Galaxy- Carbon absorbers Cross Correlation Function in the EIGER Survey

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Collaborators: Manuela Bischetti, Marta Galbiati

INAF OSSERVATORIO ASTRONOMICO DI TRIESTE

RECAP erc synergy grant

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UNIVERSITÀ DEGLI STUDI DI TRIESTE

The Circumgalactic Medium at high redshift

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

Important physical properties:

I. Column density (N)

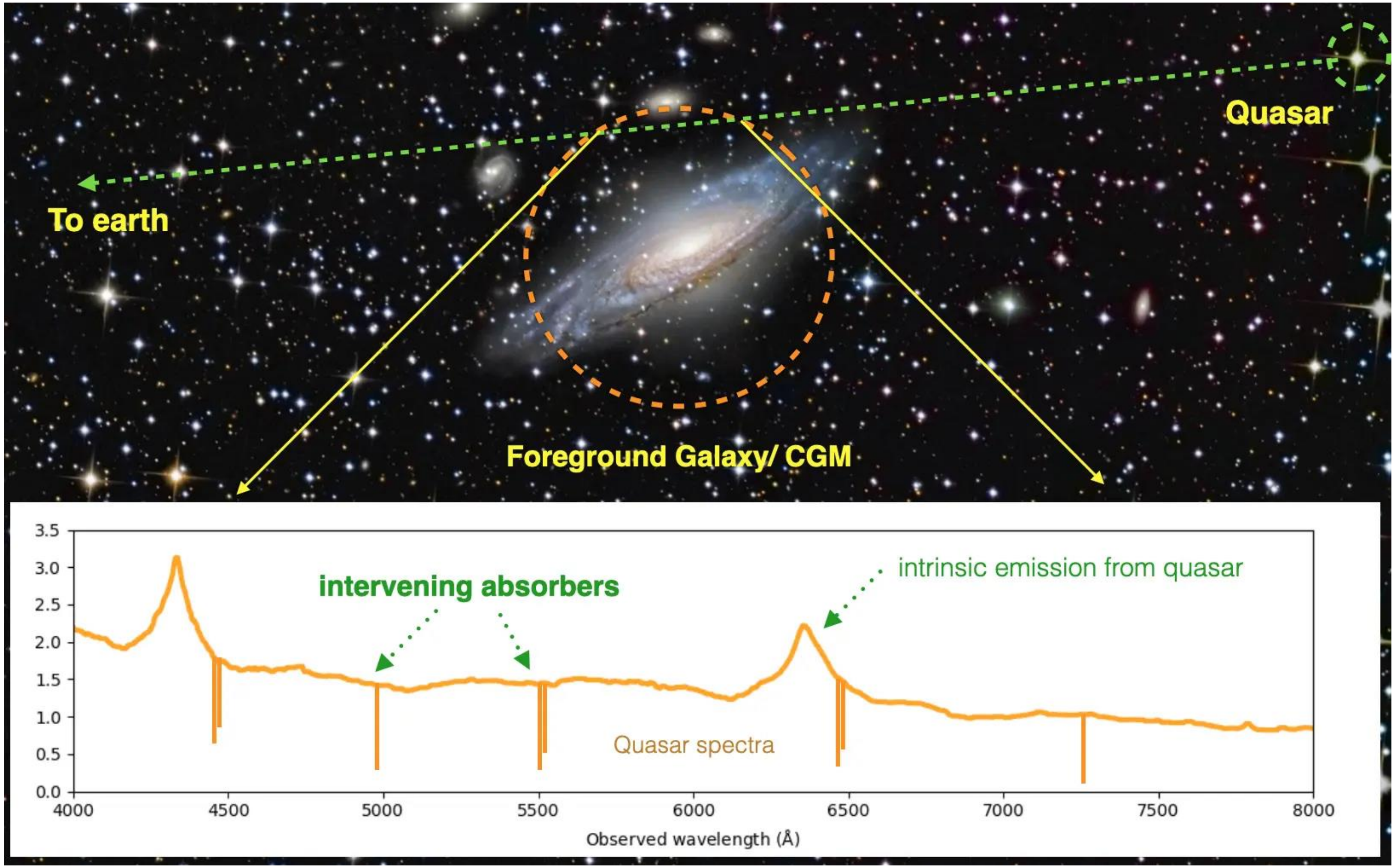
II. Doppler parameter (b)

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?

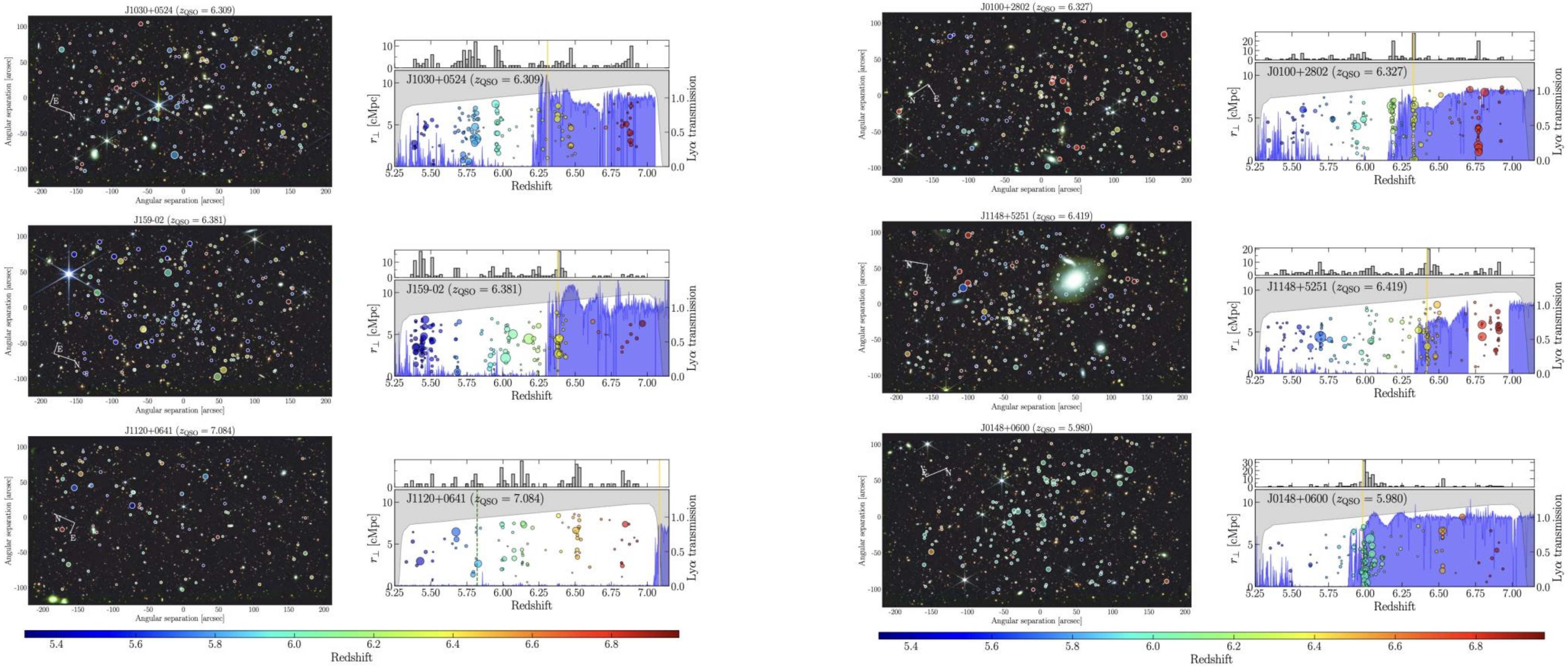


Anand+ 2021

The EIGER Survey

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



Kashino+ 2026

The working sample (1)

For each quasar field we have:

- [O III] emitters in the field of view with Ra, Dec, z (Kashino+ 2026)
- CII + CIV Absorption systems in the redshift range z = [5.2, 6.52], with their column density
  - Absorption systems for J1120 come from Bosman+ 2017
  - Absorption systems for J1148 come from Becker+ 2006

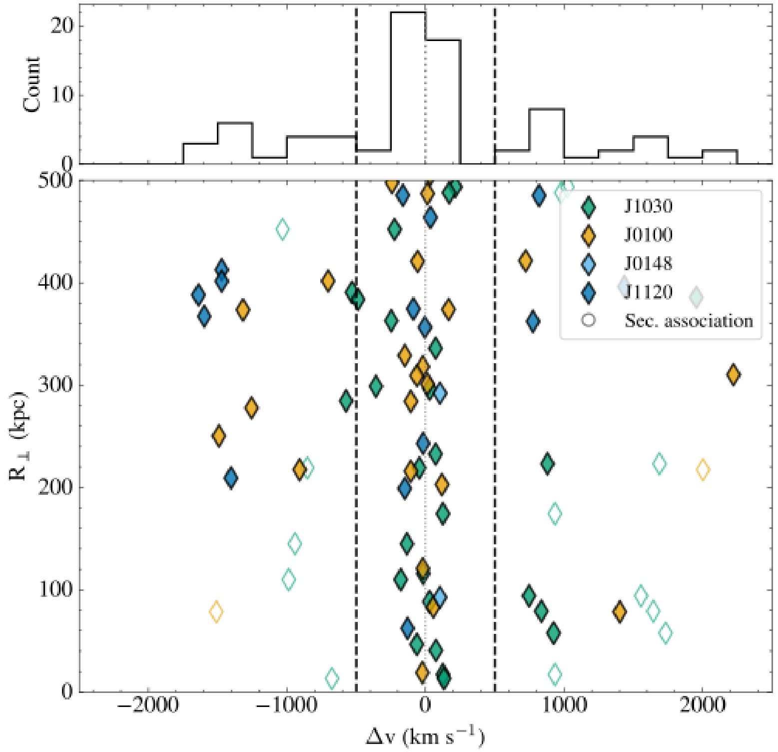
To complete the useful information, we compute:

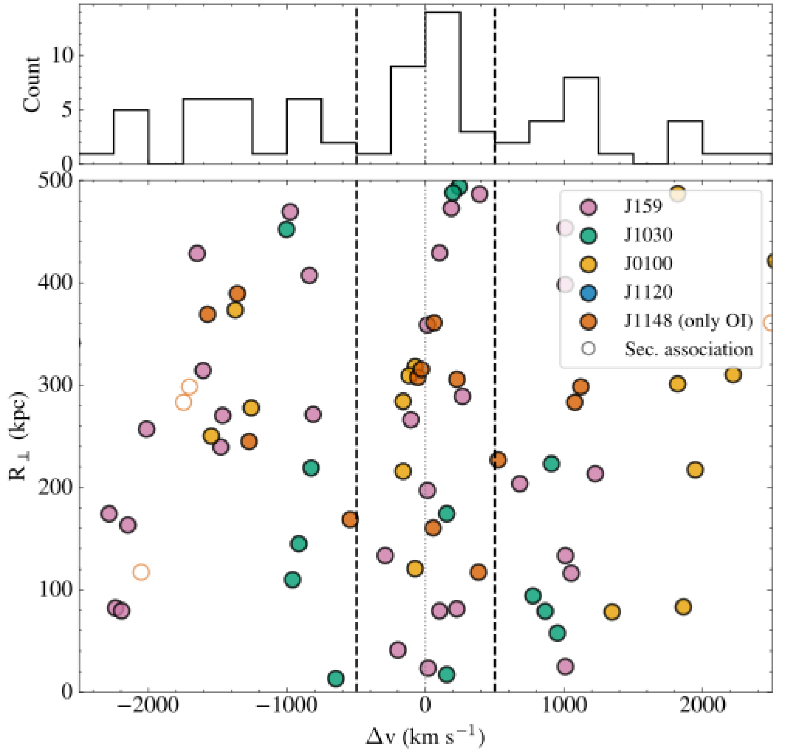
- Impact parameter ($R_{\perp}$)
- Redshift distance in terms of velocity (Δv)

We focused our analysis **only** on **CII + CIV absorption systems**, with **log(N) > 12.0** and **log(N) > 13**, respectively.

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

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





The working sample (2)

For each quasar field we have:

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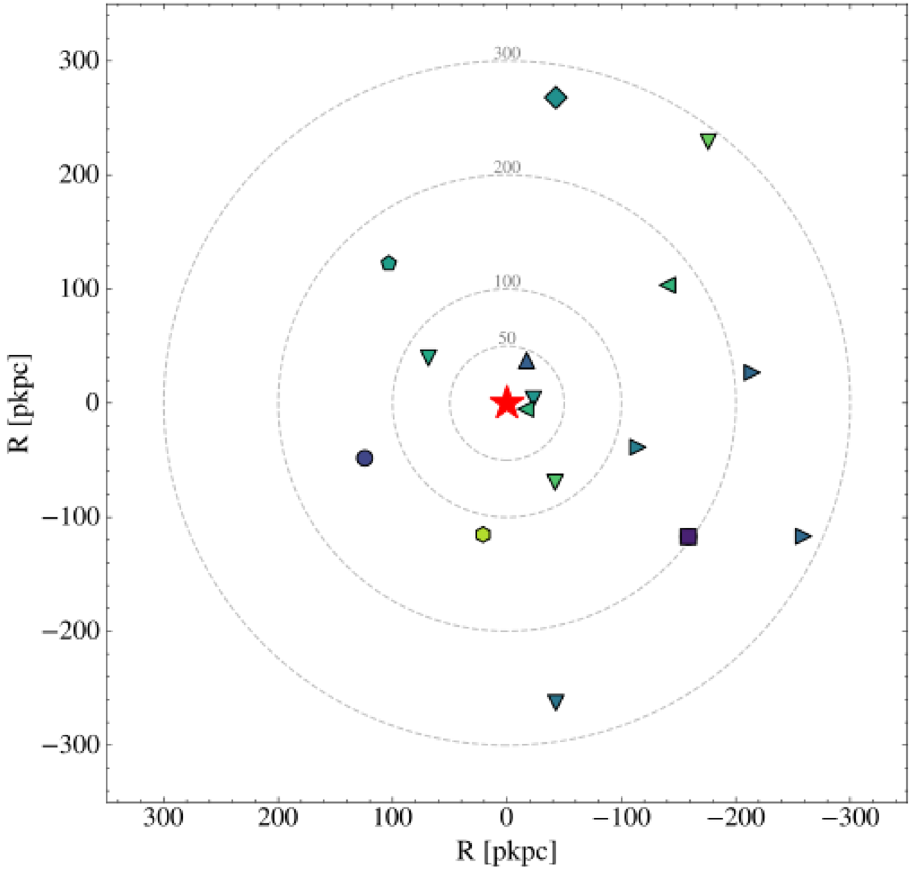
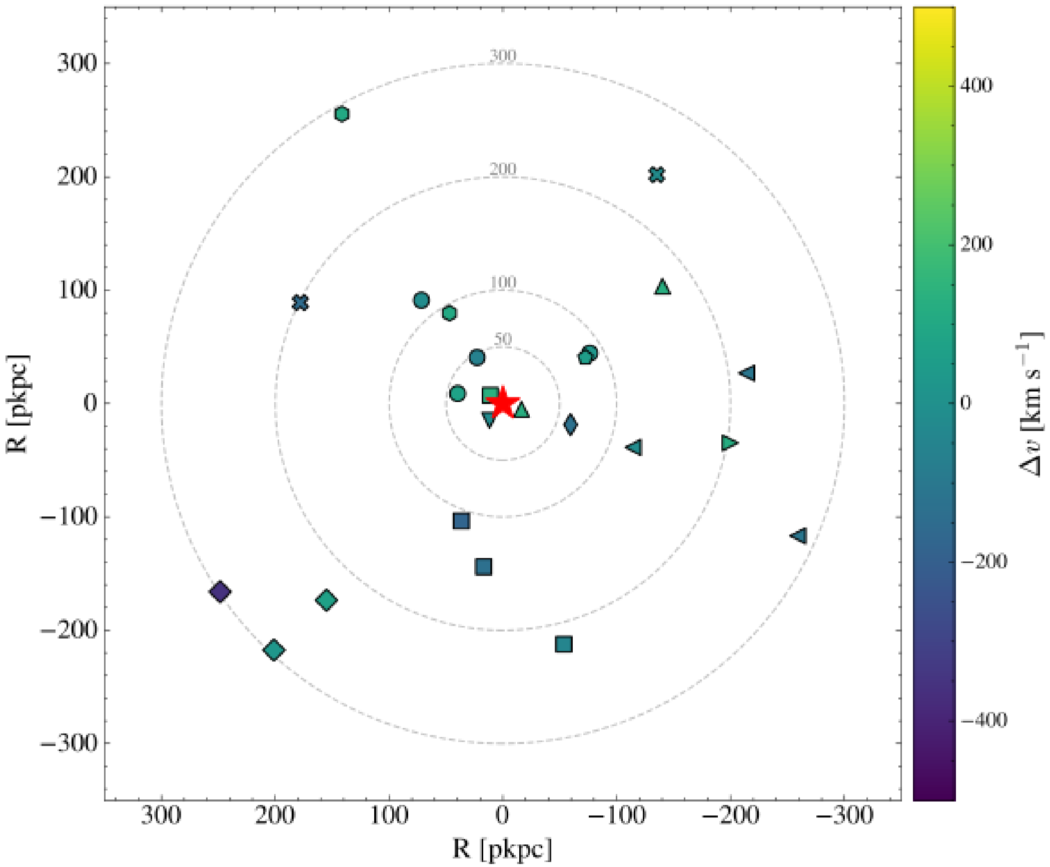


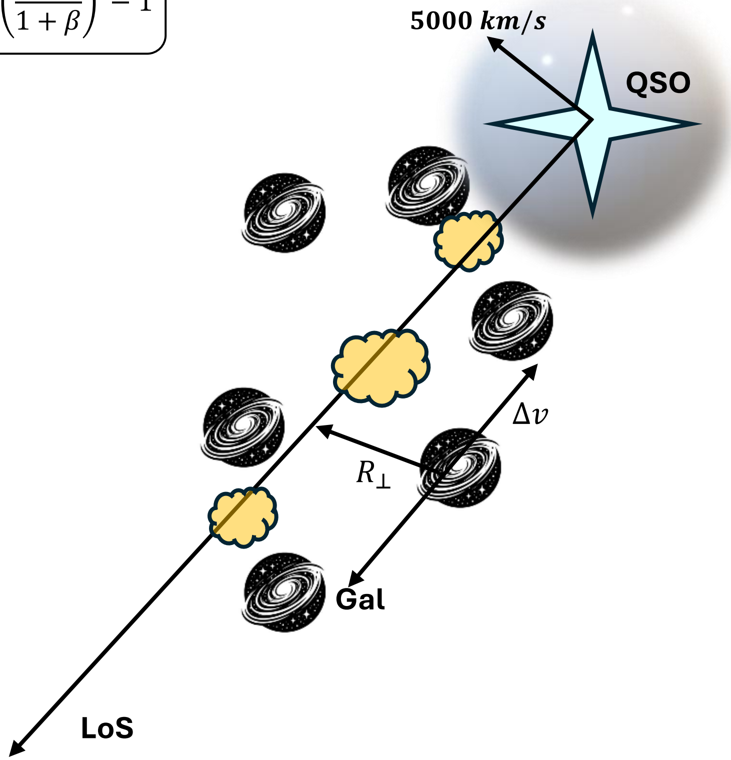


CII Covering Fraction (1)

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

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

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



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

Where:

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

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

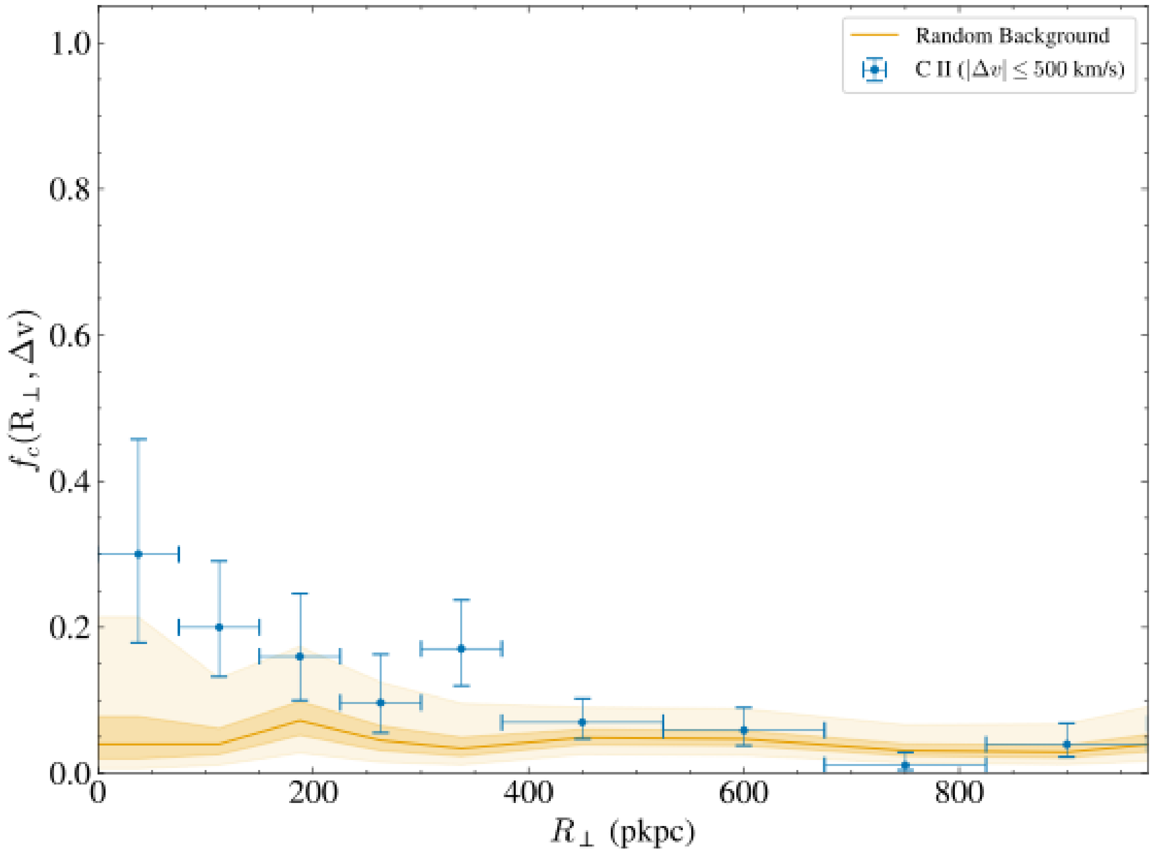
$$f_c^{bkg}(R_\perp, \Delta v) = \frac{\sum_{k=1}^{6} \sum_{m \neq k} \sum_{j \in G_k(R_{\perp,m})} 1_j(\Delta v_{max})}{\sum_{k=1}^{6} \sum_{m \neq k} \sum_{j \in G_k(R_{\perp,m})} 1}$$

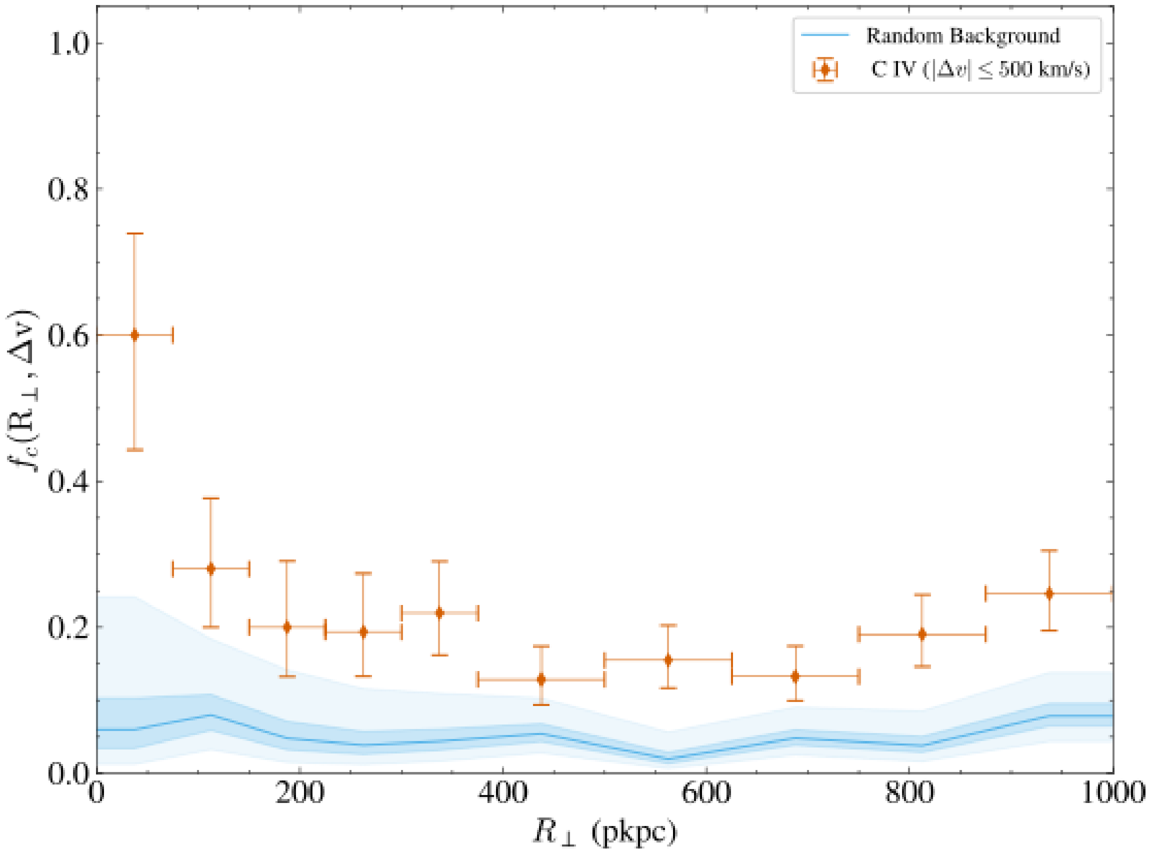
Where:

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

CII/CIV Covering Fraction (2)

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

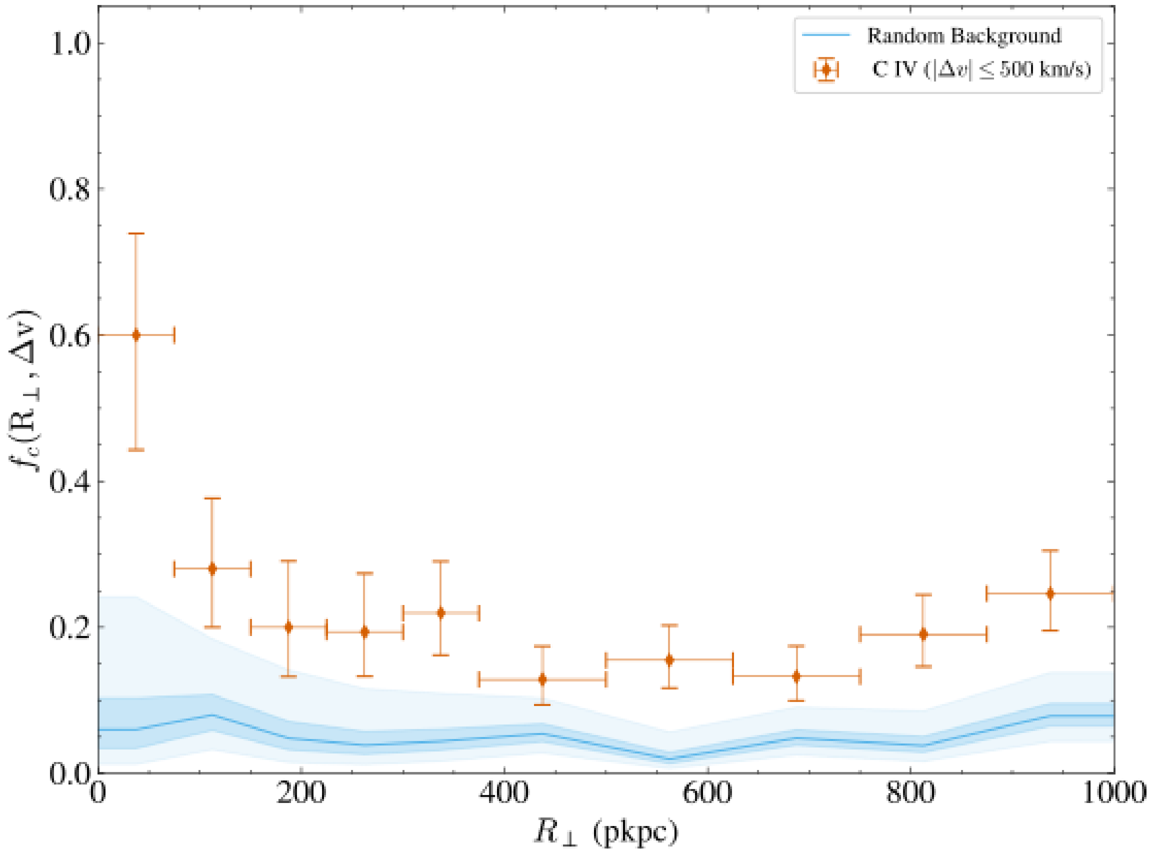


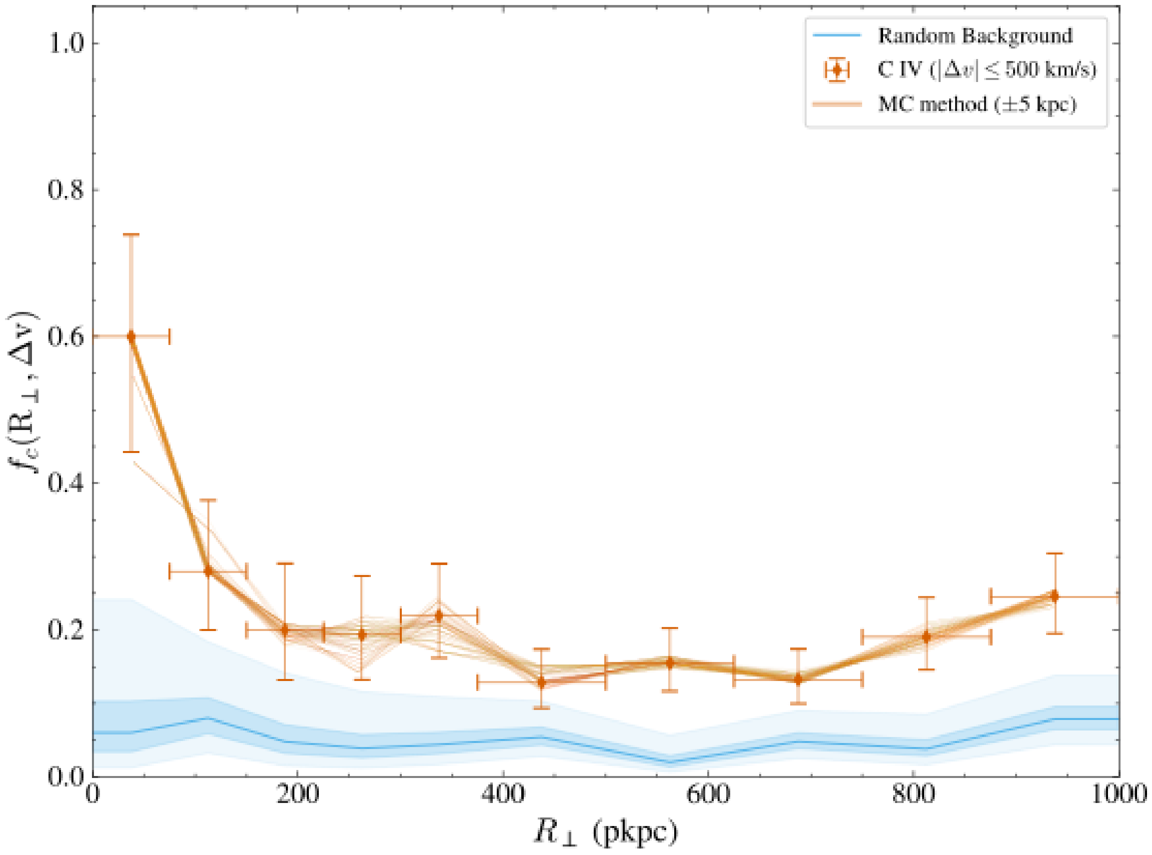


The vertical error bars account for the 1σ = 68% Wilson-score confidence intervals, while the horizontal bars reproduce the width of each radial interval.

CIV Covering Fraction (3)

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





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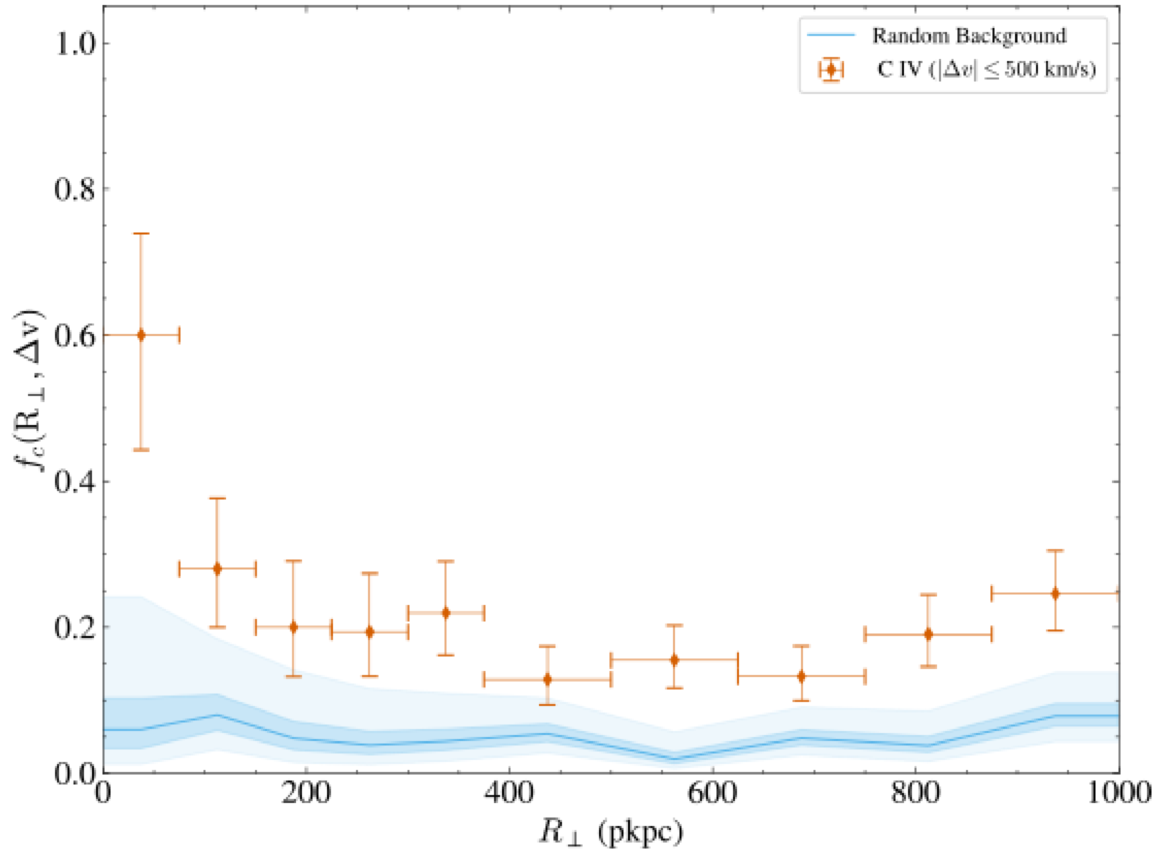
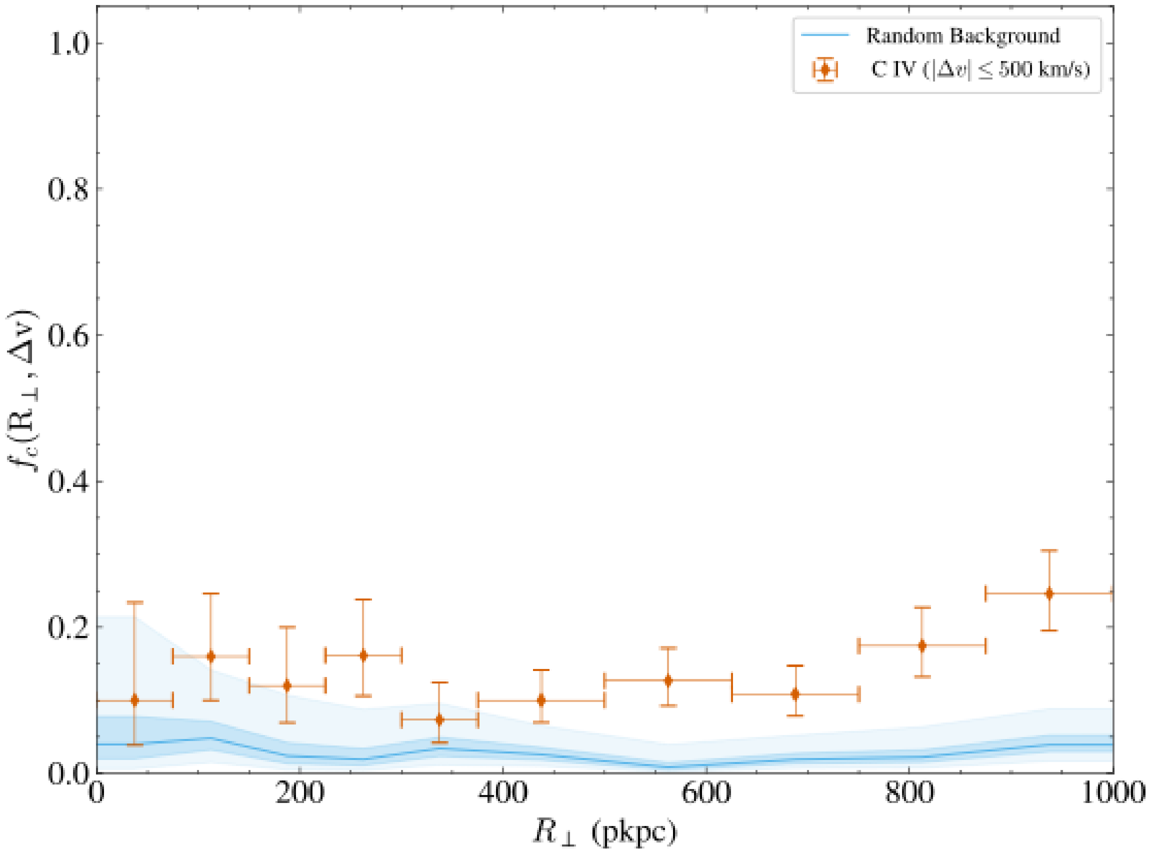
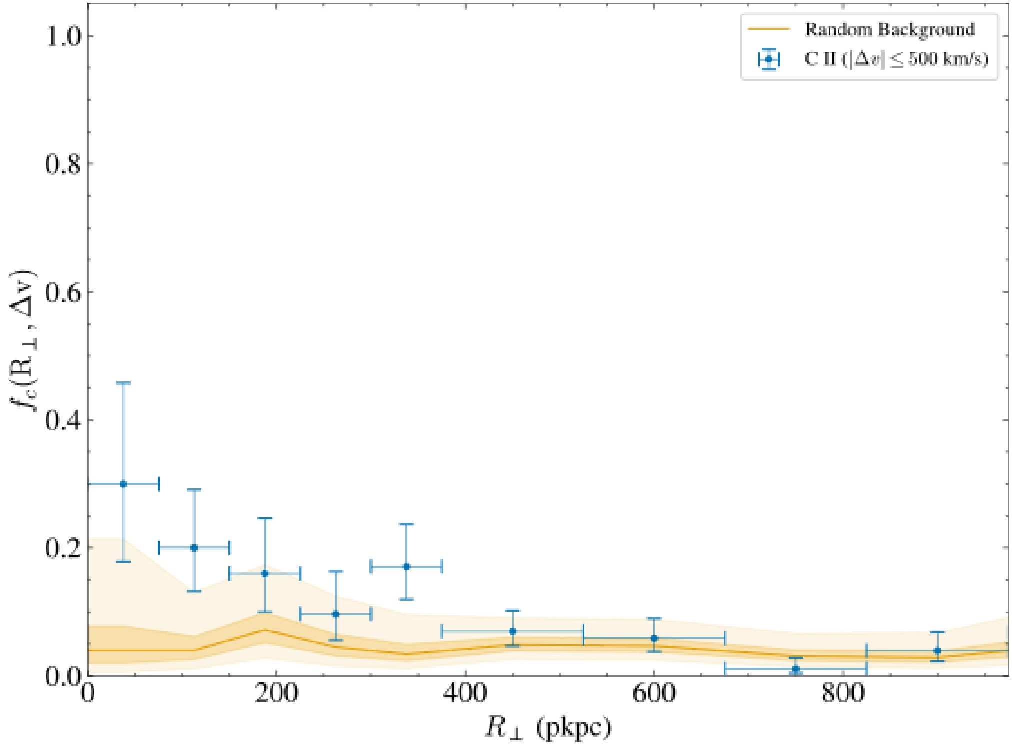


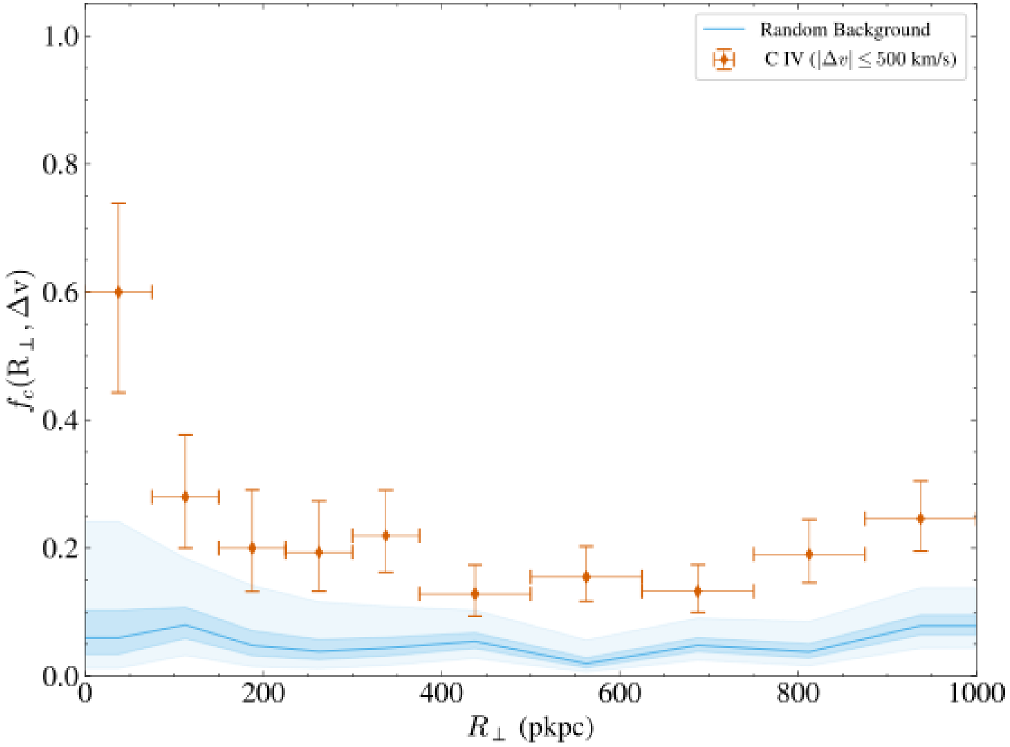


This panel represent the C IV covering fraction considering only the C IV absorption systems uncontaminated by low-ionization absorption system

Covering Fraction → C II+C IV gas mass

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





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

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

$$M_{CII+CIV}(0 - 300\ kpc) \approx 1.4 \cdot 10^6 M_\odot$$

$$M_{O\ I}(0 - 300\ kpc) \approx 2 \cdot 10^6 M_\odot$$

Higginson+ 2026

Neglecting CIII (λ 977 Å)

CII 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 Δr given by

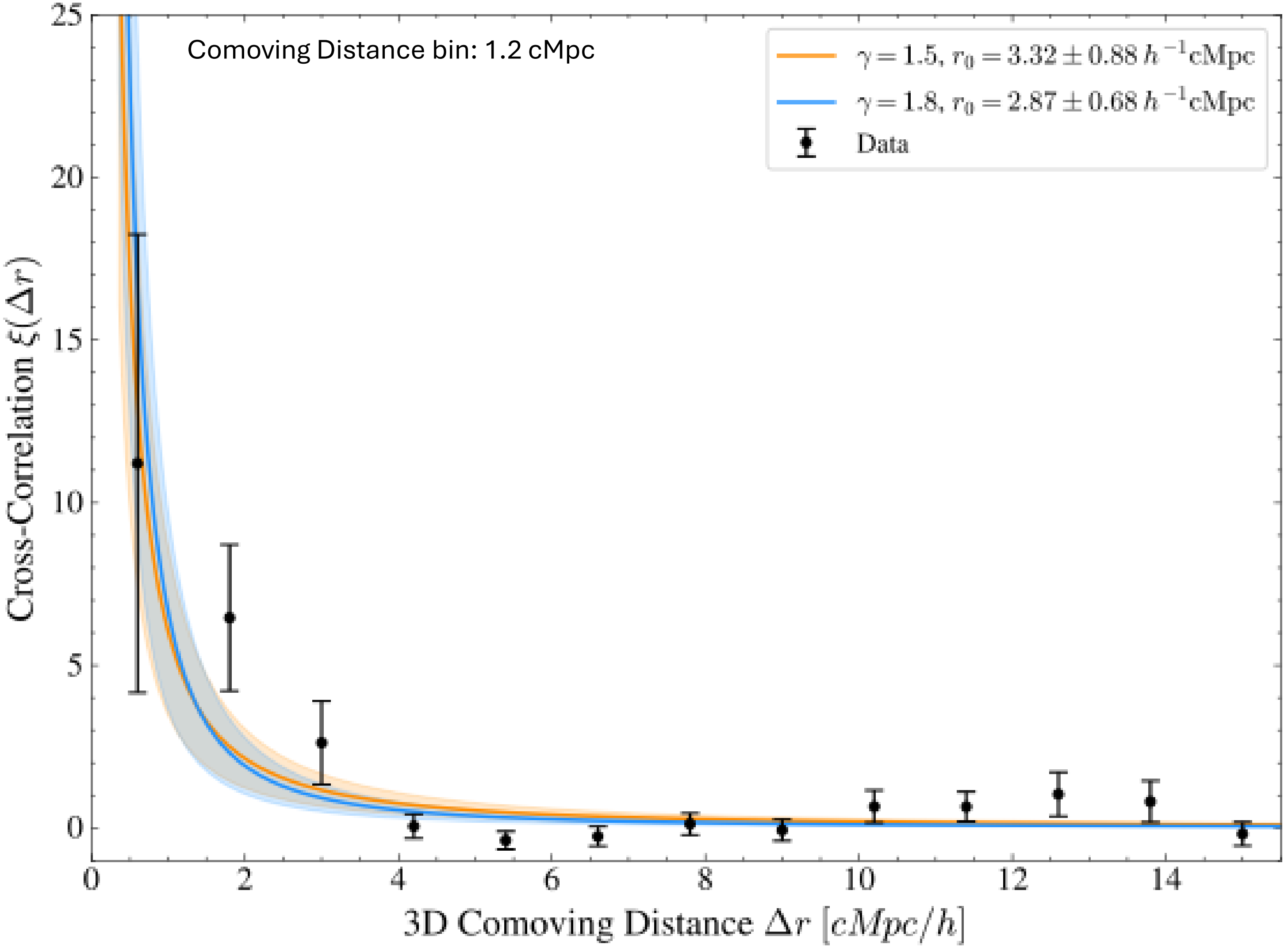
$$\Delta r = \sqrt{r_{1,\|}^2 + r_{2\|}^2 - 2 r_{1,\|} r_{2,\|} \cos \Delta\theta}$$

2. Peebles estimator:

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

3. Errors estimated with Poisson statistics:

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



CIV 3D Cross-Correlation Function (1)

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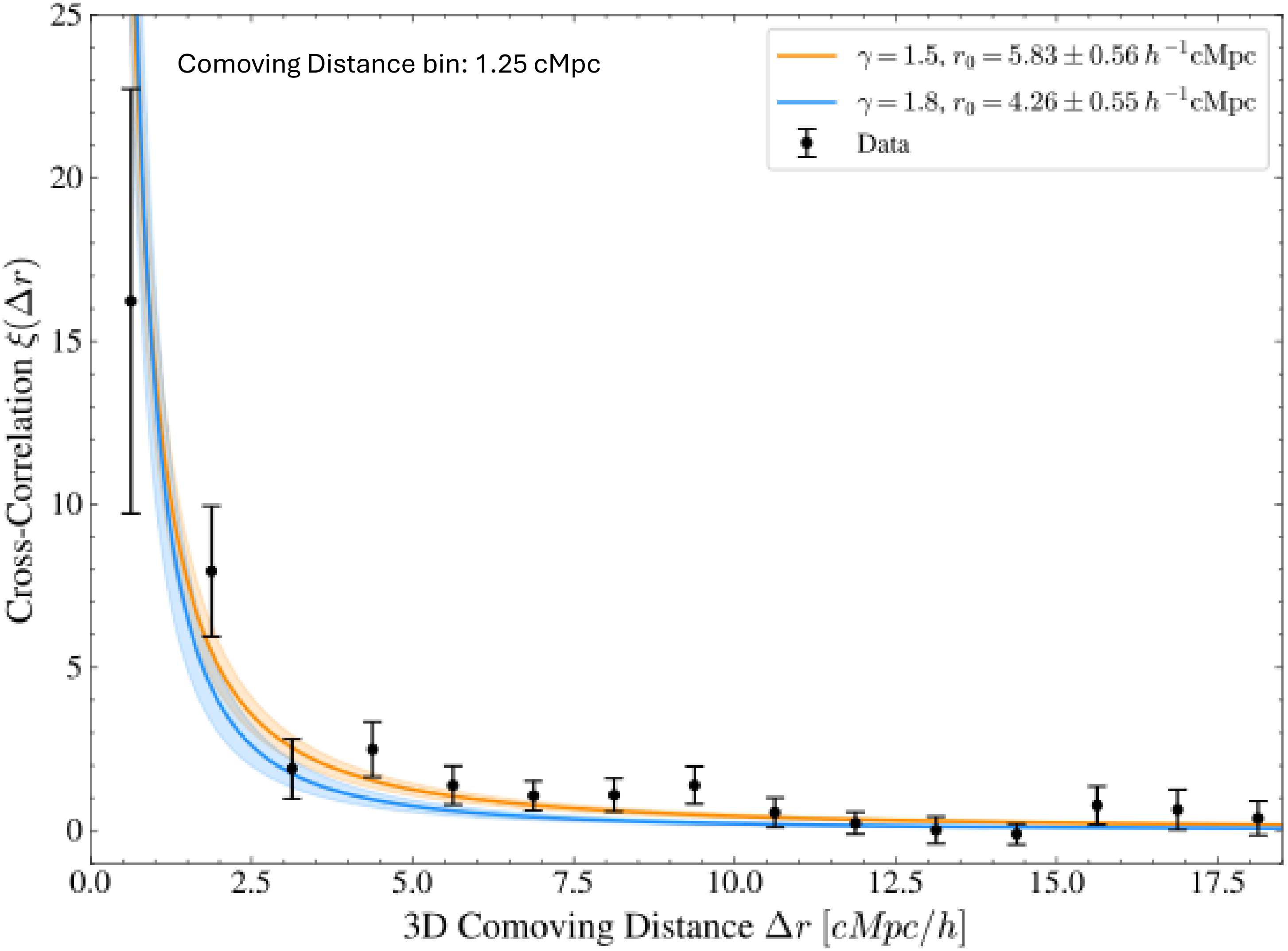
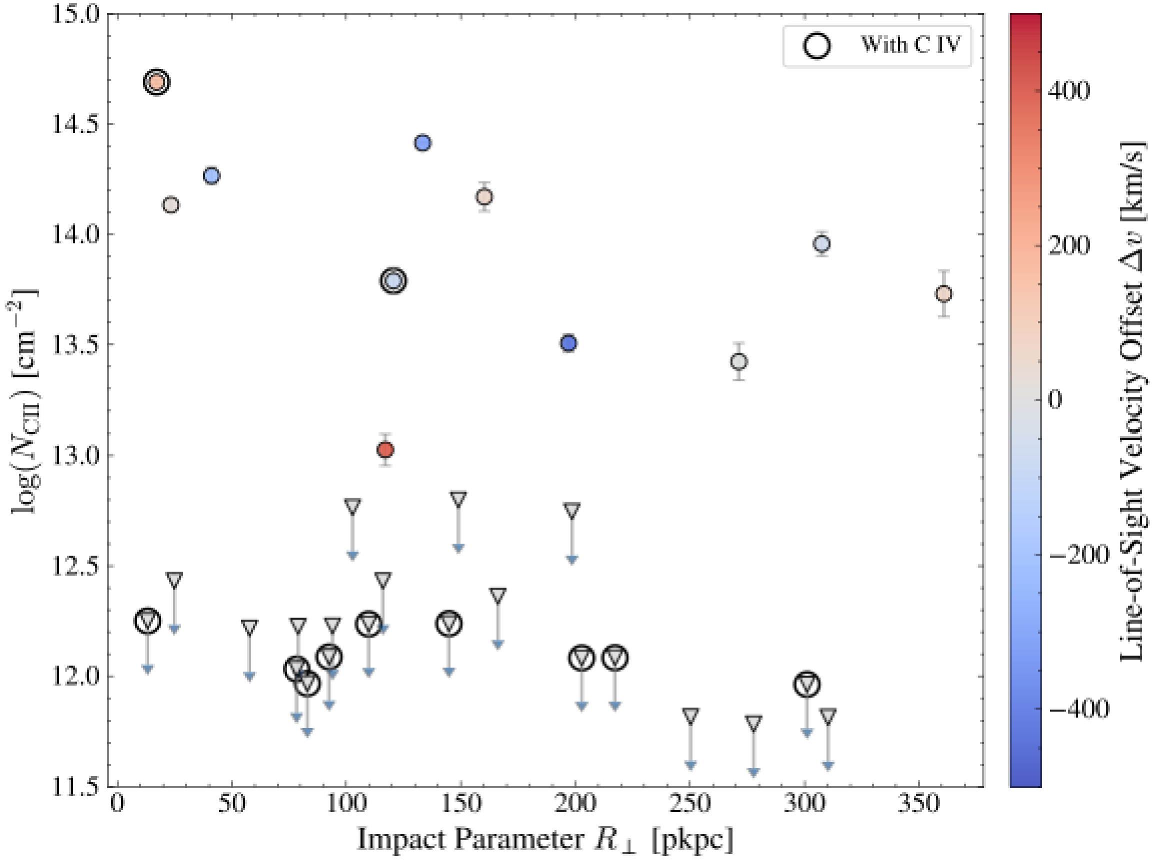


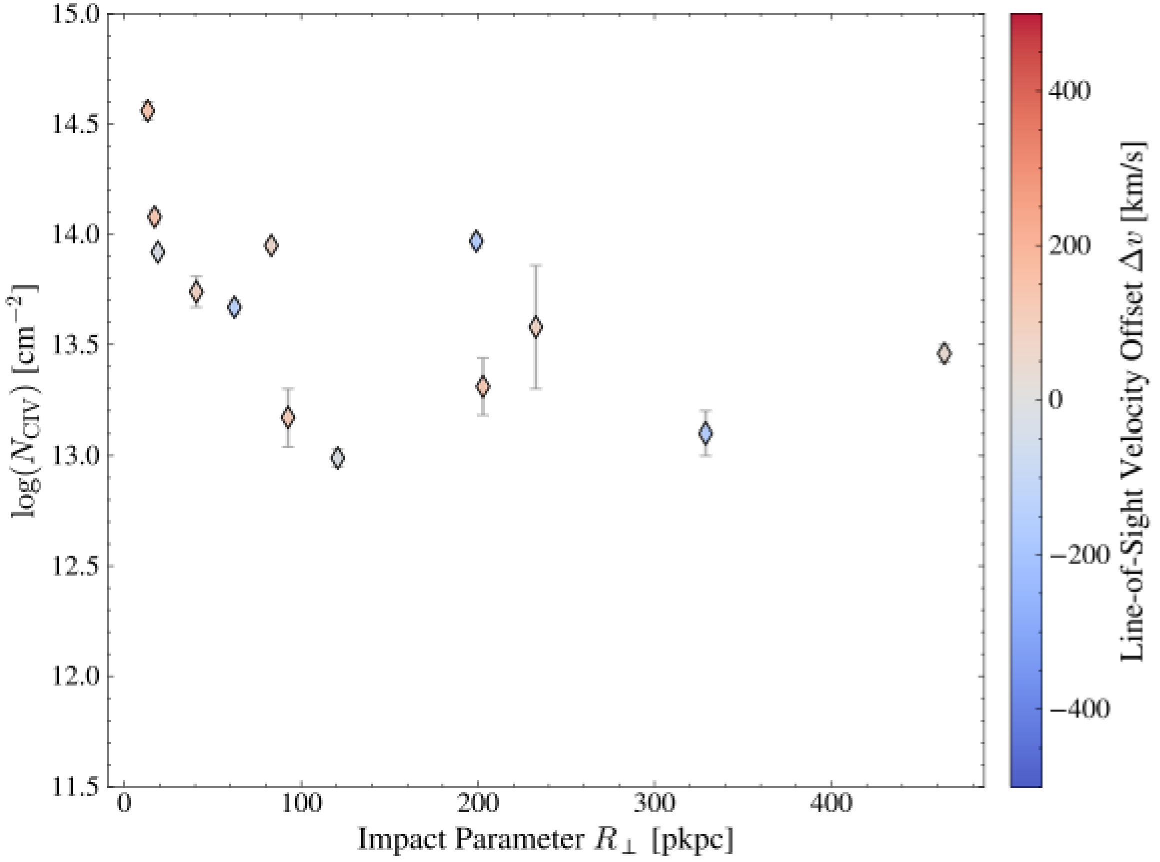
C II / C IV log(N) profile

Upper limits (only C II) →

$$EW_{min,obs} \approx \frac{3 \times \lambda_{ion,obs}}{R \times (S/N)_{pix} \times \sqrt{n_{samp}}}$$

$$N \approx \alpha \, \frac{EW_{rest,ion}}{f_{osc} \times \lambda_{rest,ion}}$$





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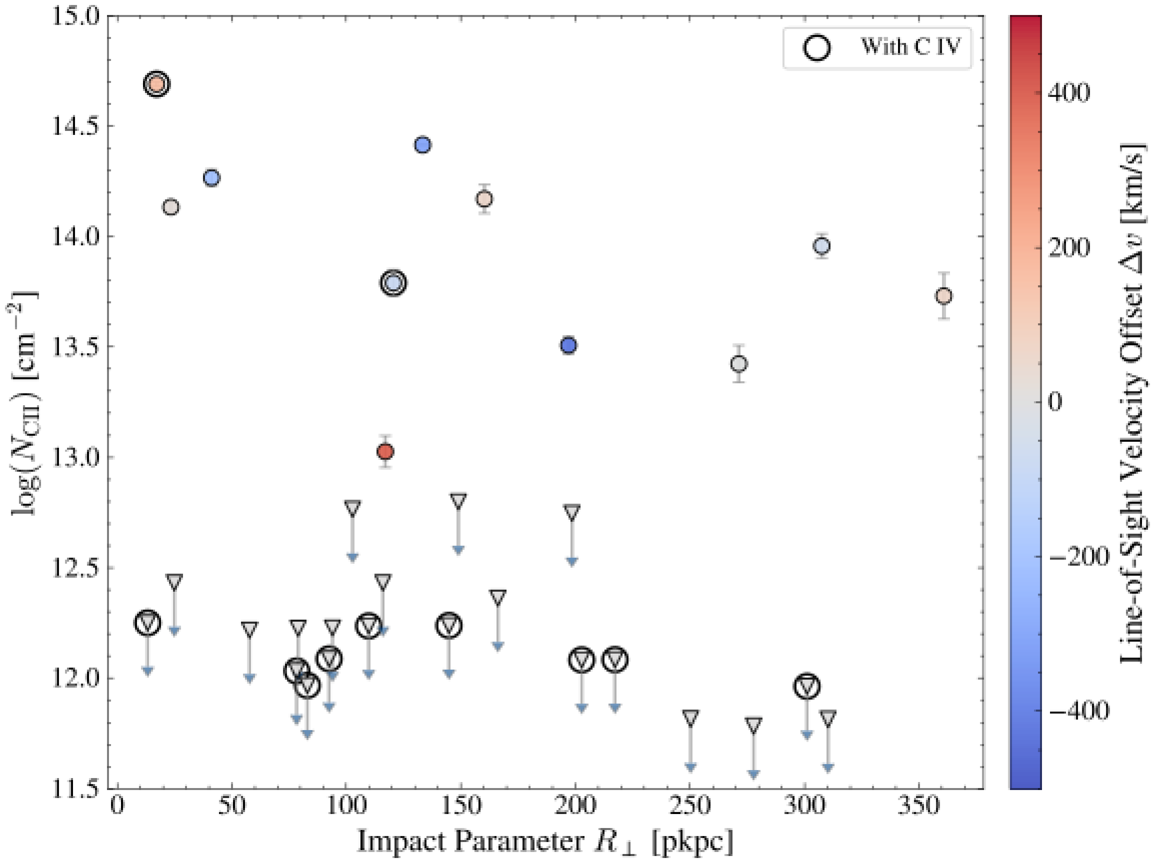
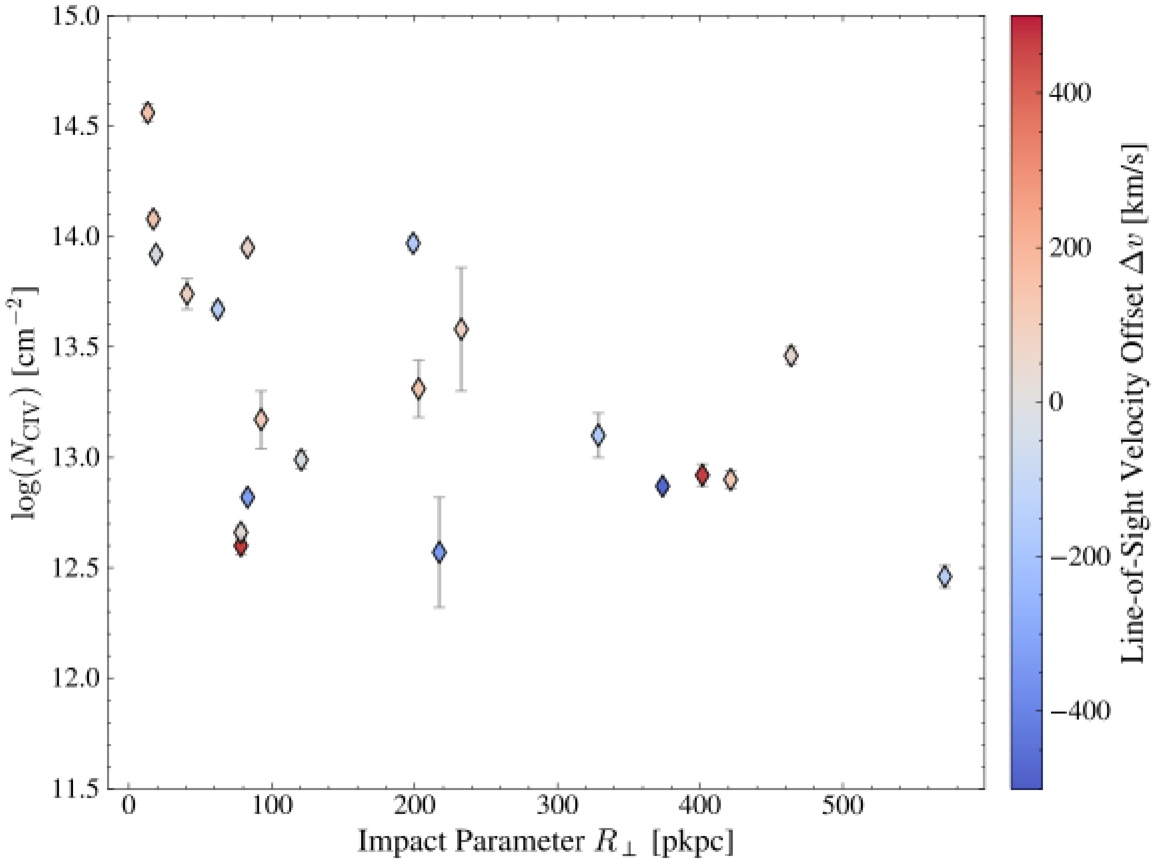


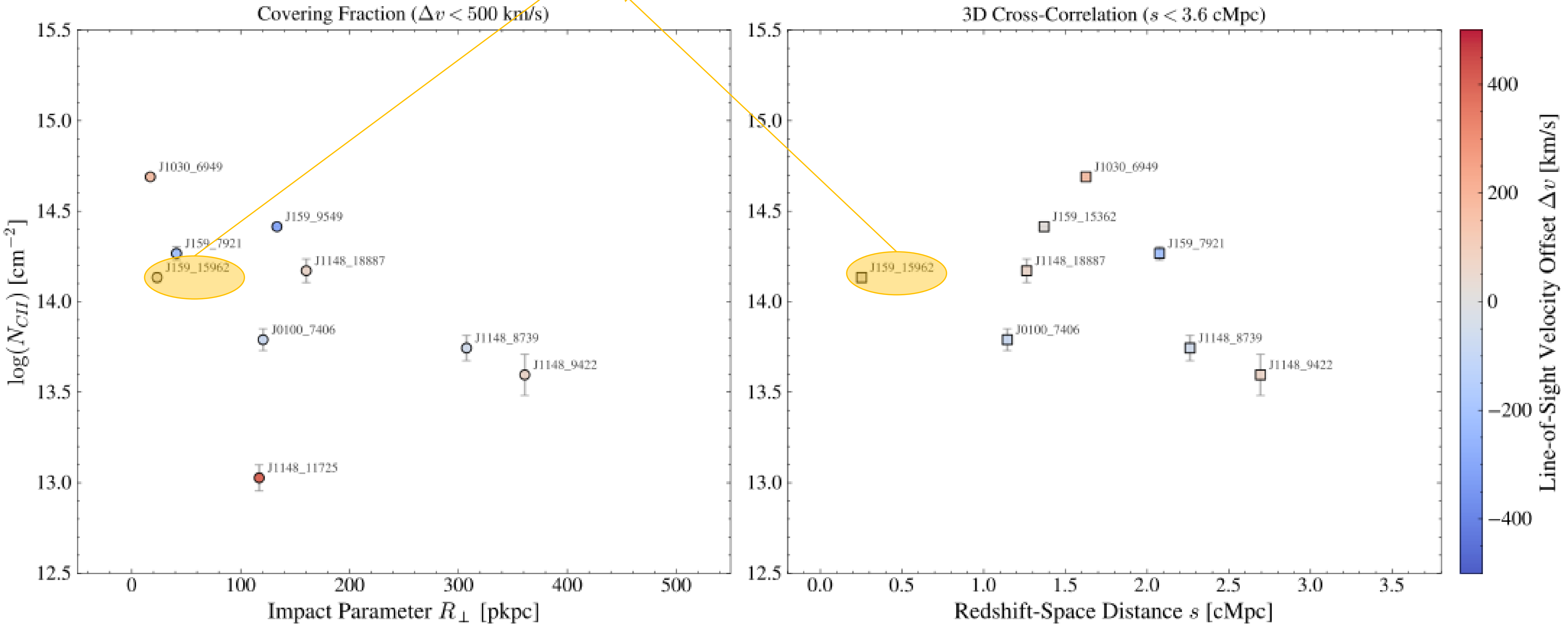


Backup Slide

CII log(N) profile

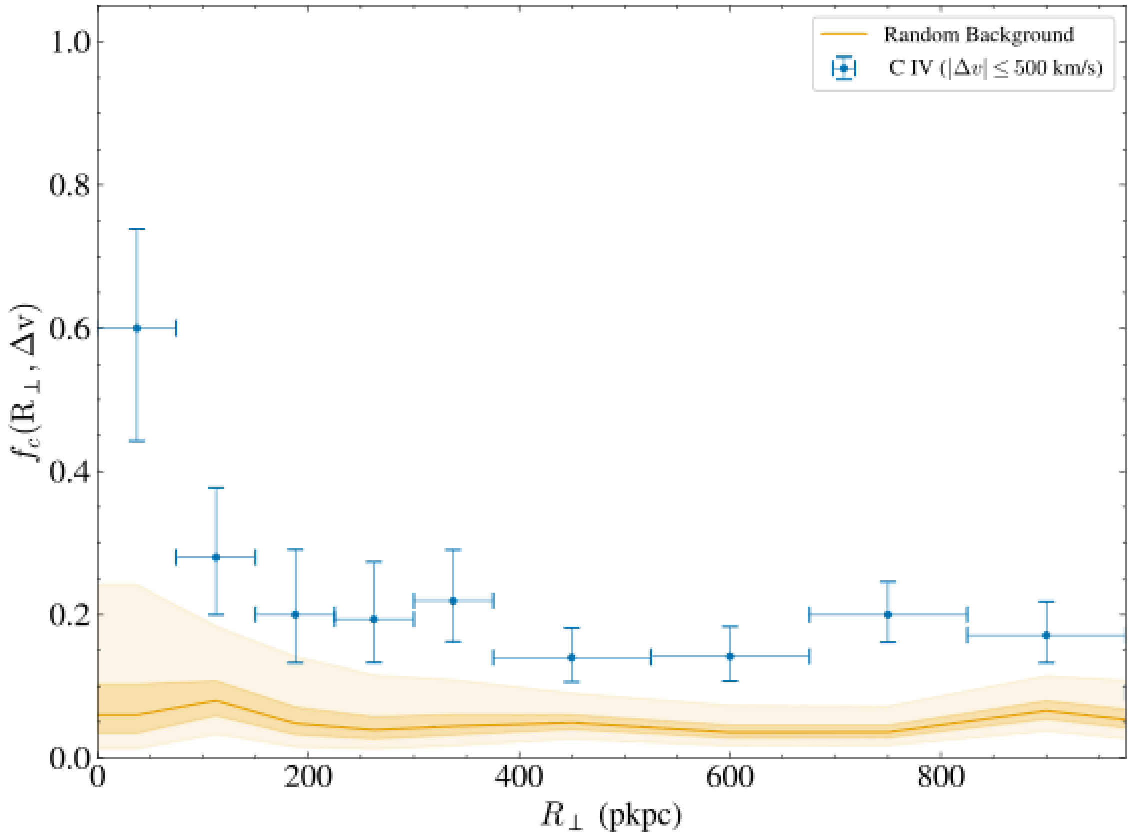
J159 | Gal ID: 15962 ($z_{gal} = 6.2390$) → CII ($z_{abs} = 6.2386$) | $R_\perp = 23.4$ pkpc | $\Delta v = 18.4$ km/s

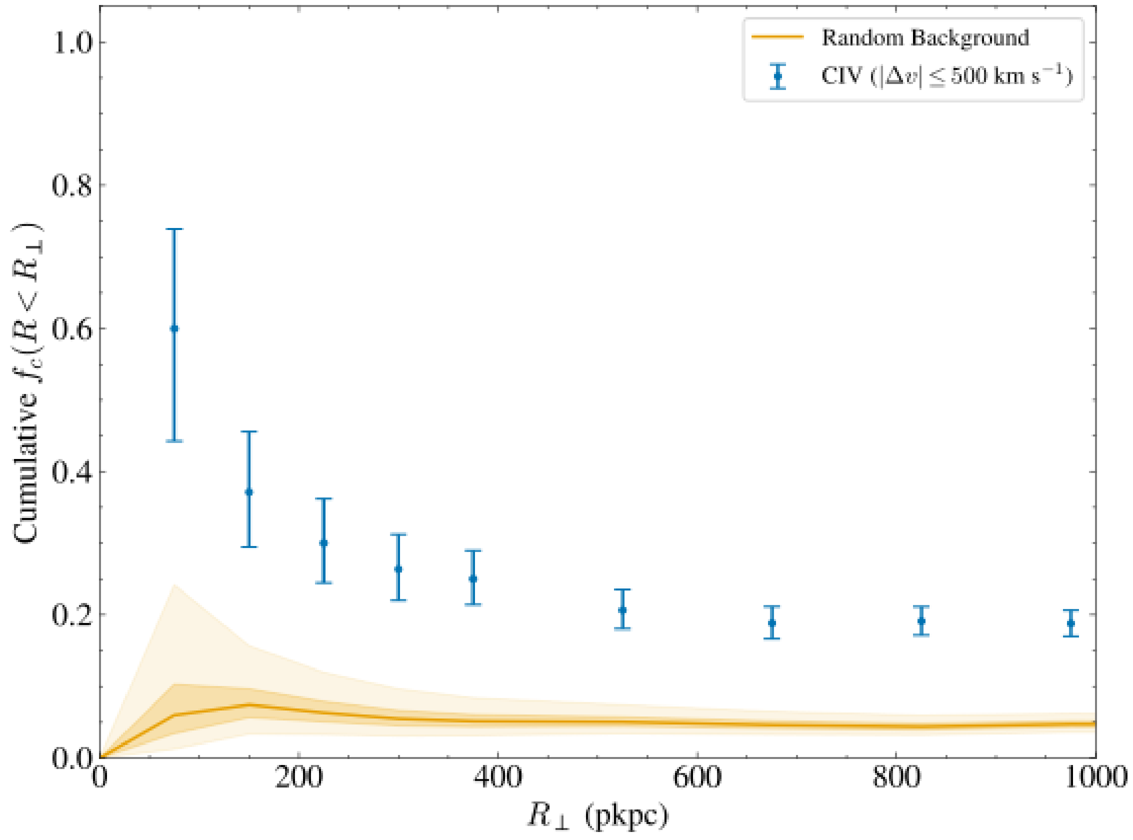
J159 | Gal ID: 15962 ($z_{gal} = 6.2390$) → CII ($z_{abs} = 6.2386$) | $s_{3D} = 0.25$ cMpc | $\Delta v = 18.4$ km/s



CIV Covering Fraction (2)

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





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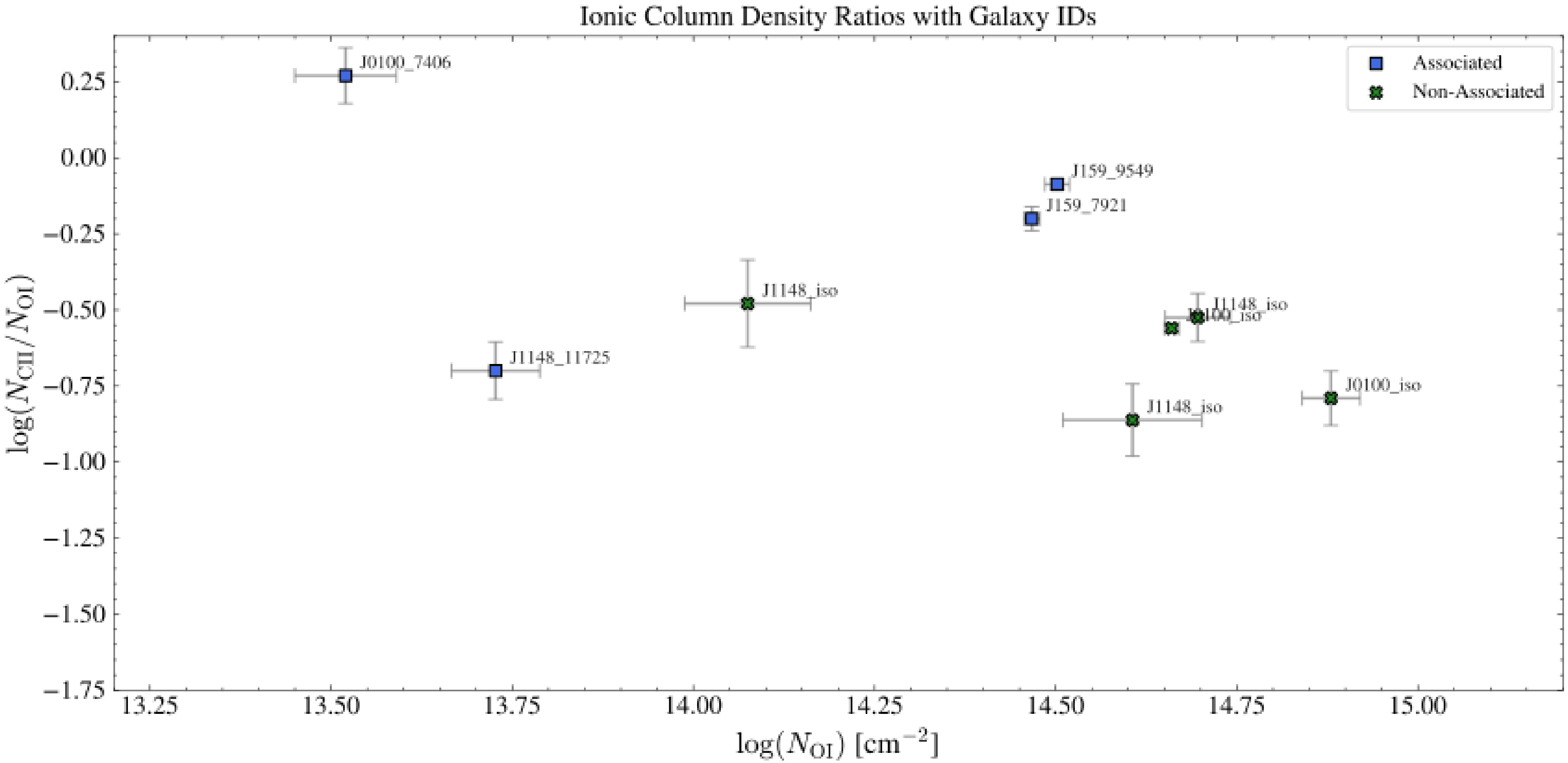
Metal abundances



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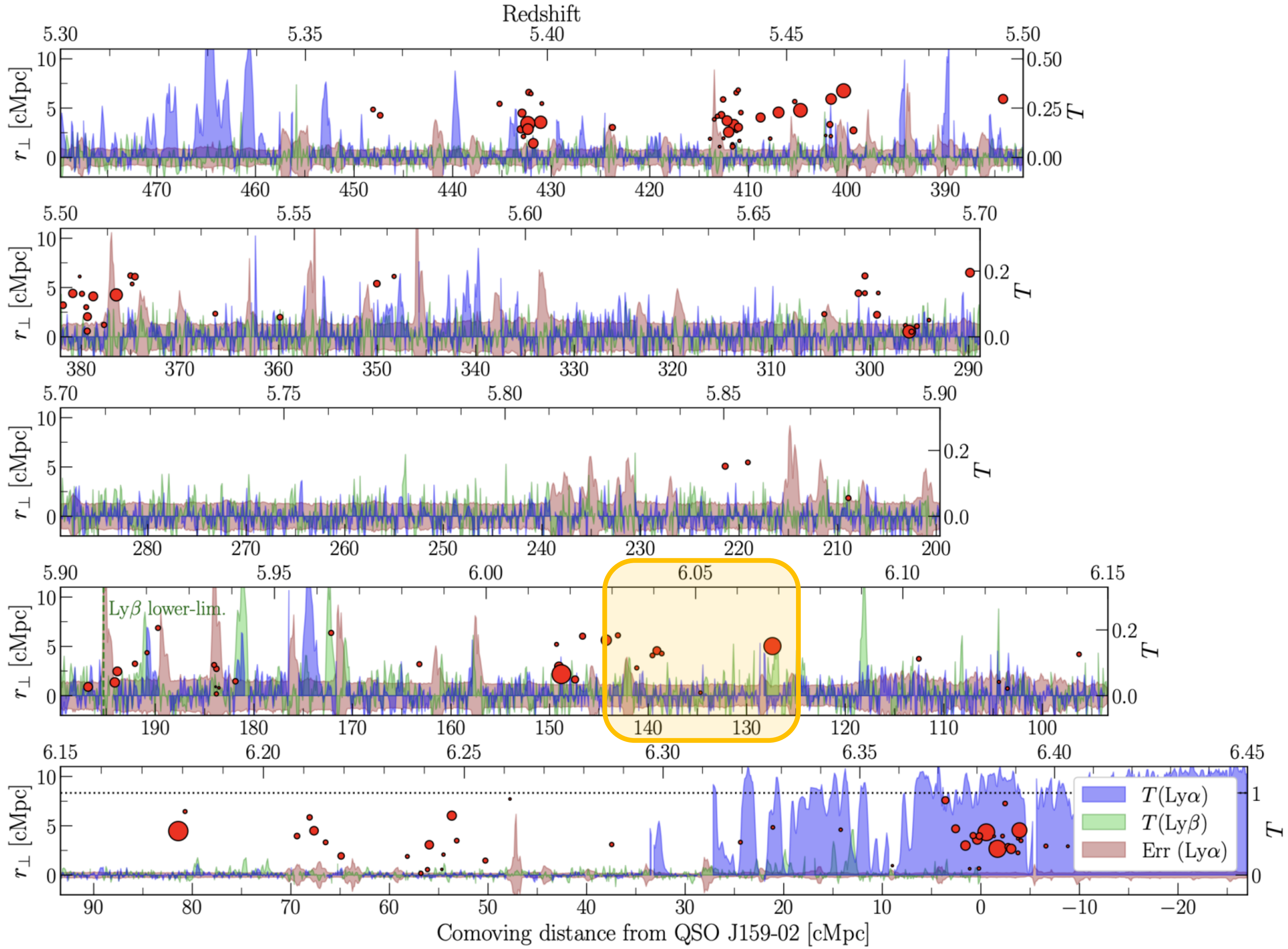
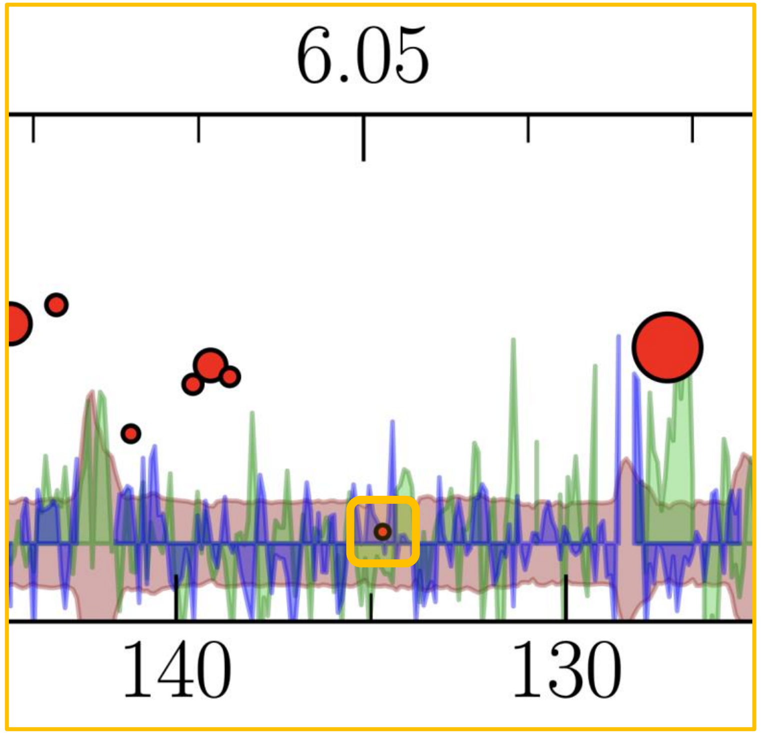
Software used: *Astrocook* (Cupani+ 2020)

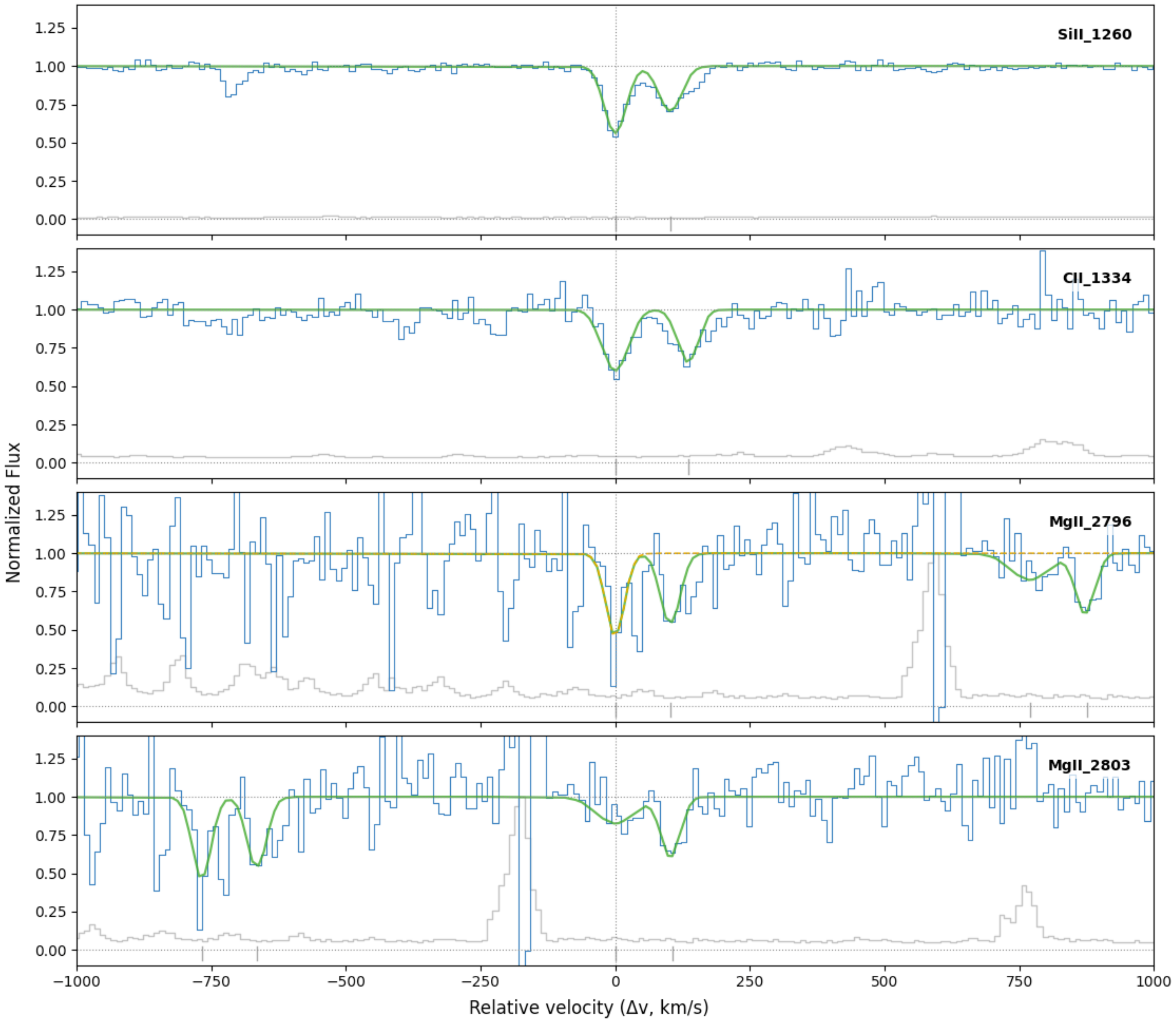
Intervening absorbers in J159-02 spectrum (2)





Kashino+ 2026

Intervening absorbers in J159-02 spectrum (3)



Absorption system at $z \sim 6.23694$

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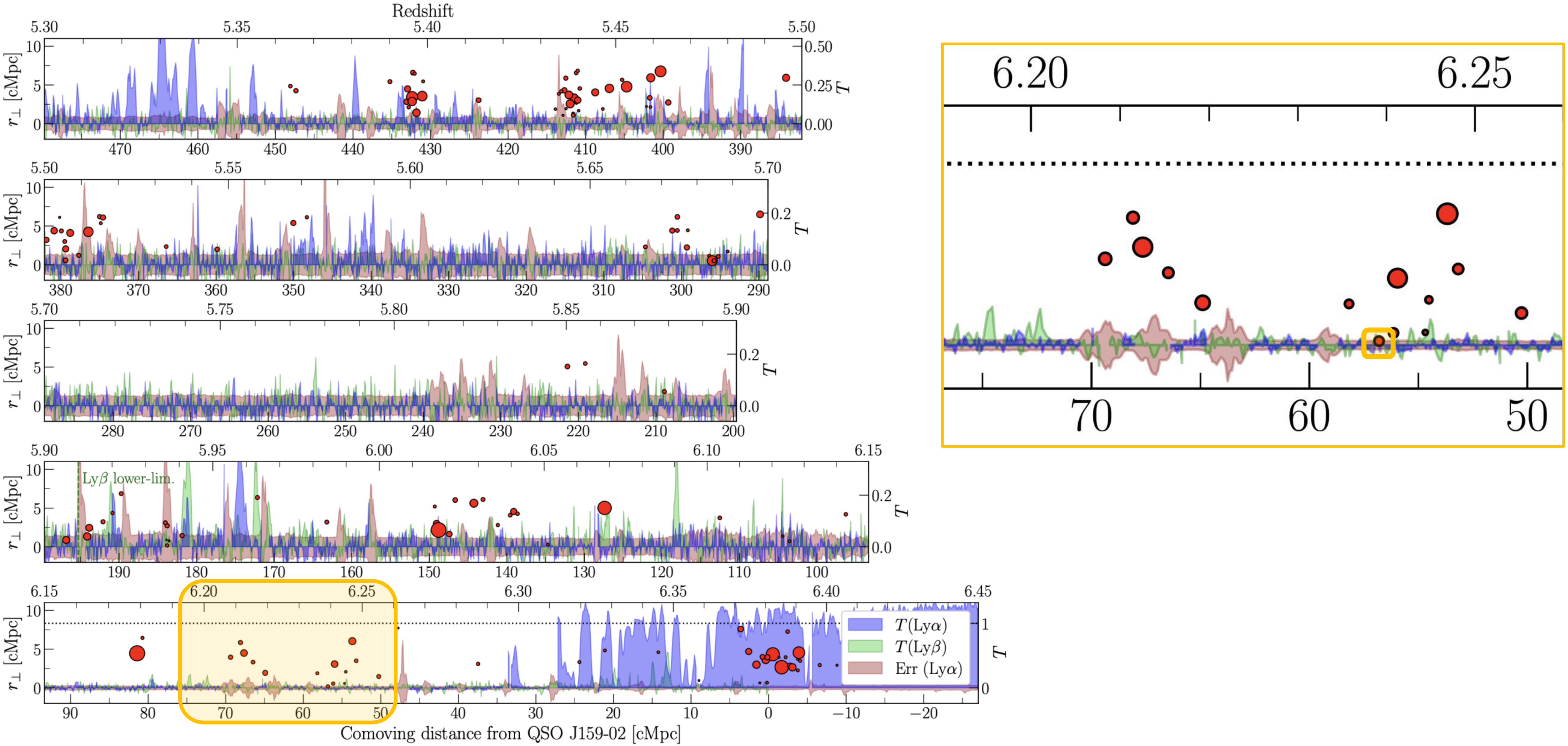
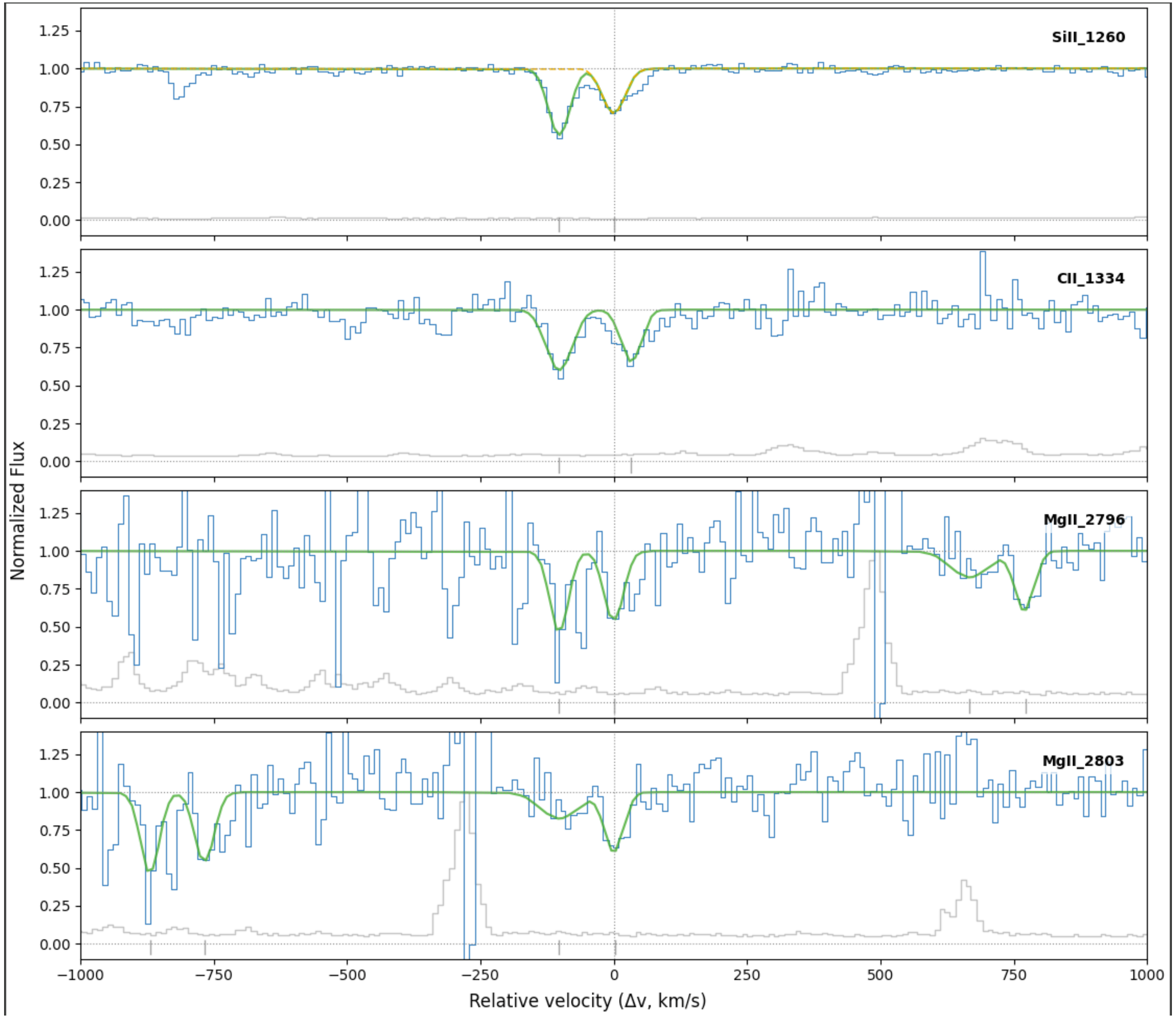
Intervening absorbers in J159-02 spectrum (3)



Kashino+ 2026

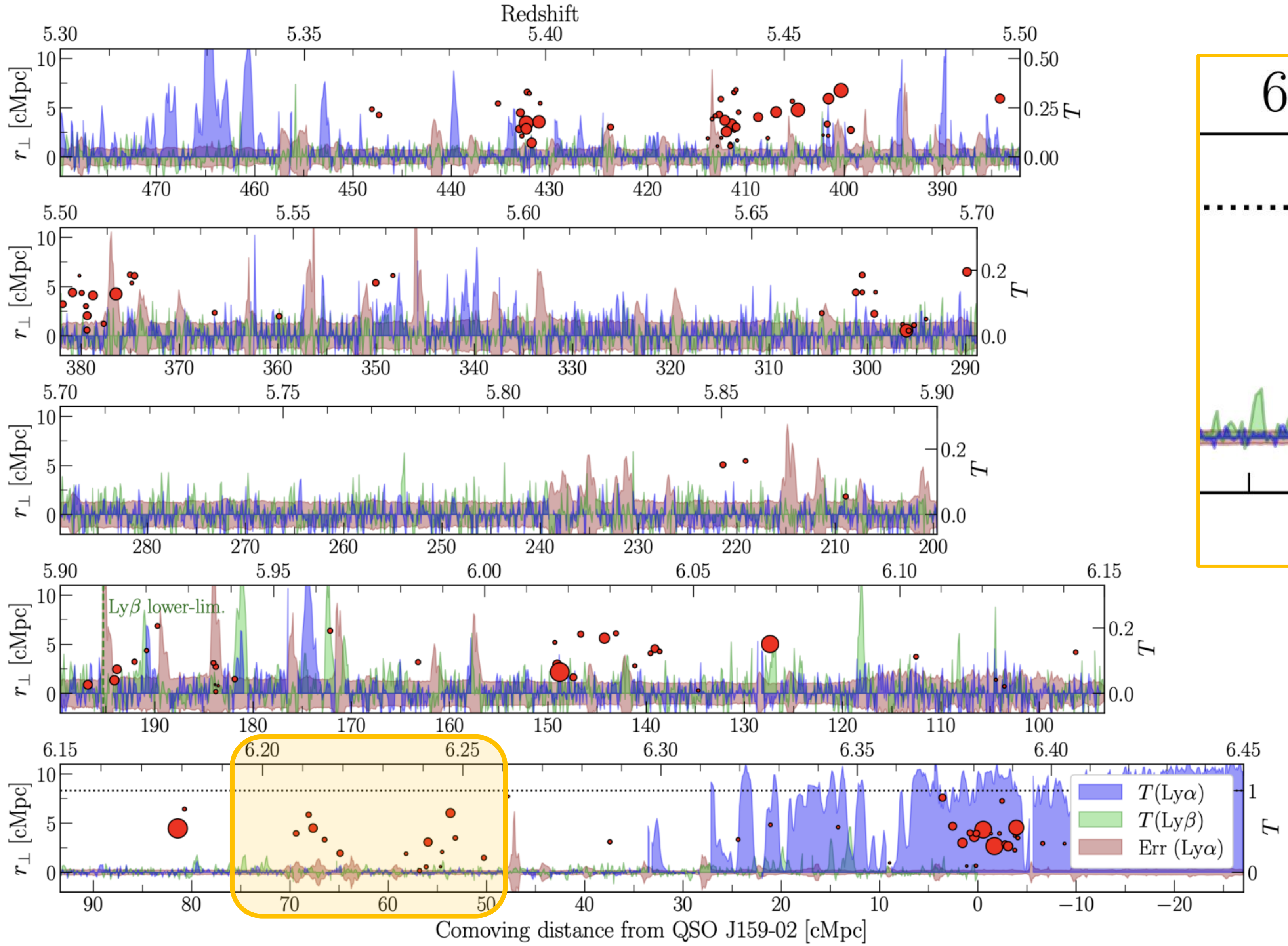
Intervening absorbers in J159-02 spectrum (4)

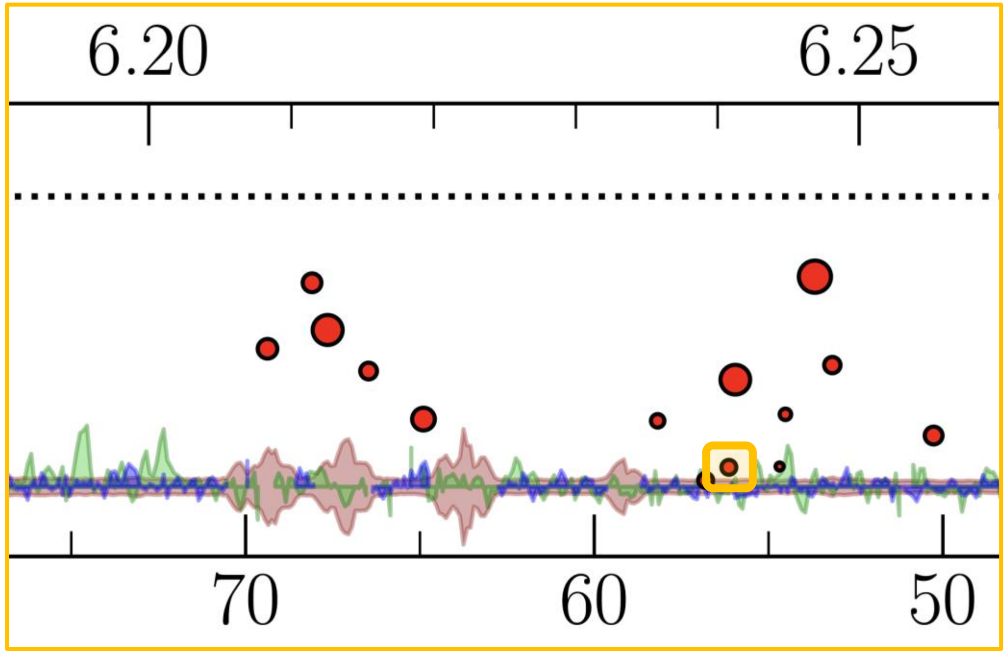


Absorption system at $z \sim 6.23941$

Software used: *Astrocook* (Cupani+ 2020)

Intervening absorbers in J159-02 spectrum (4)





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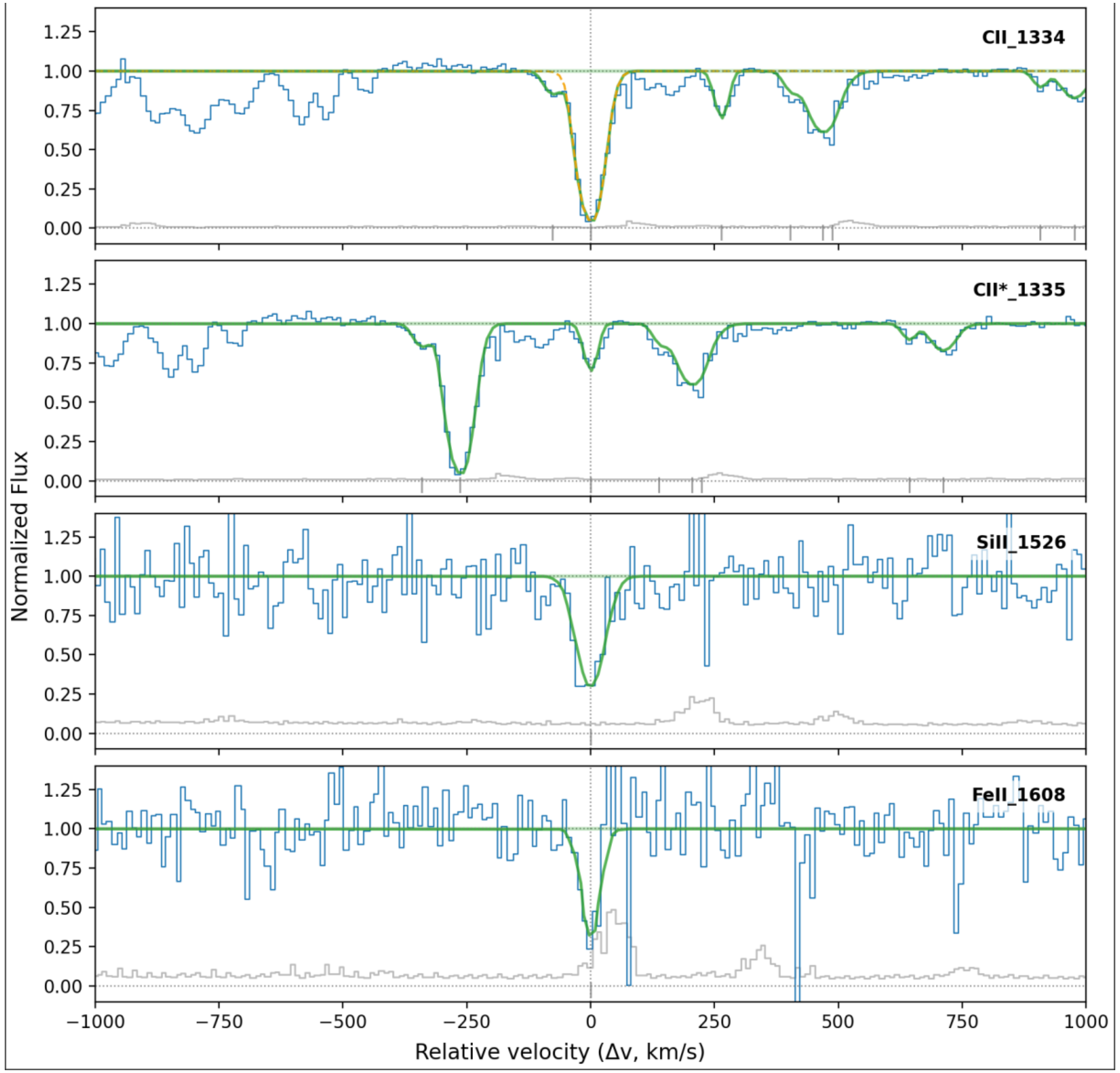
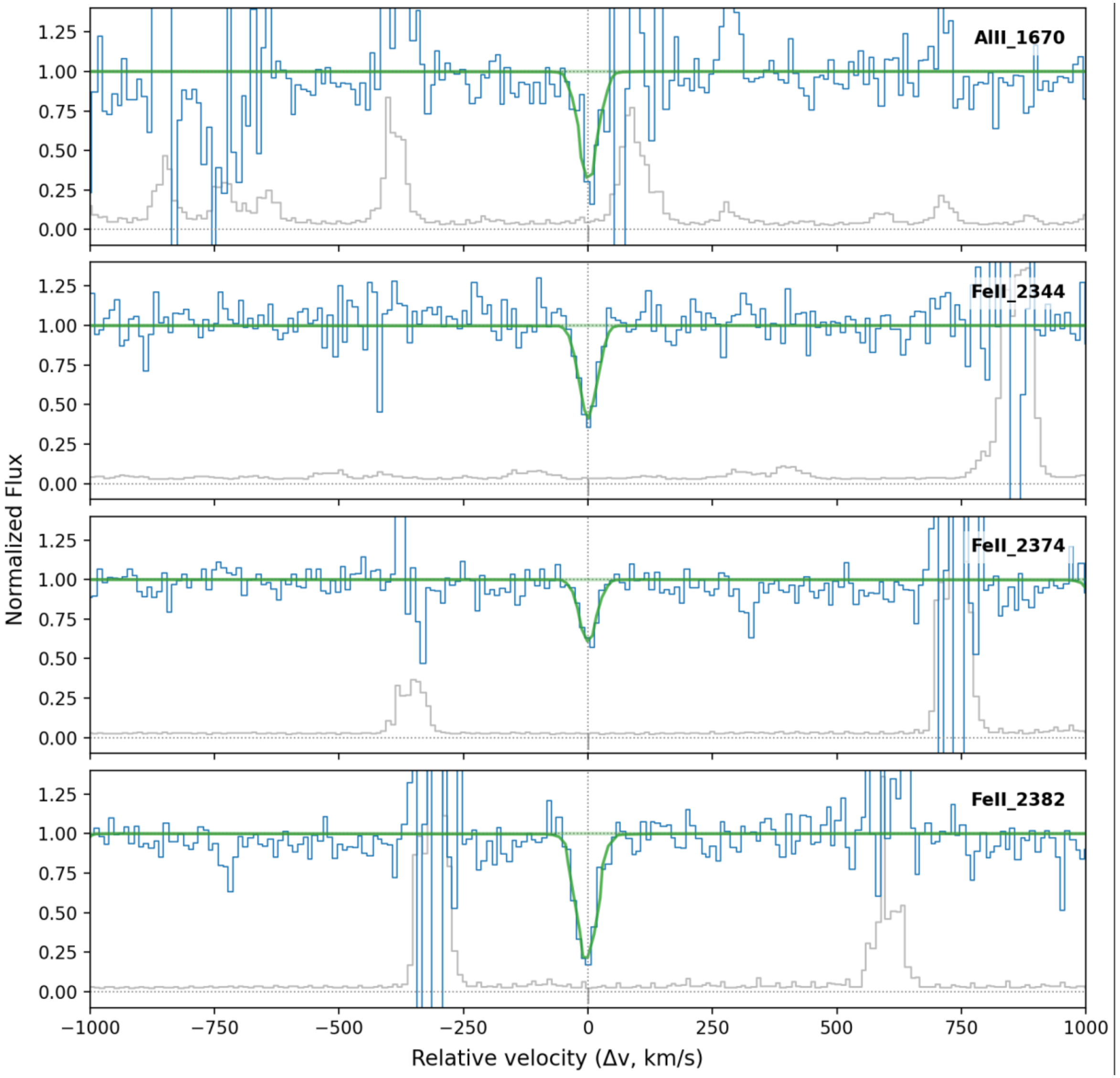
Intervening absorbers in J159-02 spectrum (5)

Absorption system at $z \sim 5.73491$





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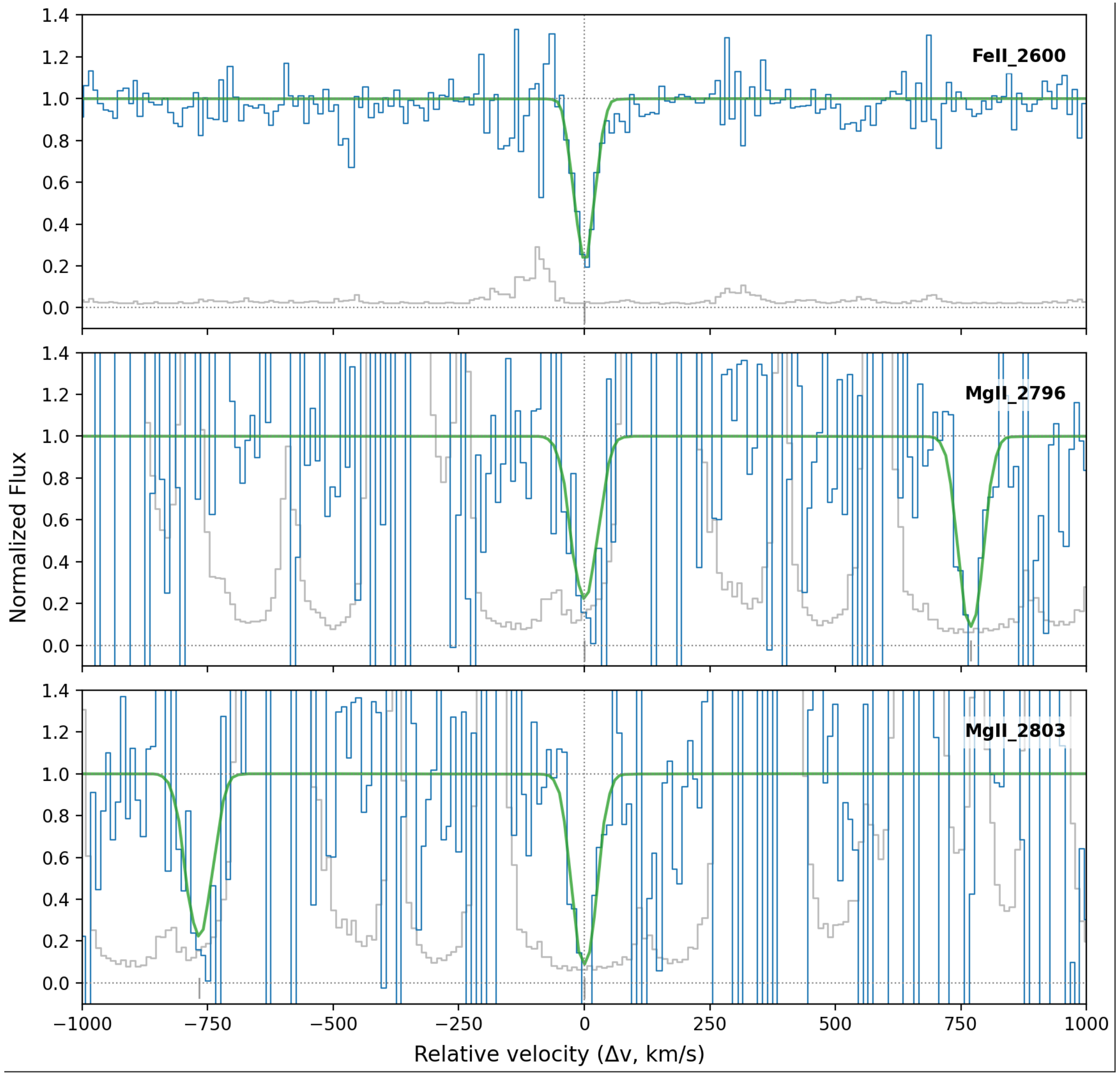
Intervening absorbers in J159-02 spectrum (5)



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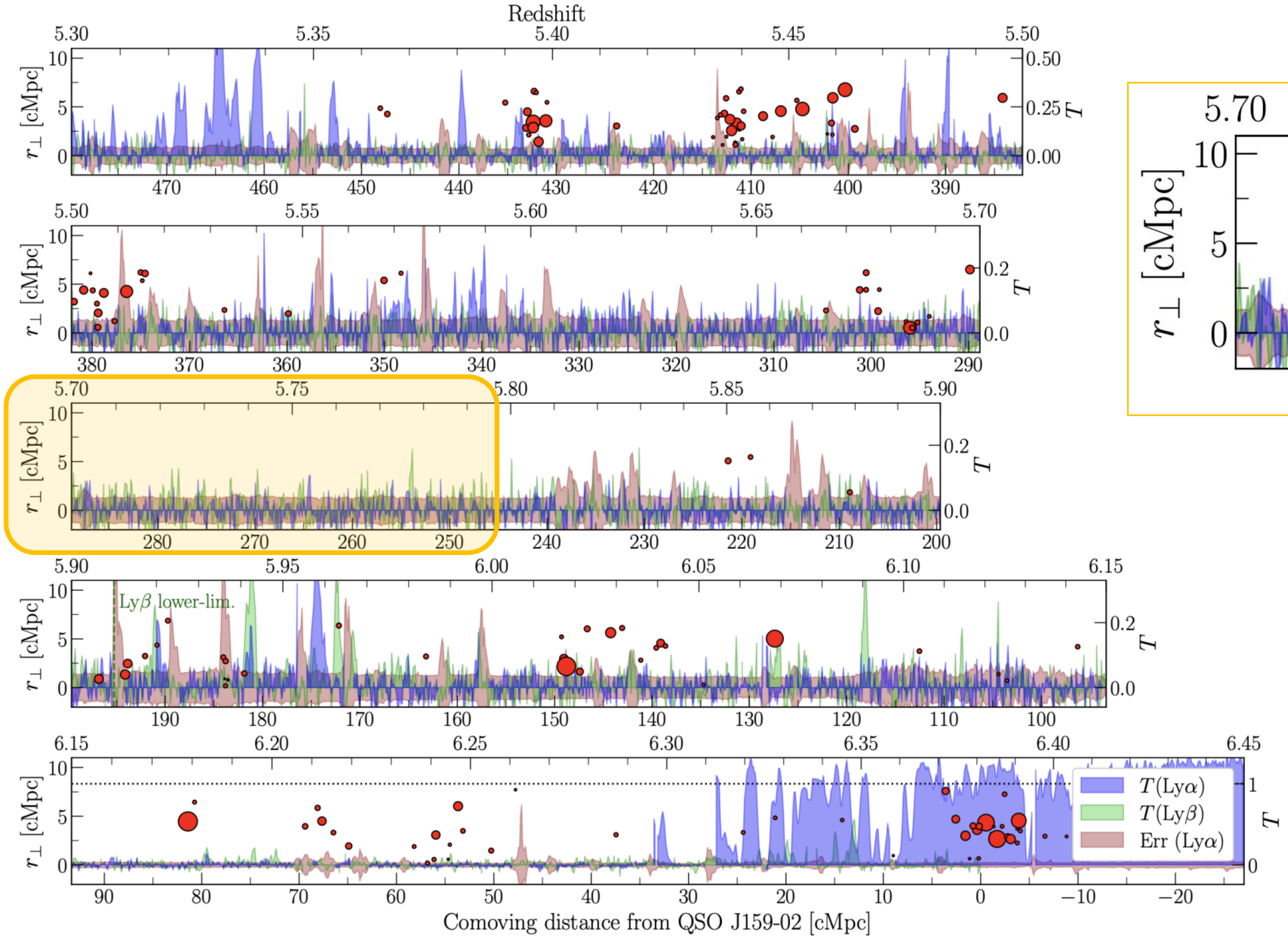
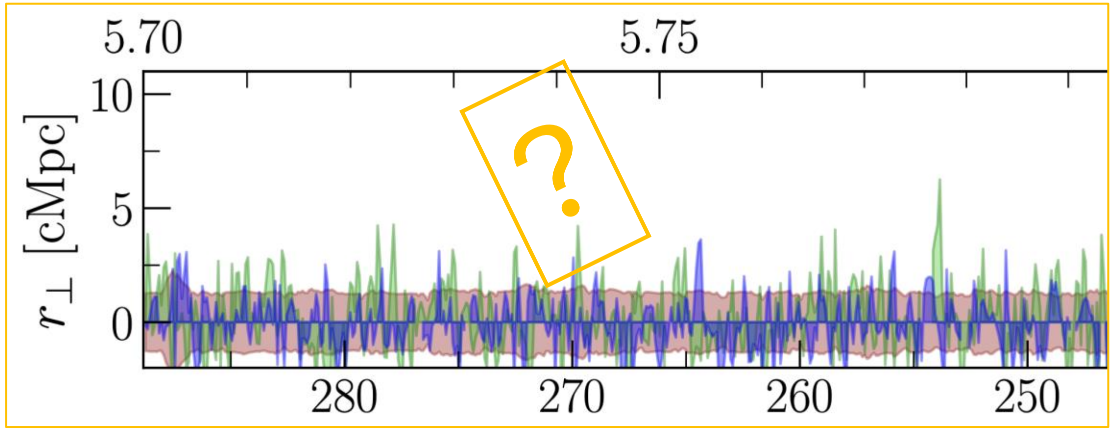




Low ionization absorption system without [O III] emitters counterpart!

Kashino+ 2026

Summary and Conclusion

- We reduced 2D raw spectroscopic data of the quasar PSOJ159-02 using ***PypeIt*** (Prochaska et al. 2020)

- Analysis of the continuum and emission lines, with a focus on C IV and Mg II

- BH mass and λ_{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
$$\boldsymbol{L_{bol} = 5.15 \times \lambda L_{\lambda}(3000\,\text{Å})\; erg/s = (3.01 \pm 0.03) \times 10^{47}\; erg/s}$$

Mg II BH mass

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

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

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

C IV BH mass

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

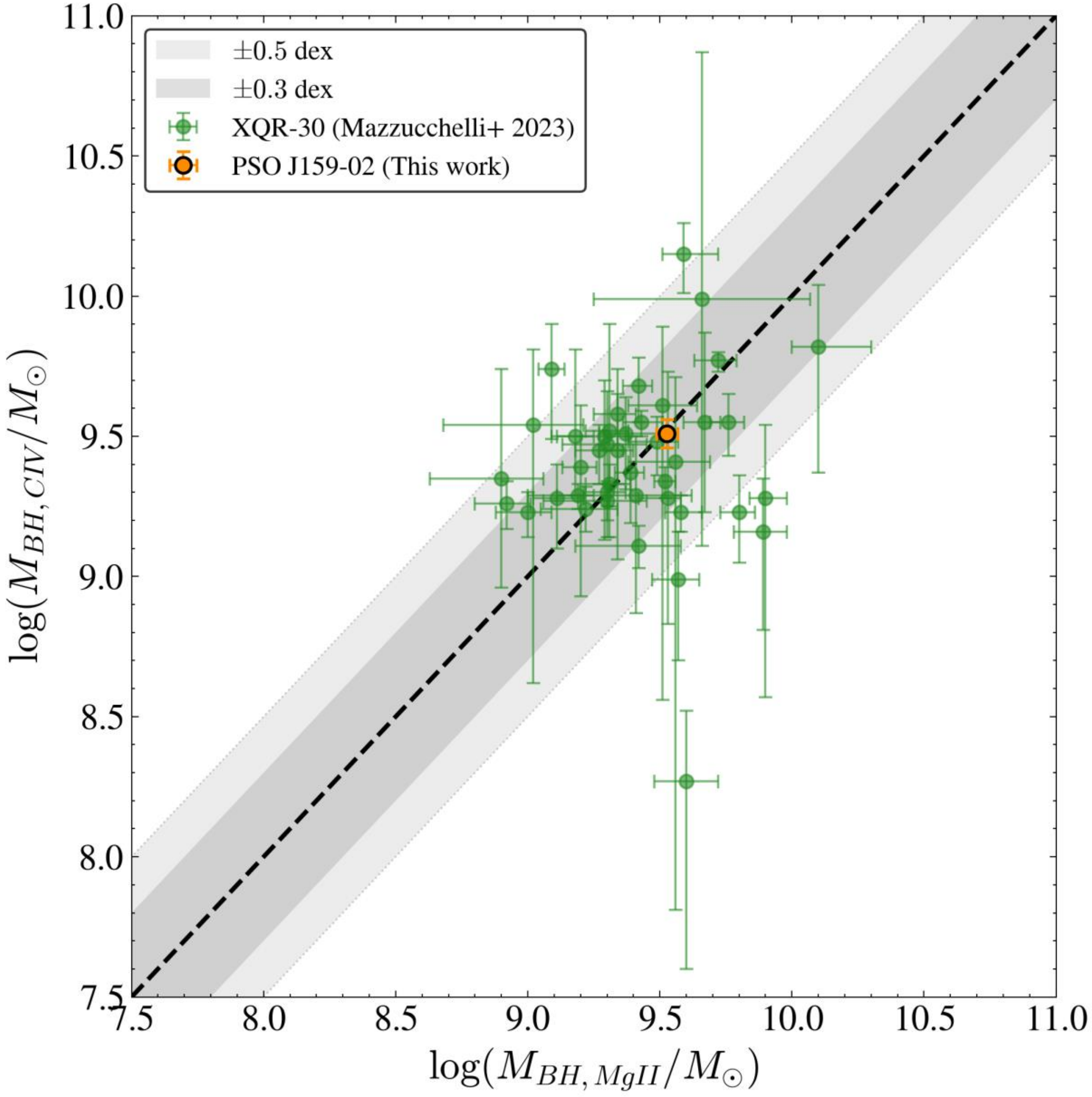
$$M_{\rm BH,CIV} = 10^{6.66} \left[\frac{FWHM_{\rm C\,IV,corr}}{10^3\ {\rm km\,s^{-1}}}\right]^2 \left[\frac{\lambda L_\lambda\,(1350\,\text{Å})}{10^{44}\ {\rm erg\,s^{-1}}}\right]^{0.53} M_\odot$$

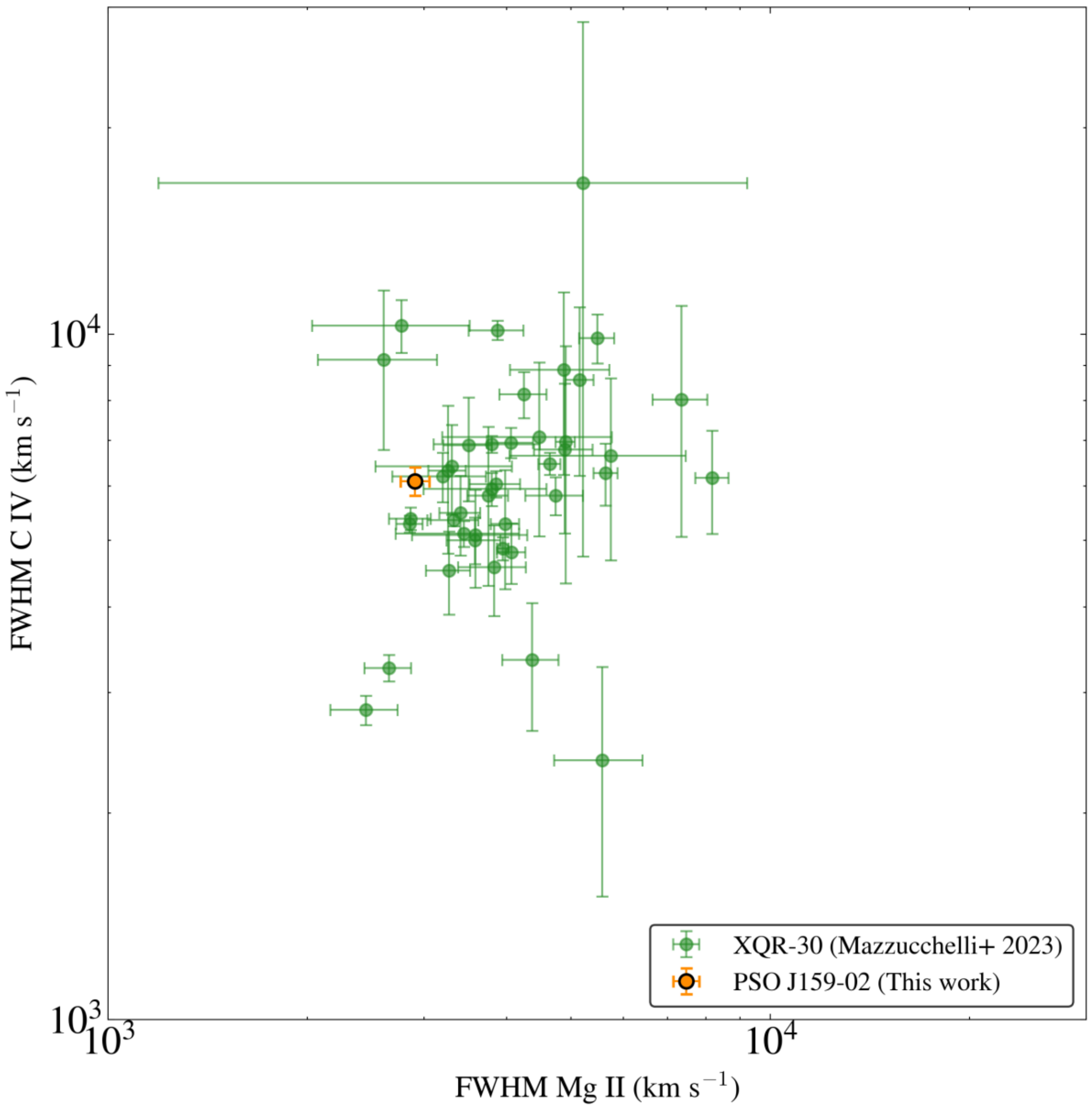
$$\log\left(\frac{M_{BH,C\ IV}}{M_\odot}\right) = 9.51 \pm 0.05$$

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

→ **Excellent agreement!**

Rest-frame UV properties – comparison with literature





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