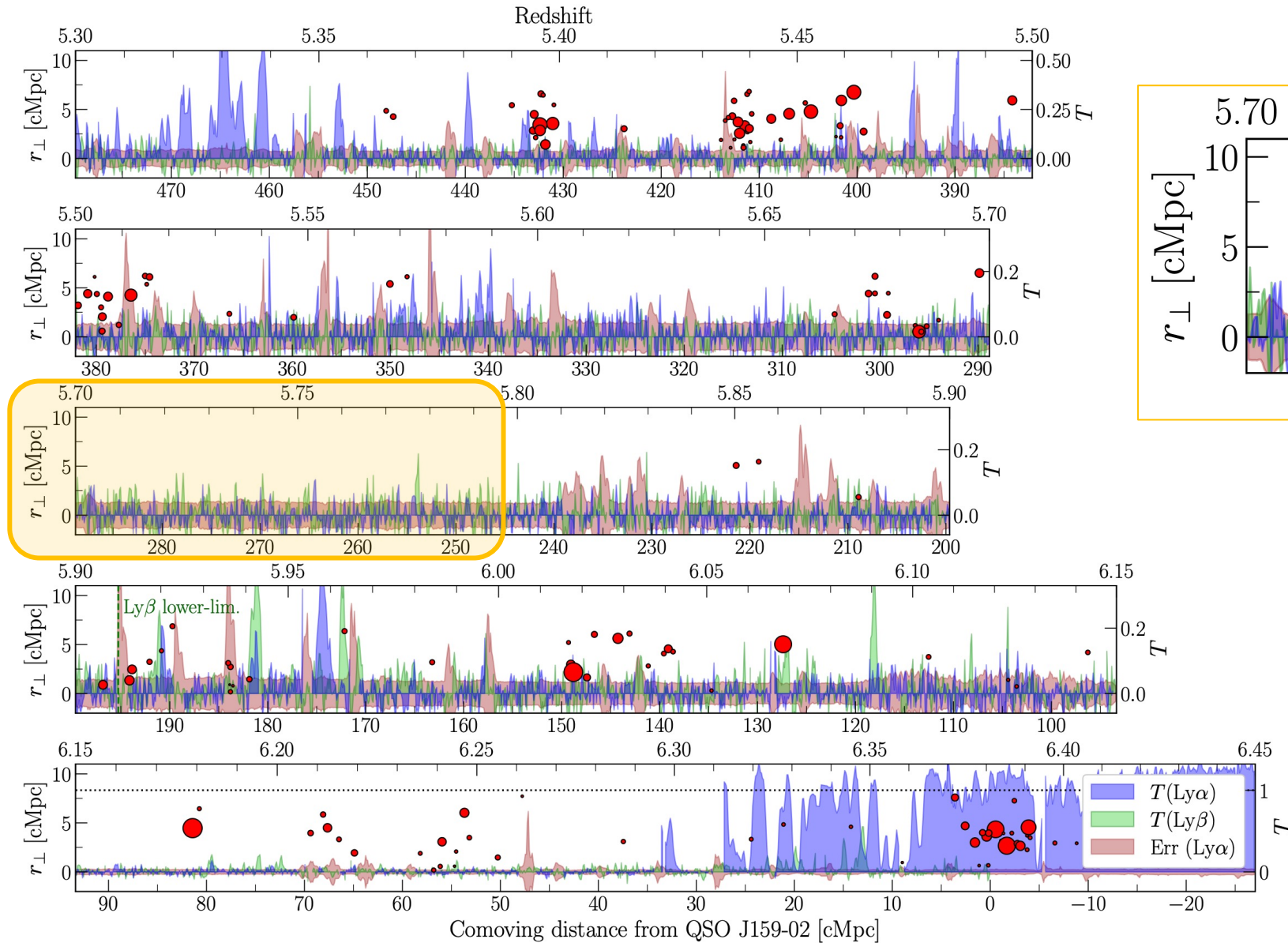


# Intervening absorbers in J159-02 spectrum (5)



Absorption system at  $z \sim 5.73491$

# Intervening absorbers in J159-02 spectrum (5)



Low ionization absorption system without [O III] emitters counterpart!

# Summary and Conclusion

- We reduced 2D raw spectroscopic data of the quasar PSOJ159-02 using *Pypelt* (Prochaska et al. 2020)
- Analysis of the continuum and emission lines, with a focus on C IV and Mg II
- BH mass and  $\lambda_{Edd}$  estimate, comparing their values with literature
- Identifying absorption systems in the spectrum at different redshifts
- Constraining the galaxy-absorbers cross correlation function

# Rest-frame UV properties - BH mass and Eddington ratio

We derive the bolometric luminosity at 3000 Å (Richard+ 2006) obtaining  
 $L_{bol} = 5.15 \times \lambda L_{\lambda}(3000 \text{ \AA}) \text{ erg/s} = (3.01 \pm 0.03) \times 10^{47} \text{ erg/s}$

## Mg II BH mass

We use the **scaling relation** from Vestergaard & Osmer (2009):

$$M_{BH, Mg II} = 10^{6.86} \left[ \frac{FWHM_{Mg II}}{10^3 \text{ km s}^{-1}} \right]^2 \left[ \frac{\lambda L_{\lambda}(3000 \text{ \AA})}{10^{44} \text{ erg s}^{-1}} \right]^{0.5} M_{\odot}$$

$$\log \left( \frac{M_{BH, Mg II}}{M_{\odot}} \right) = 9.53 \pm 0.04$$

## C IV BH mass

We use the **scaling relation** from Vestergaard & Peterson (2006):

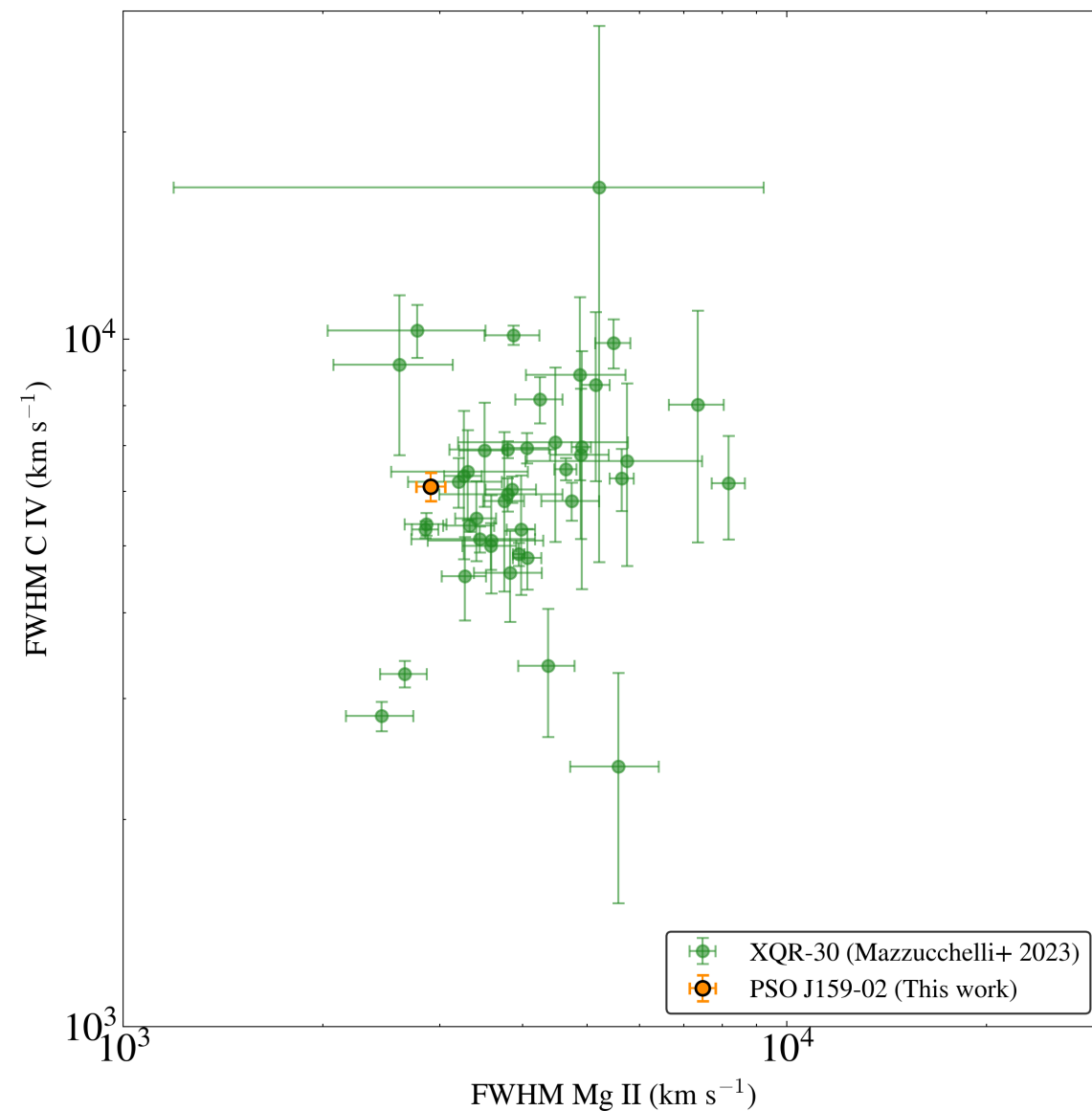
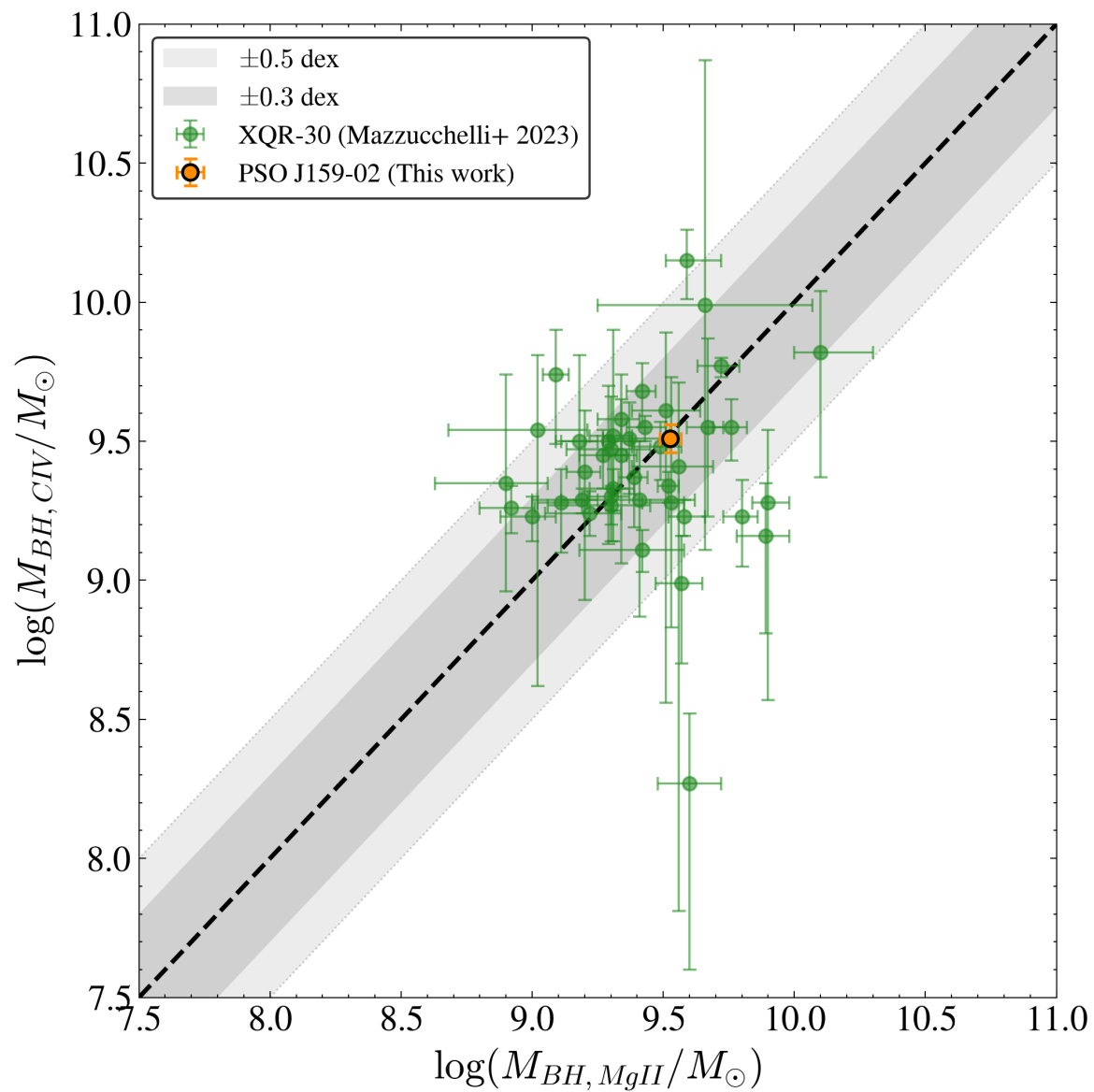
$$M_{BH, C IV} = 10^{6.66} \left[ \frac{FWHM_{C IV, corr}}{10^3 \text{ km s}^{-1}} \right]^2 \left[ \frac{\lambda L_{\lambda}(1350 \text{ \AA})}{10^{44} \text{ erg s}^{-1}} \right]^{0.53} M_{\odot}$$

$$\log \left( \frac{M_{BH, C IV}}{M_{\odot}} \right) = 9.51 \pm 0.05$$

$$\lambda_{Edd, C IV} = 0.74 \pm 0.06$$
$$\lambda_{Edd, Mg II} = 0.71 \pm 0.05$$

**Excellent agreement!**

# Rest-frame UV properties – comparison with literature



# Rest-frame UV properties – comparison with literature

