Towards a Better Understanding of Lyman Photon Escape in z > 3 Lyman-α Emitters in the JWST Era

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Kolymvari, Crete
19 April 2023

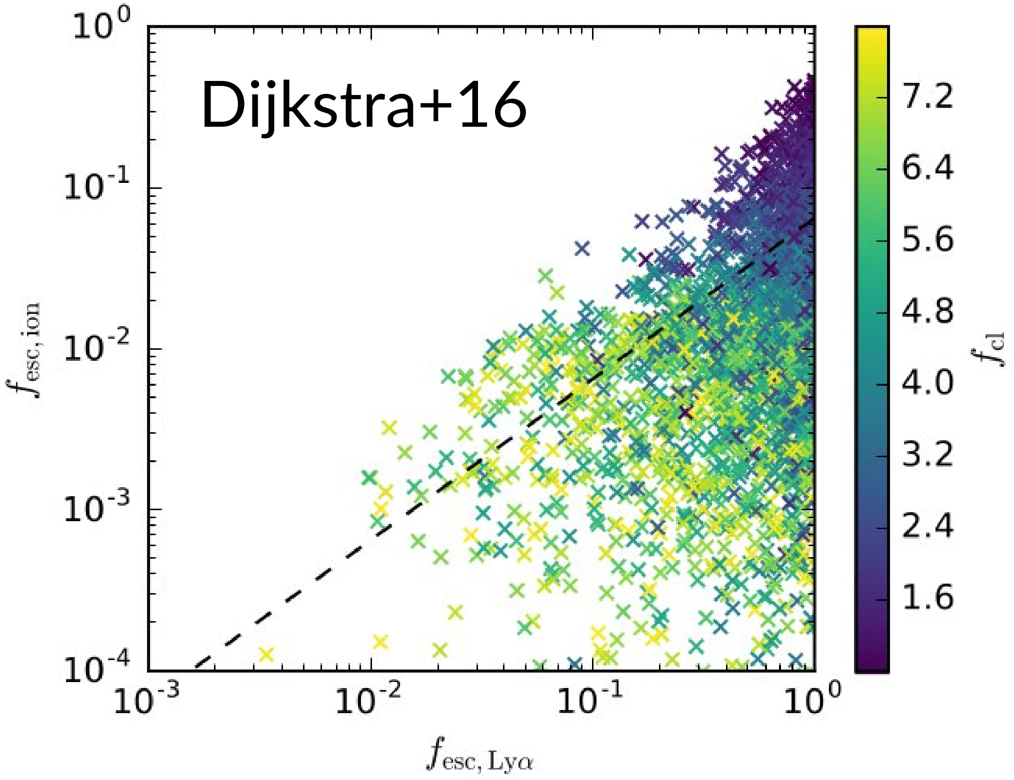
Role of LAEs in Cosmic Reionization

$f_{\rm esc}^{\rm LyC} \lesssim f_{\rm esc}^{\rm Ly\alpha}$ (e.g., Gazagnes+20, Izotov+20, Dijkstra+16, Kimm+21)

$\rightarrow$ LAEs might dominate the ionizing photon budget of SFGs at the EoR (e.g., Matthee+22)

How efficiently do Lyα photons escape at z > 5 (velocity offsets, $f_{\rm esc}^{\rm Ly\alpha}$)?

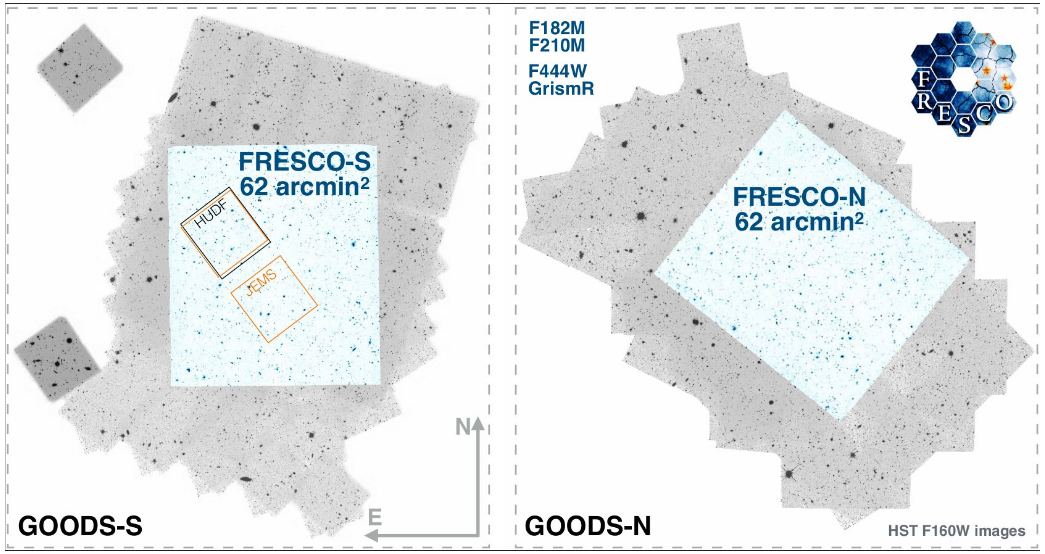
Idea: perform a joint analysis of Lyα (MUSE-Wide, MUSE HUDF) and rest-optical emission lines, e.g. Hα (JWST)



FRESCO: **F**irst **R**eionization **E**poch **S**pectroscopically **C**omplete **O**bservations

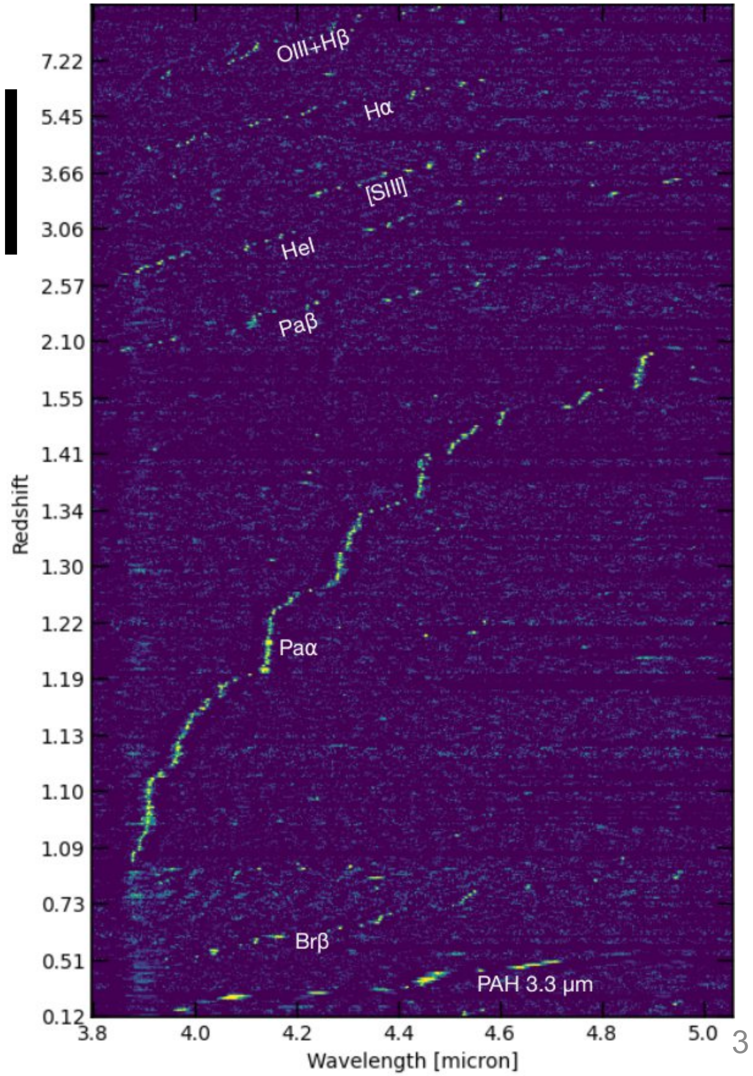
JWST Cycle 1 medium program (Oesch+23)

NIRCam/grism observations of the two CANDELS/Deep fields



- Slitless spectra at 3.9-4.9 micron (R~1600)
- Medium band imaging at 1.8-2.1 micron

covered by MUSE



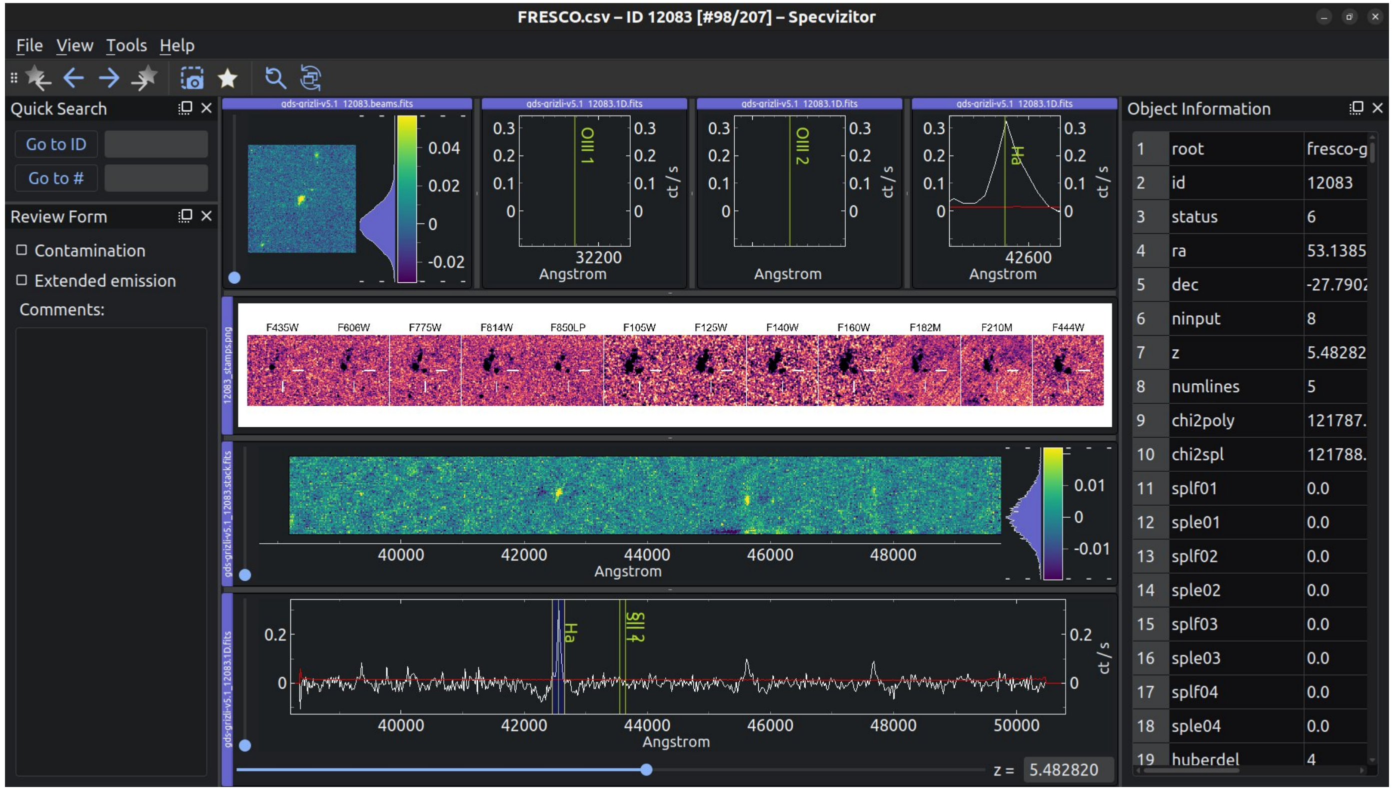
Data Processing

Spectral extraction Grizli Brammer+14

Visual inspection

`specvizitor` @J.Kerutt

```
$ pip install specvizitor
```

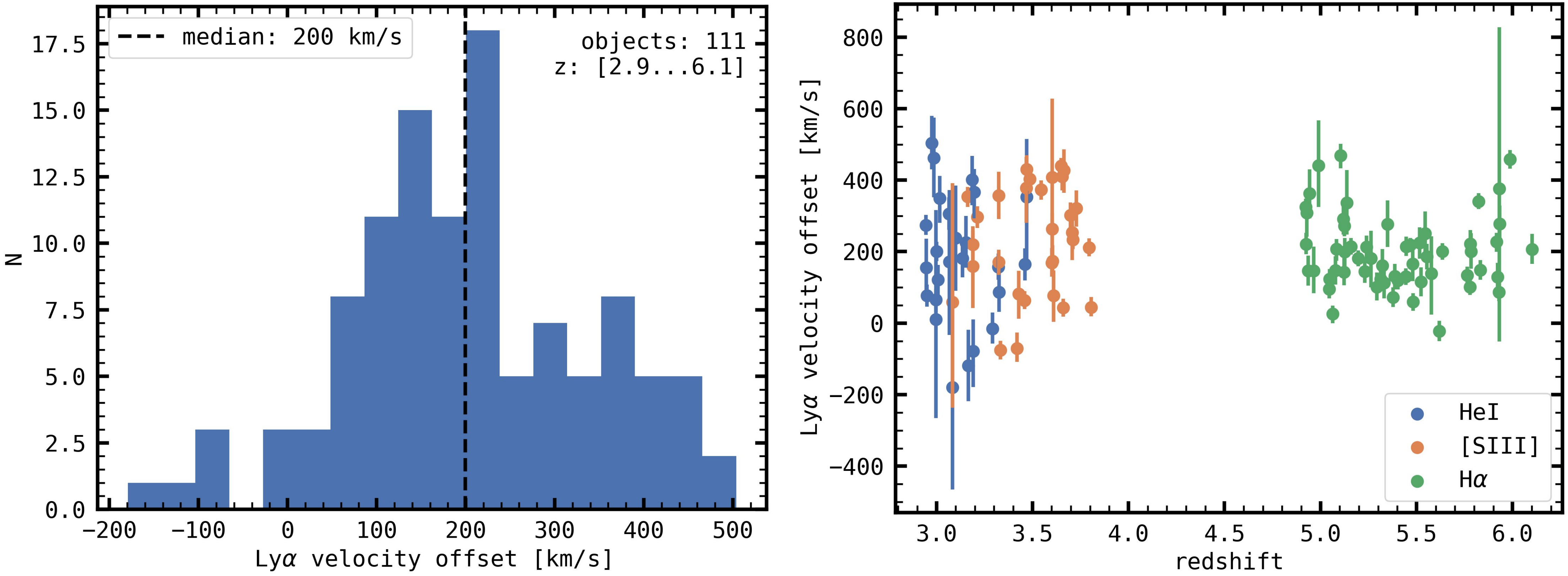


Final Sample

111 LAEs at 2.9 < z < 6.2
with JWST redshifts

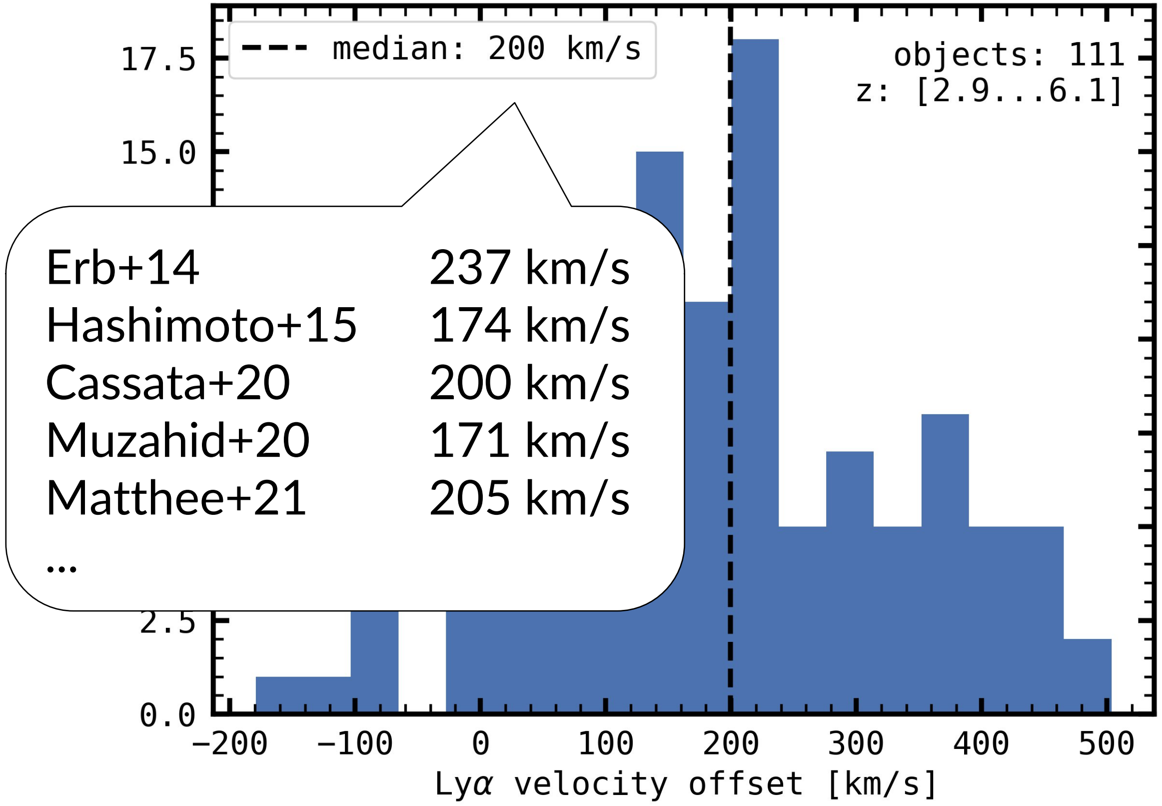
https://github.com/ivkram/specvizitor

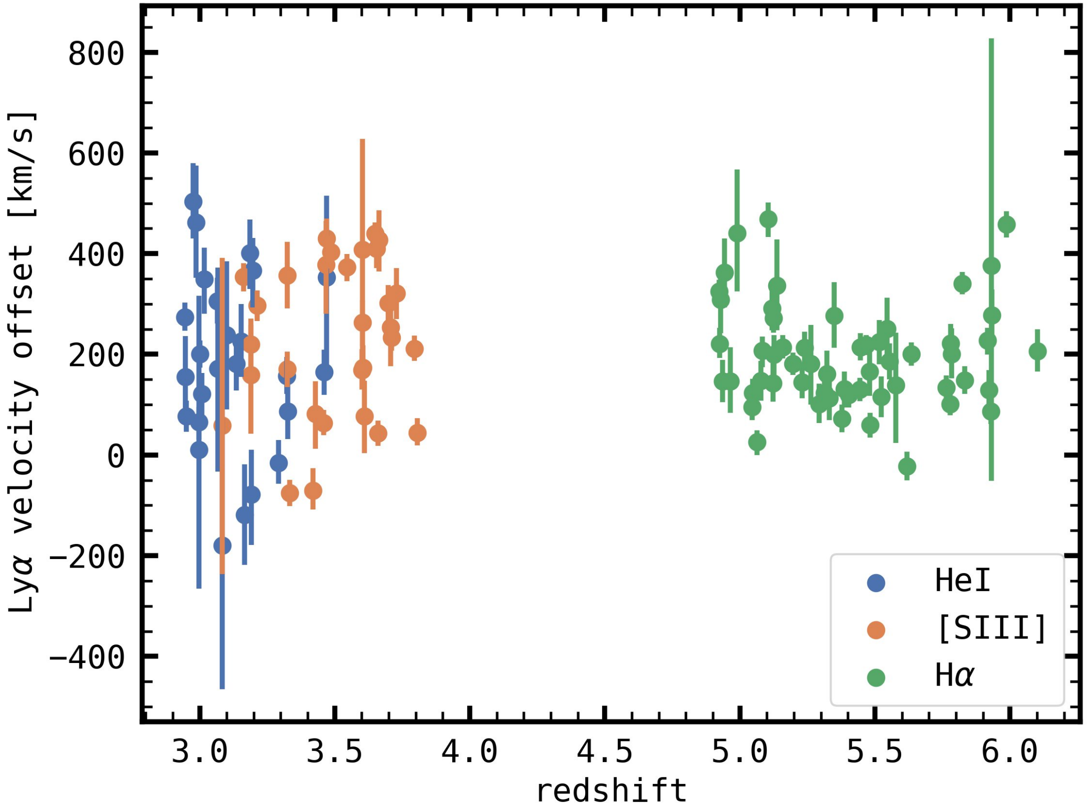
Escape: Lyα Velocity Offset



— the largest sample of Lyα velocity offsets at $z > 3$

Escape: Lyα Velocity Offset





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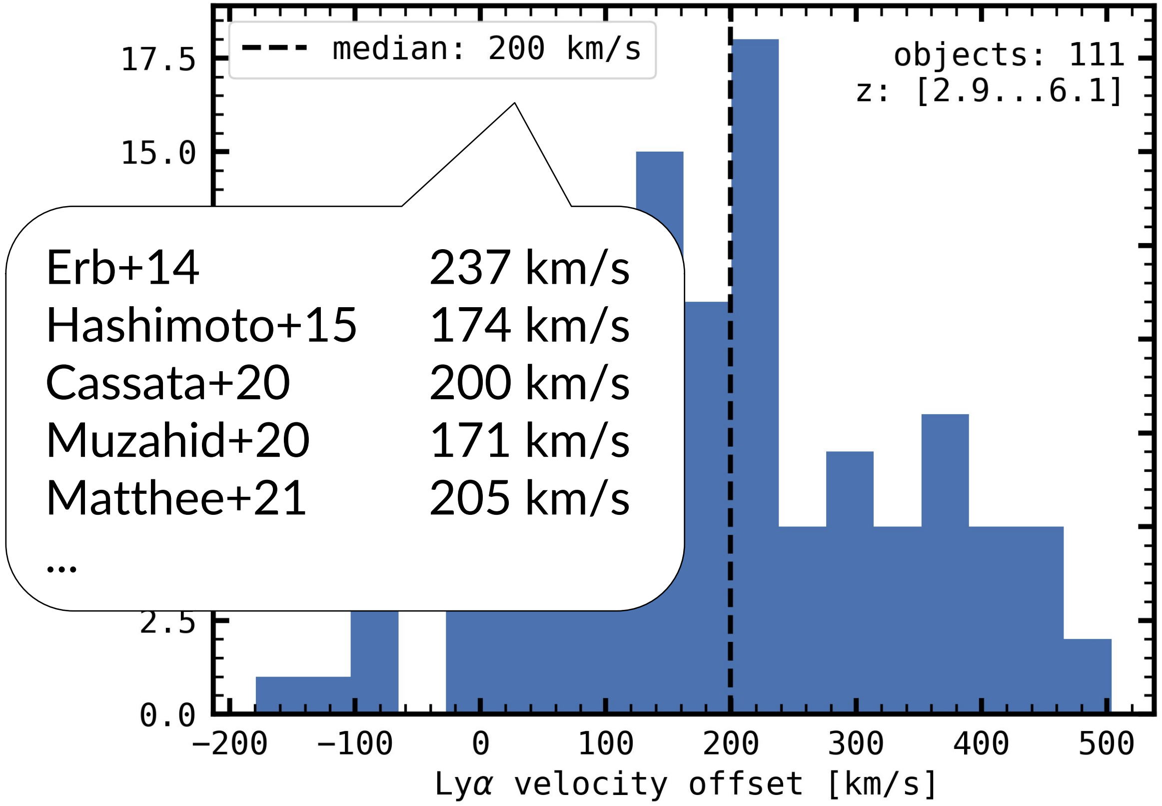
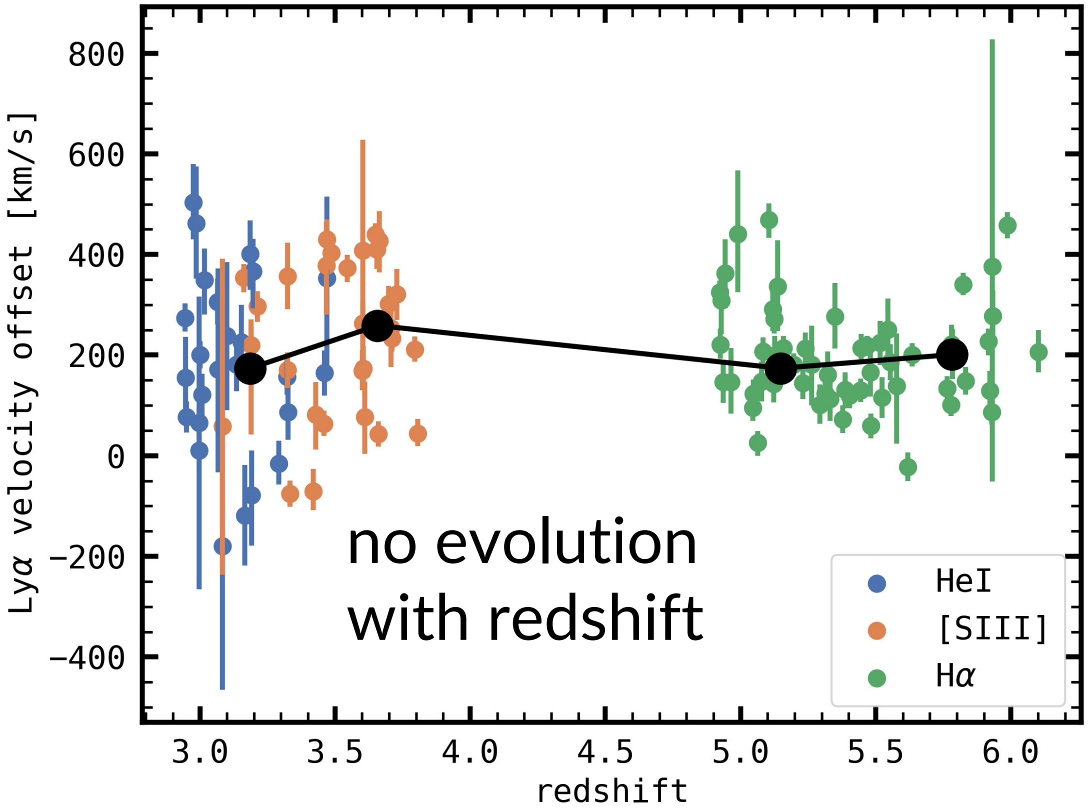


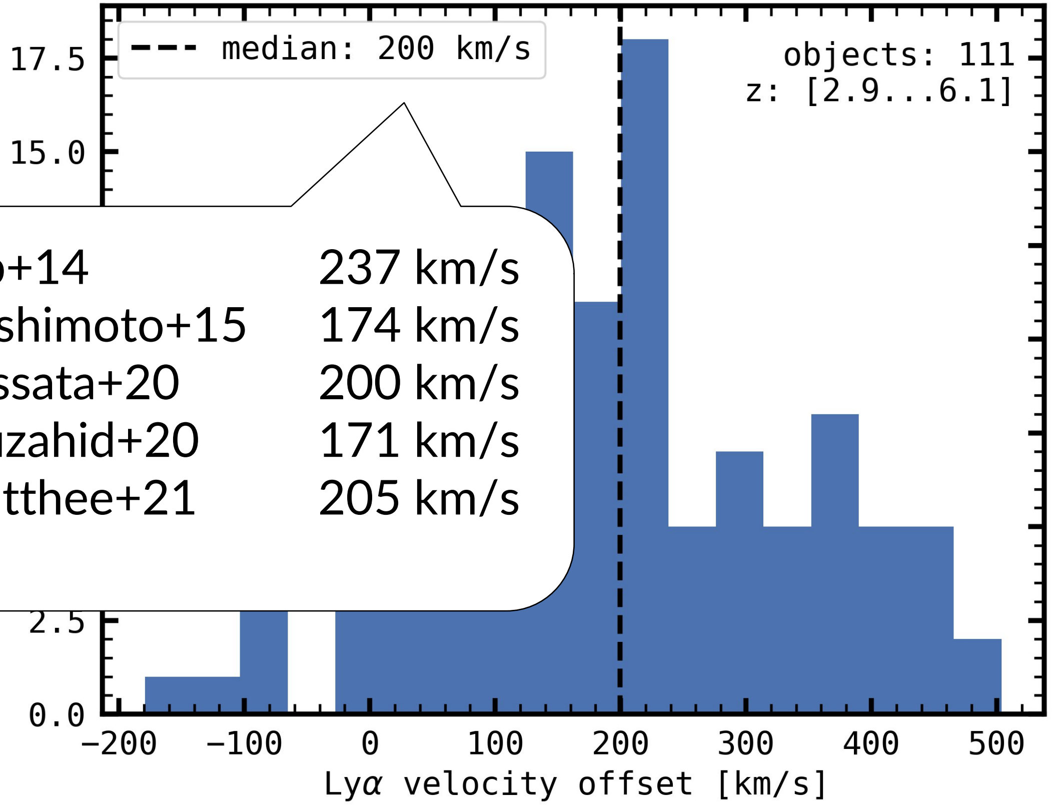


— the largest sample of Lyα velocity offsets at $z > 3$

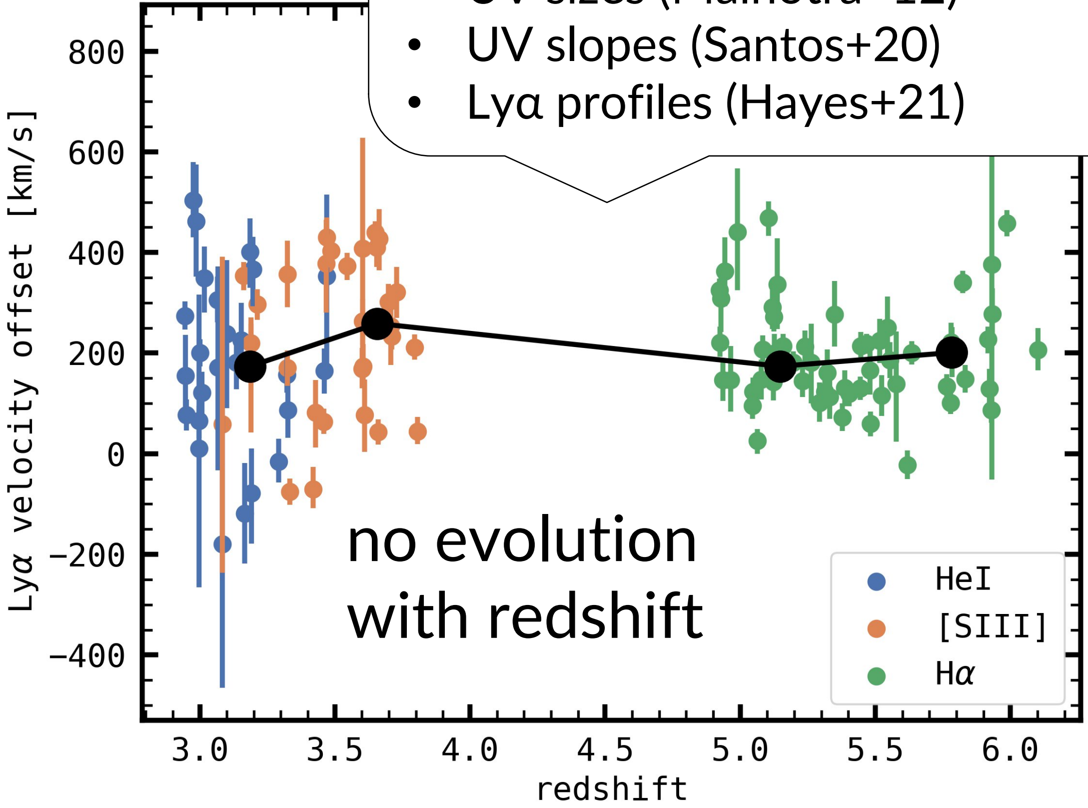
Escape: Lyα Velocity Offset

Redshift invariance of fundamental properties of LAEs ($z \approx 2-6$), e.g.:

- UV sizes (Malhotra+12)
- UV slopes (Santos+20)
- Lyα profiles (Hayes+21)



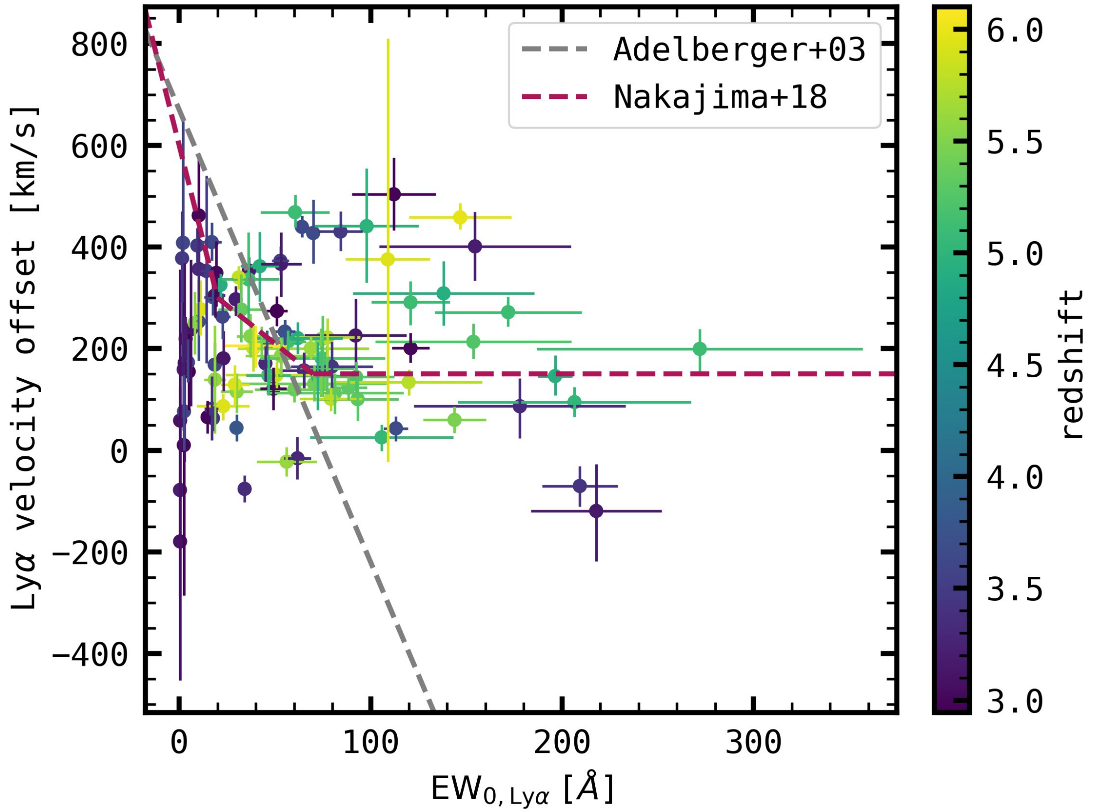
Erb+14	237 km/s
Hashimoto+15	174 km/s
Cassata+20	200 km/s
Muzahid+20	171 km/s
Matthee+21	205 km/s
…	

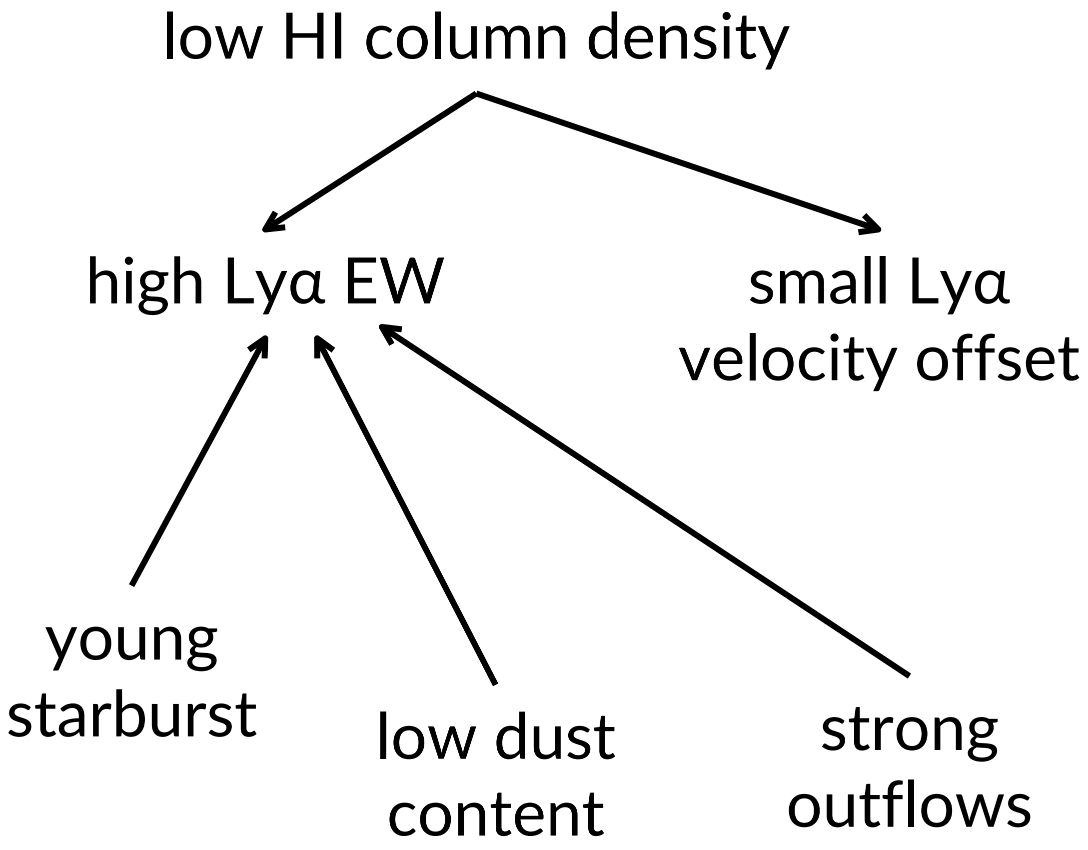


no evolution with redshift

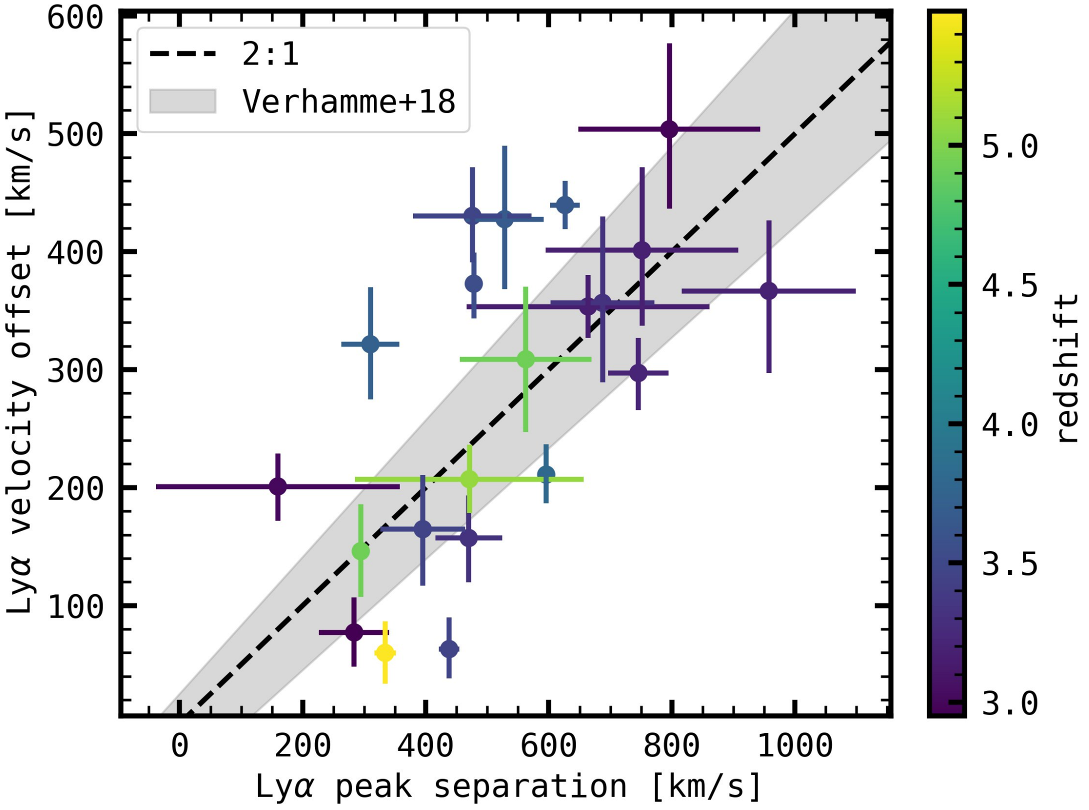
— the largest sample of Lyα velocity offsets at $z > 3$

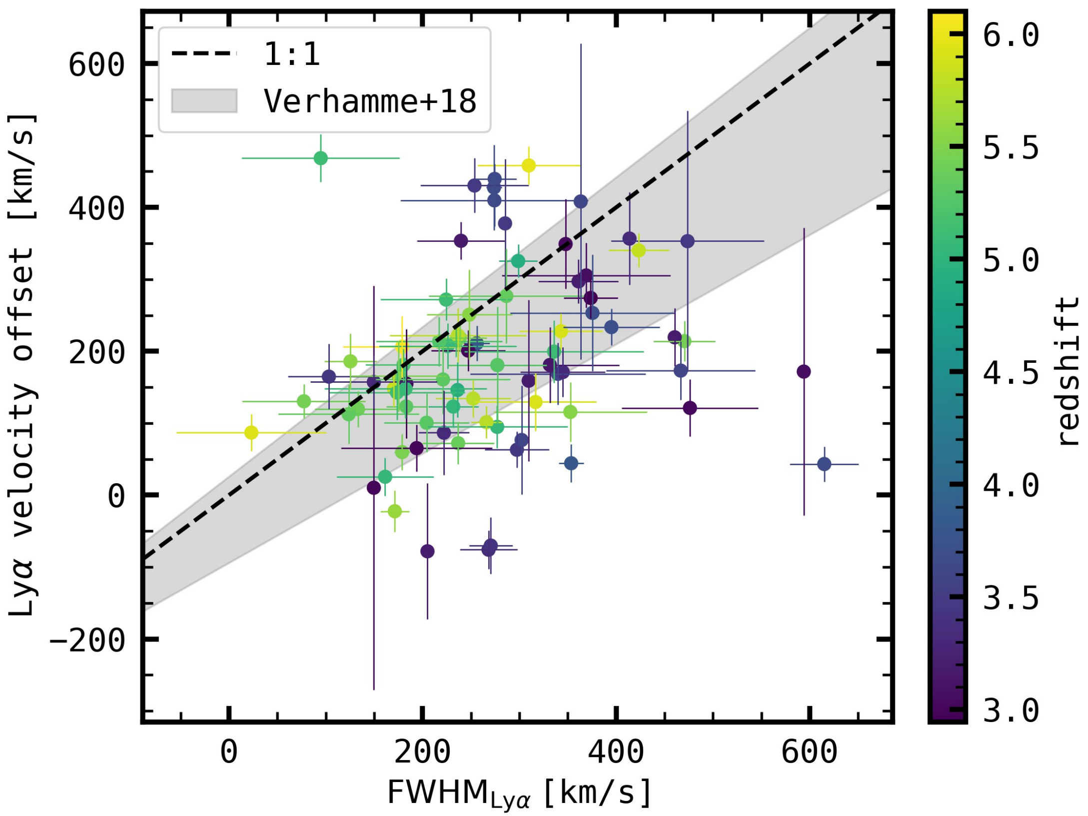
Lyα Velocity Offset vs. Lyα Equivalent Width





Recovering Systemic Redshifts





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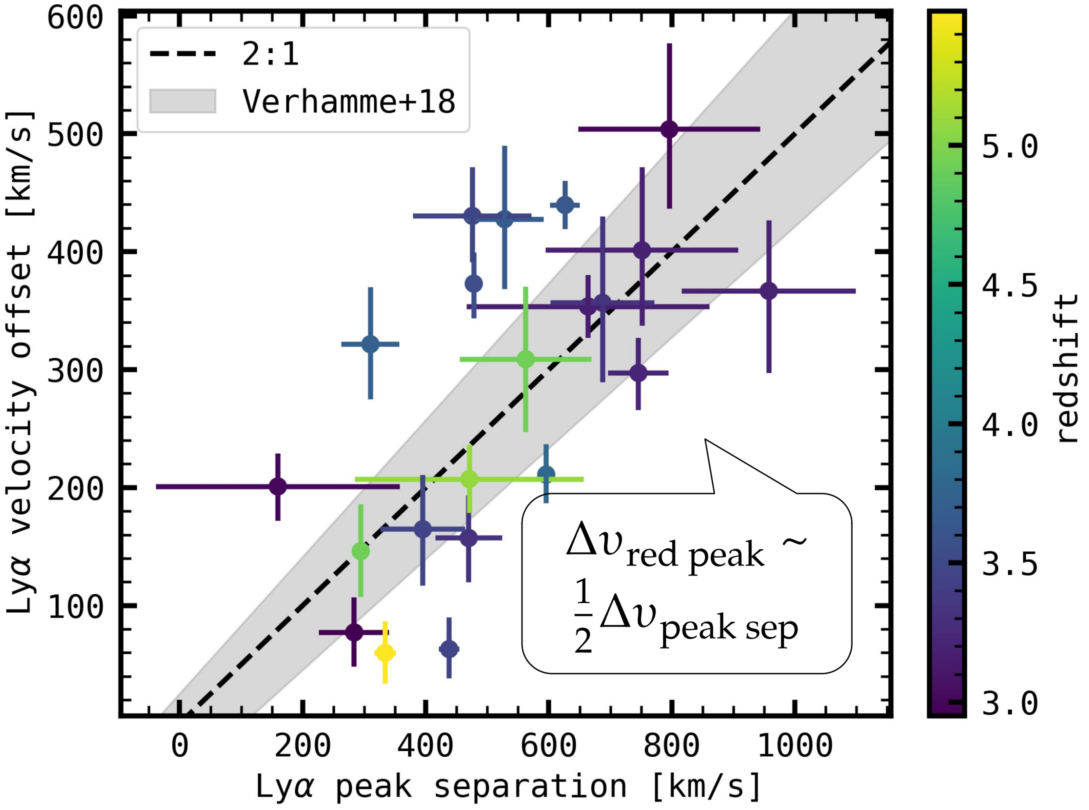

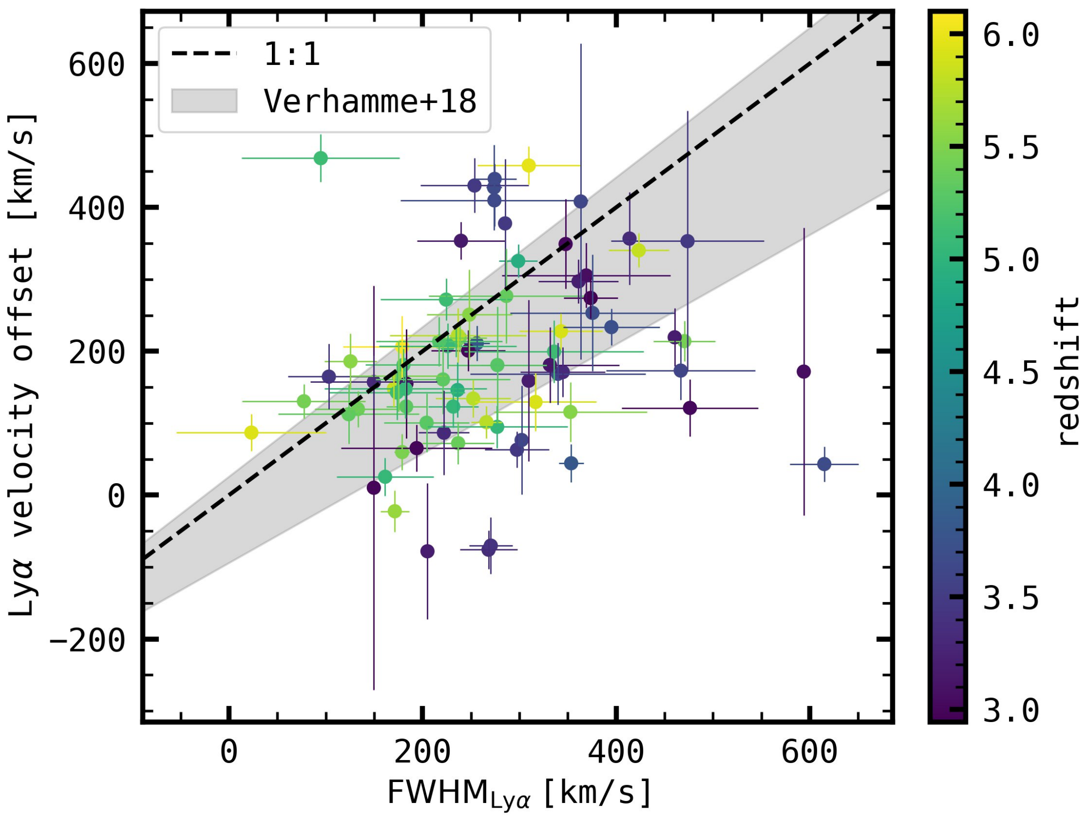

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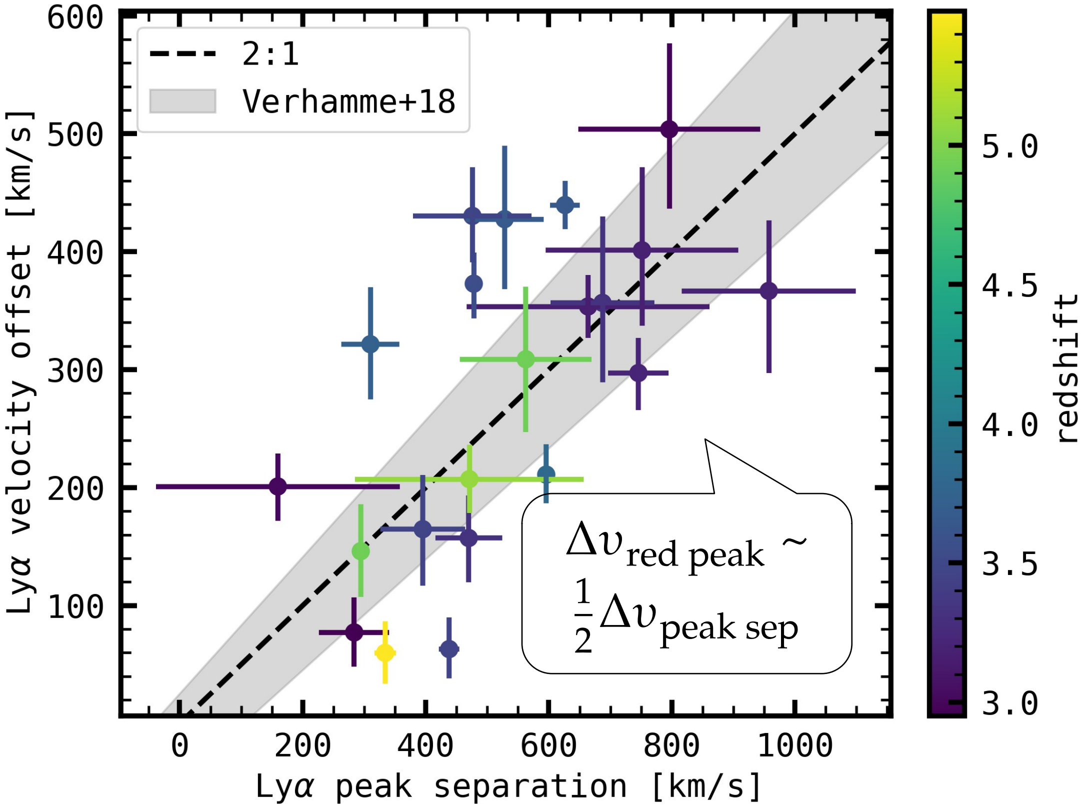
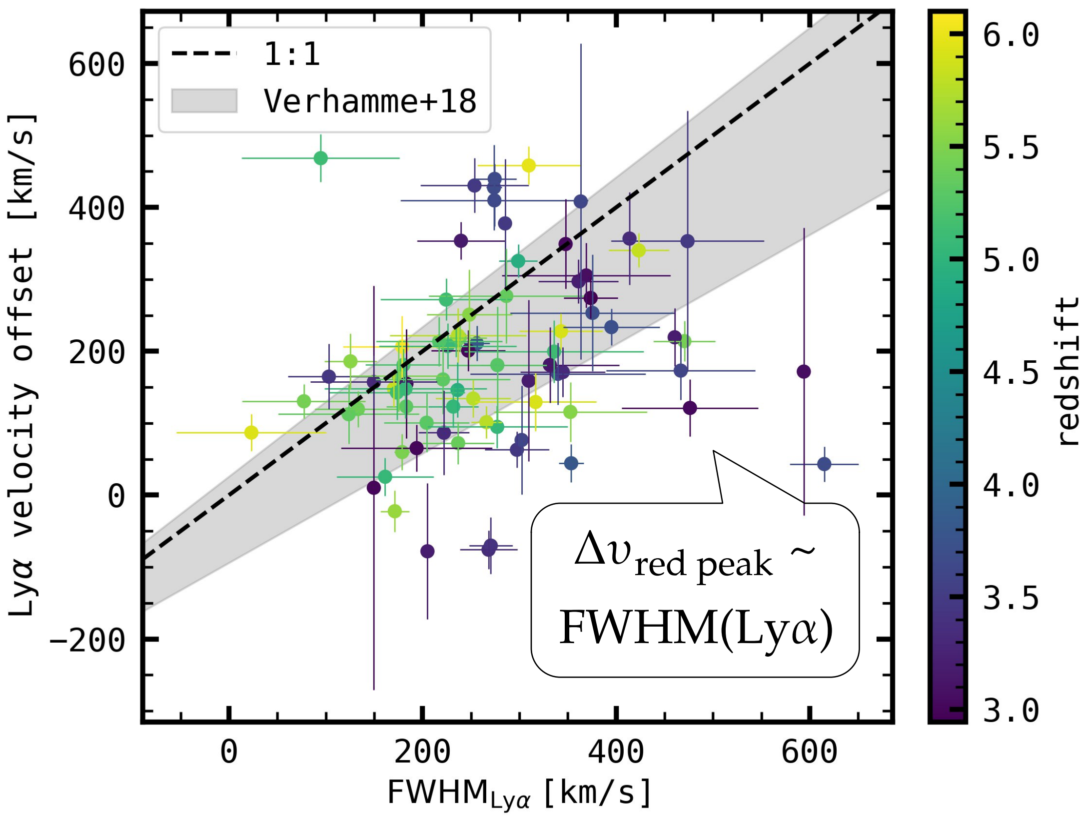
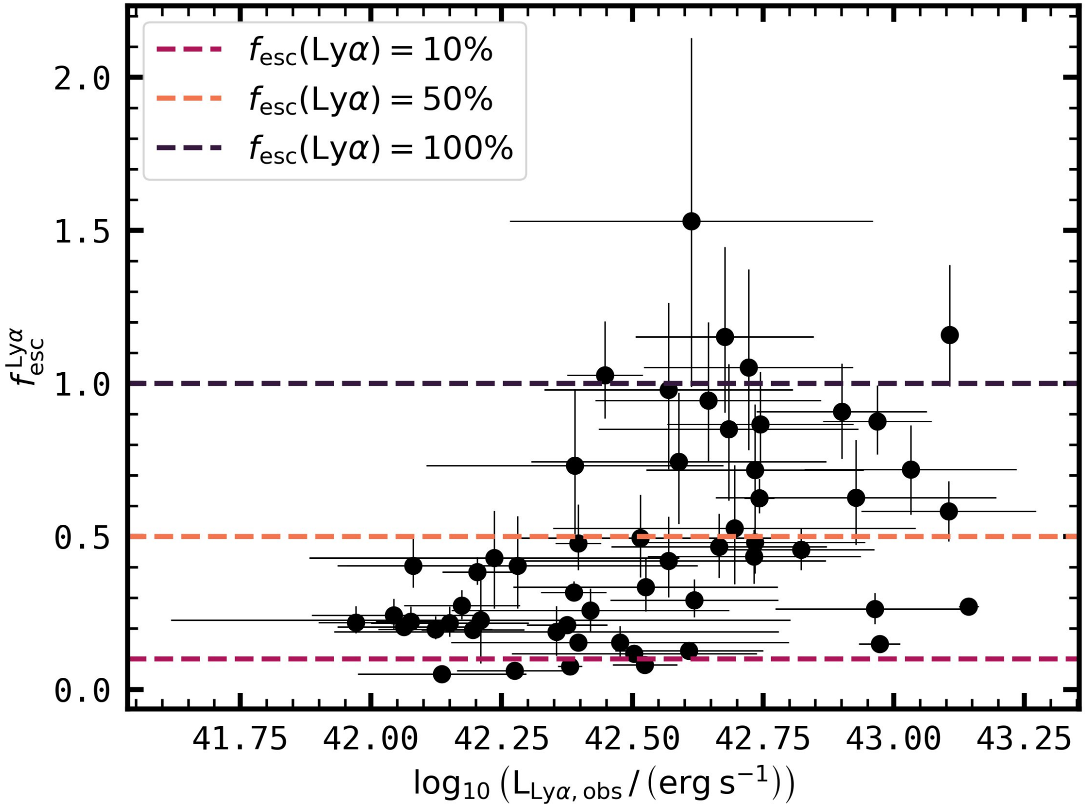




Escape: Lyα Escape Fraction



Case B recombination:

$$f_{esc}^{Ly\alpha} = \frac{L_{Ly\alpha,obs}}{L_{Ly\alpha,int}} = \frac{L_{Ly\alpha,obs}}{8.7 L_{H\alpha,int}}$$

Dust attenuation:

$$L_{H\alpha,int} = L_{H\alpha,obs} \times 10^{0.4E(B-V)_{neb} k_{H\alpha}}$$

– SED fitting with Bagpipes (Carnall+18)

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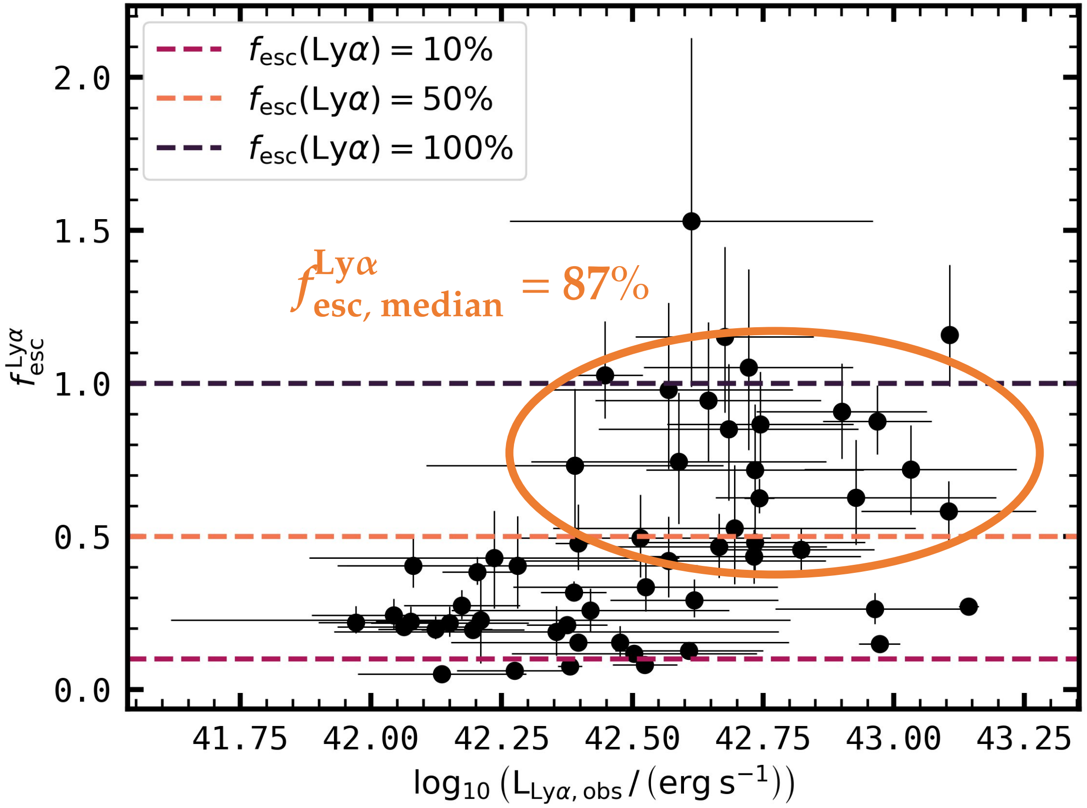

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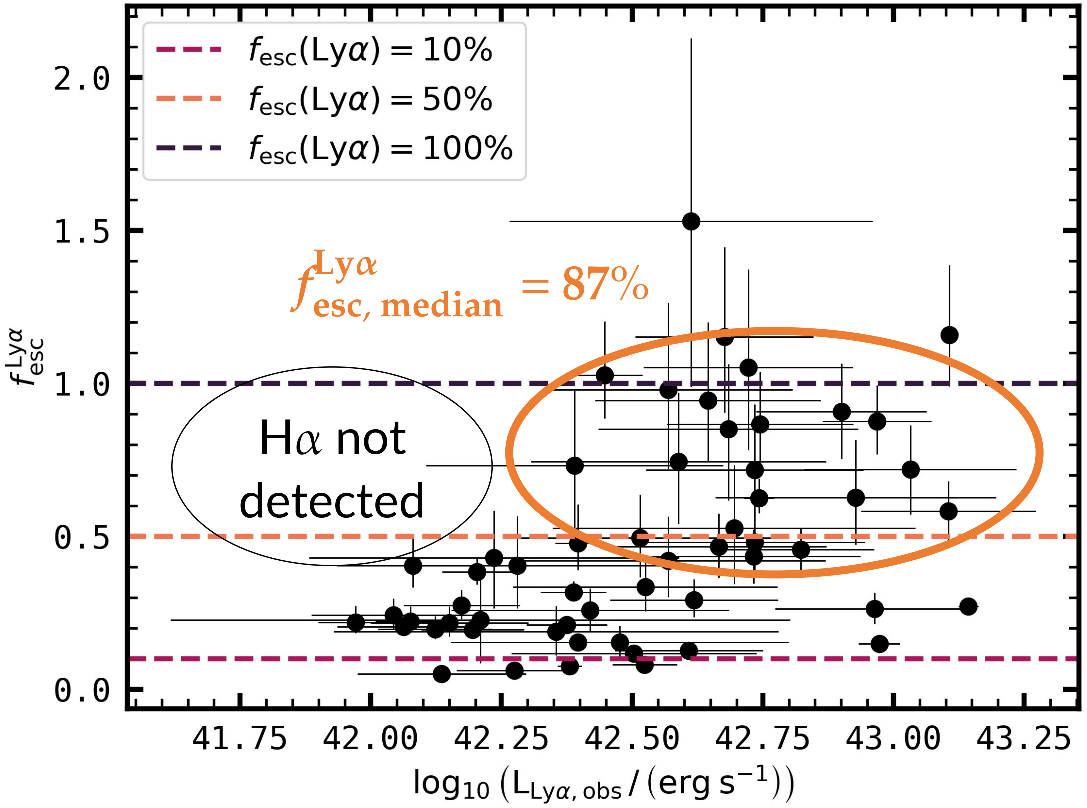

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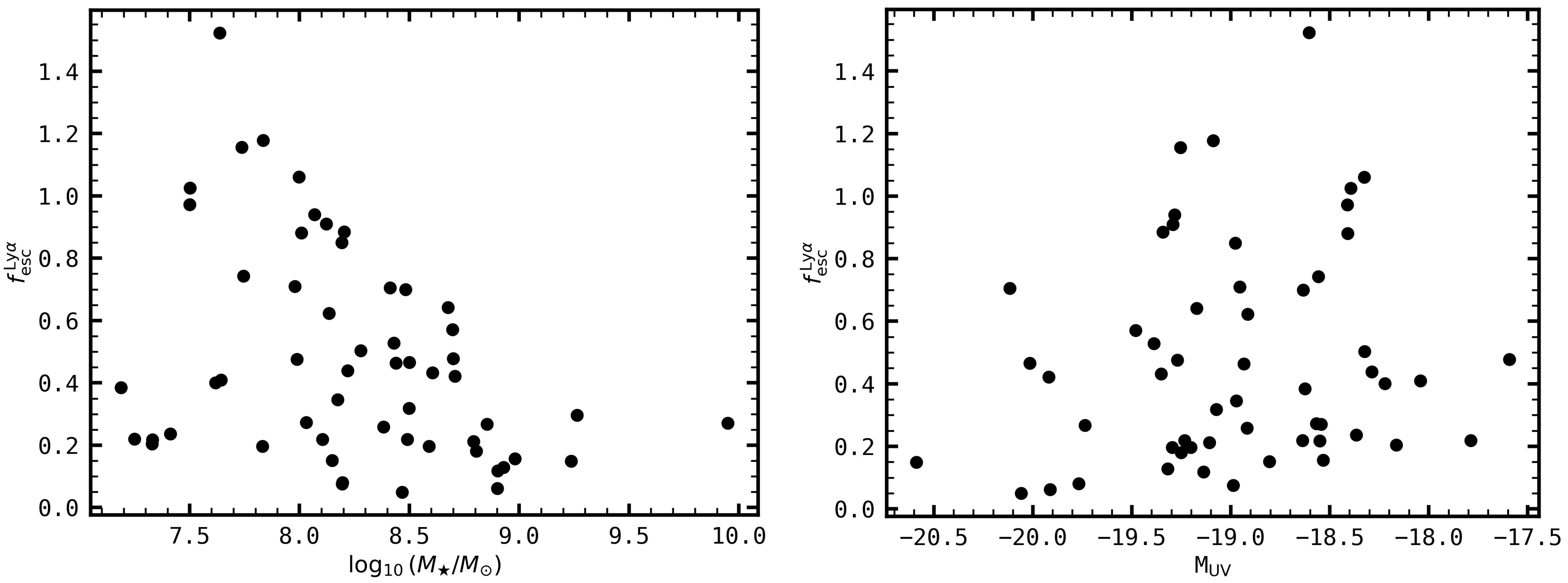
Lyα Escape Fraction vs. $M_\star$ and M_{UV}



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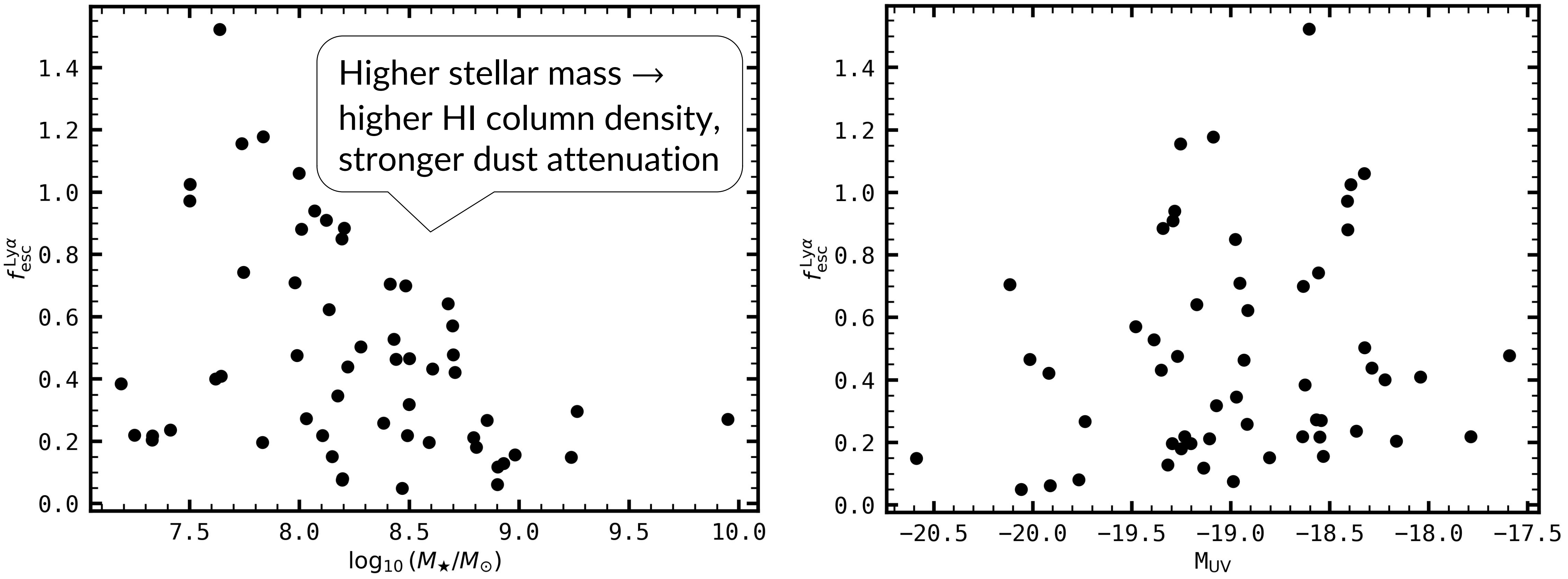
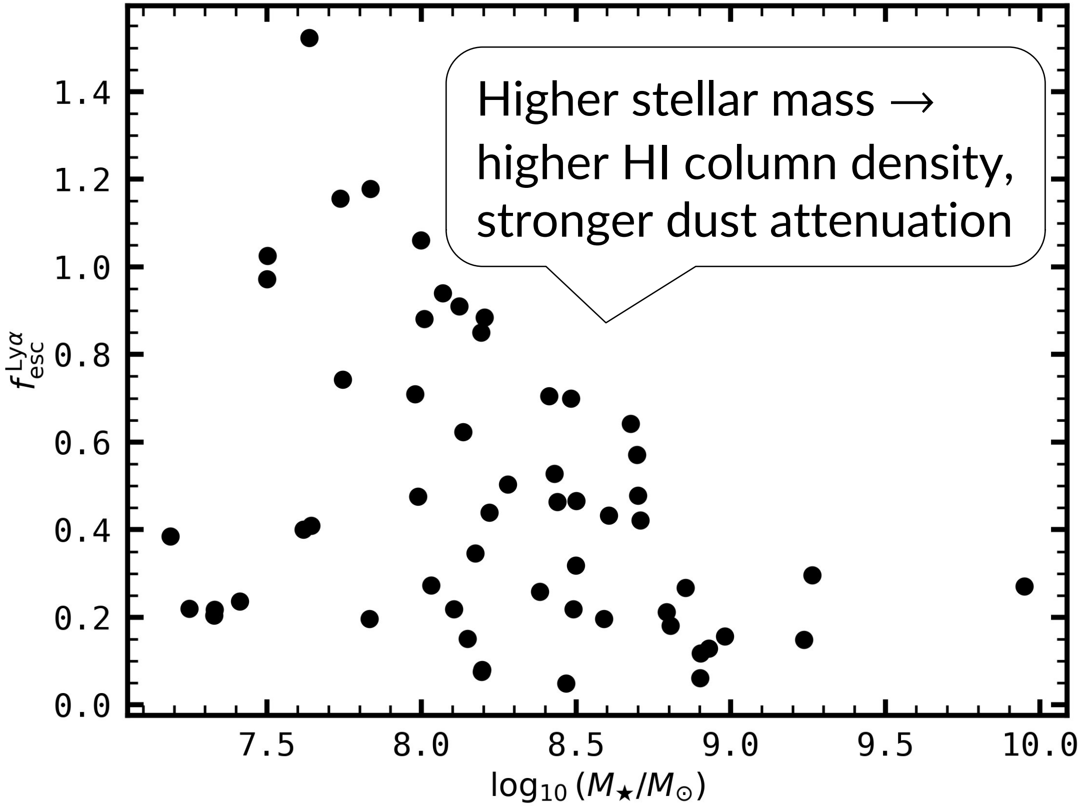
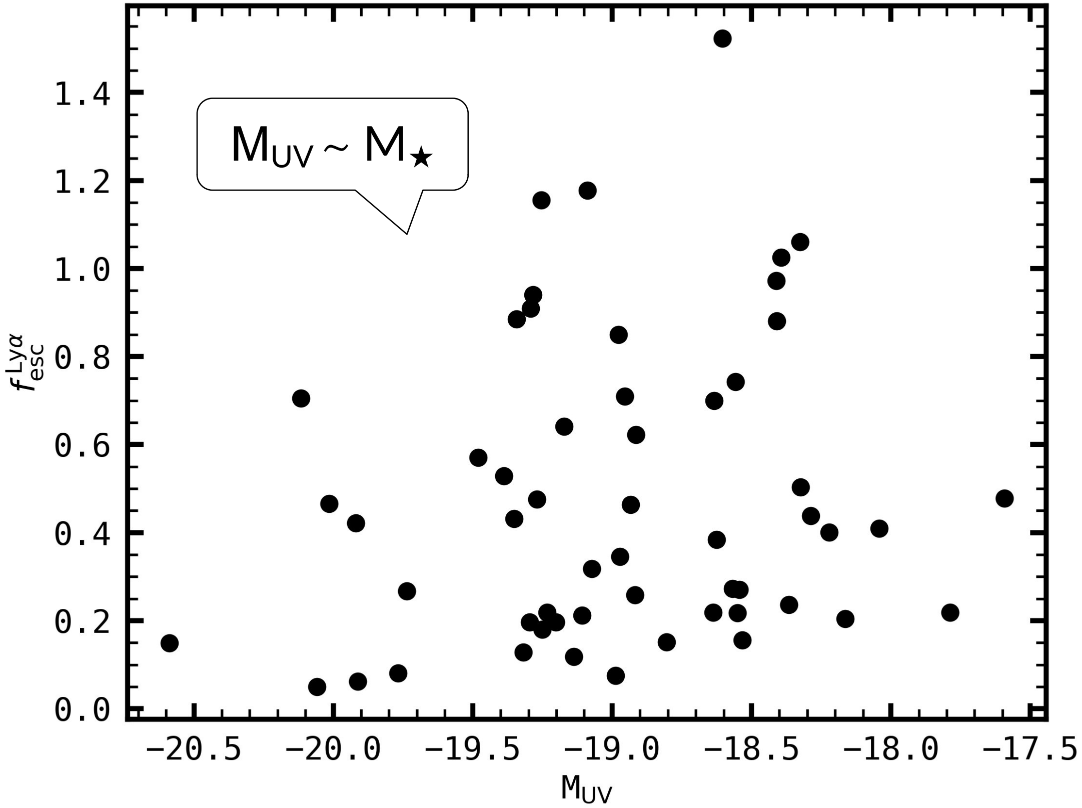
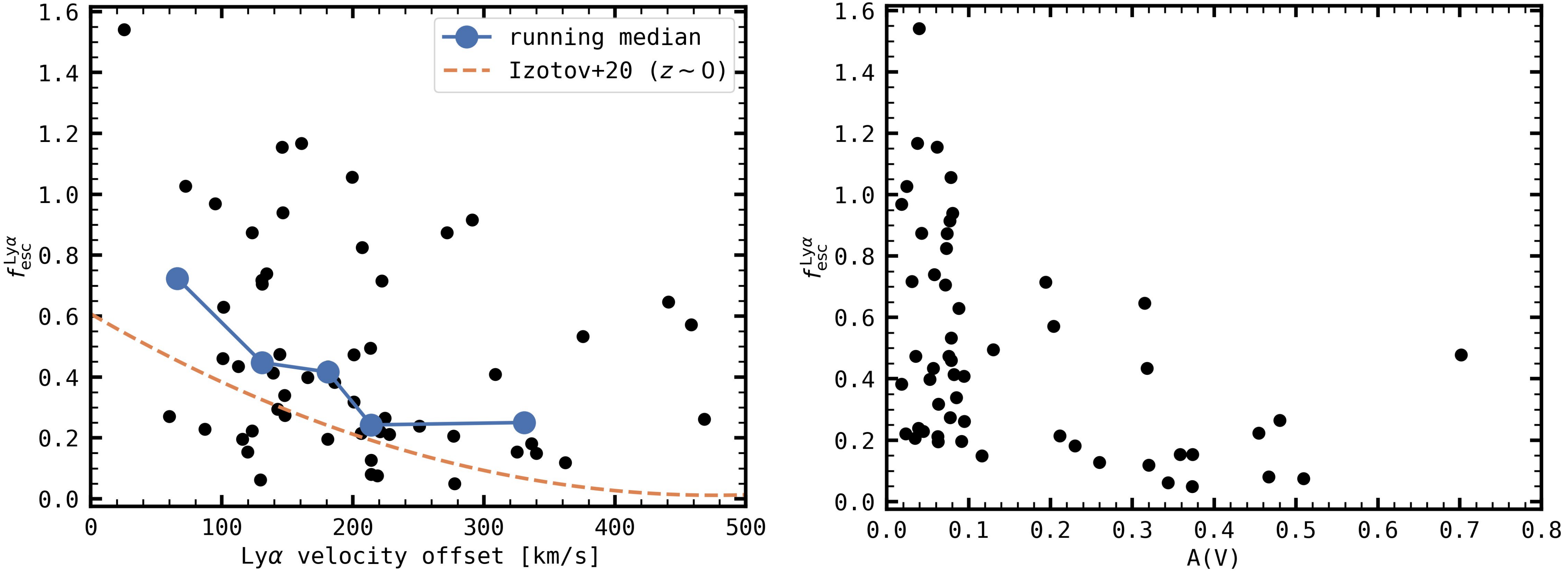


Lyα Escape Fraction vs. M★ and M_{UV}





Lyα Escape Fraction vs. Lyα Velocity Offset



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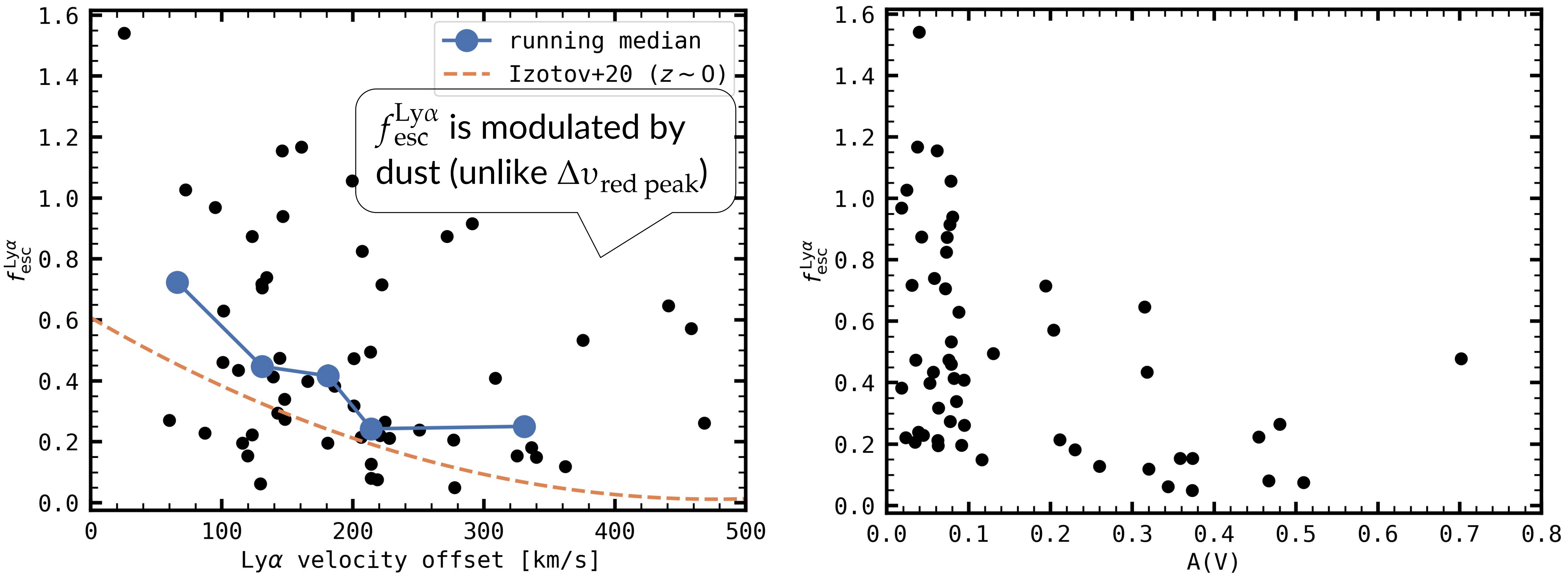

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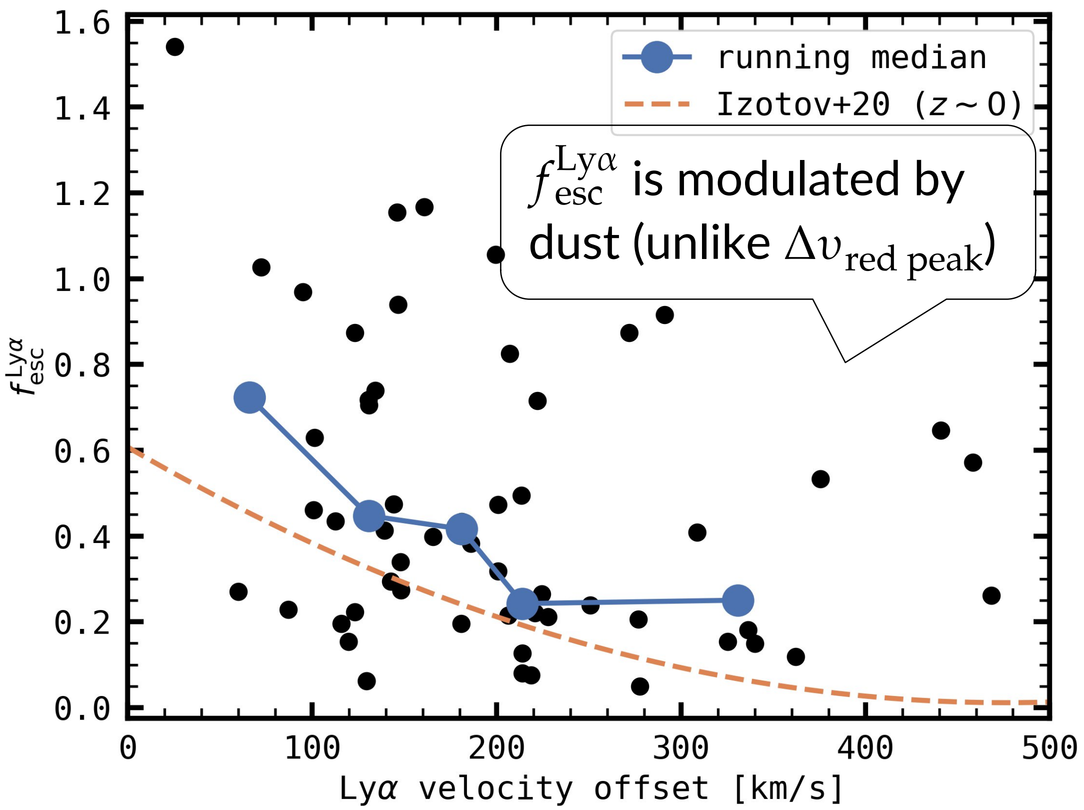
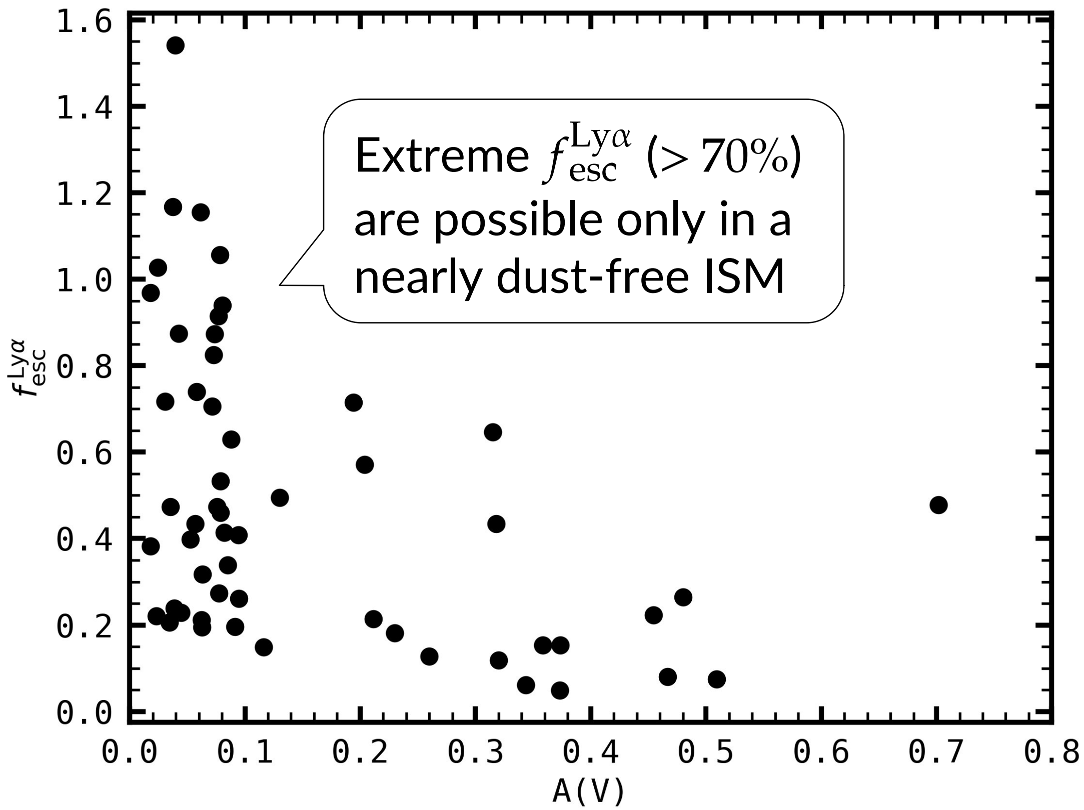
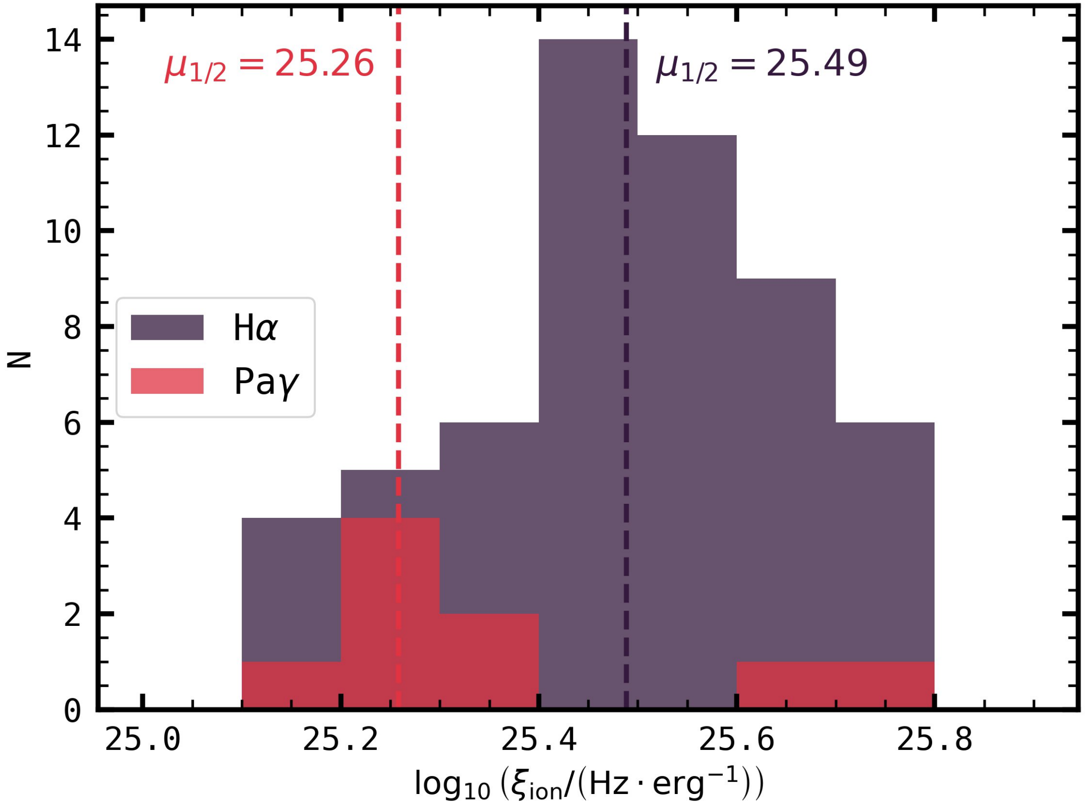




Production: Ionizing Photon Production Efficiency



$$\xi_{ion} = \frac{N(H^0)}{L_{1500}} \sim \frac{L(\mathrm{H}\alpha)}{(1 - f_{esc})} \frac{1}{L_{1500}}$$

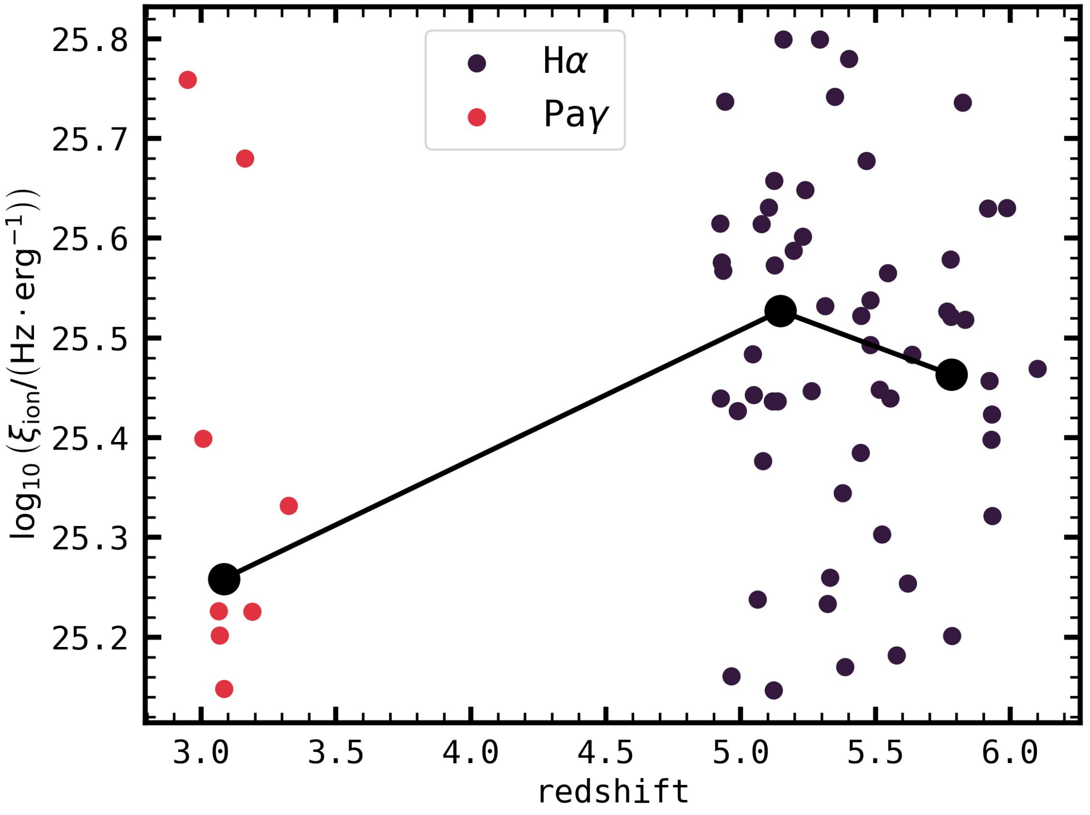
assuming = 0% (for now)

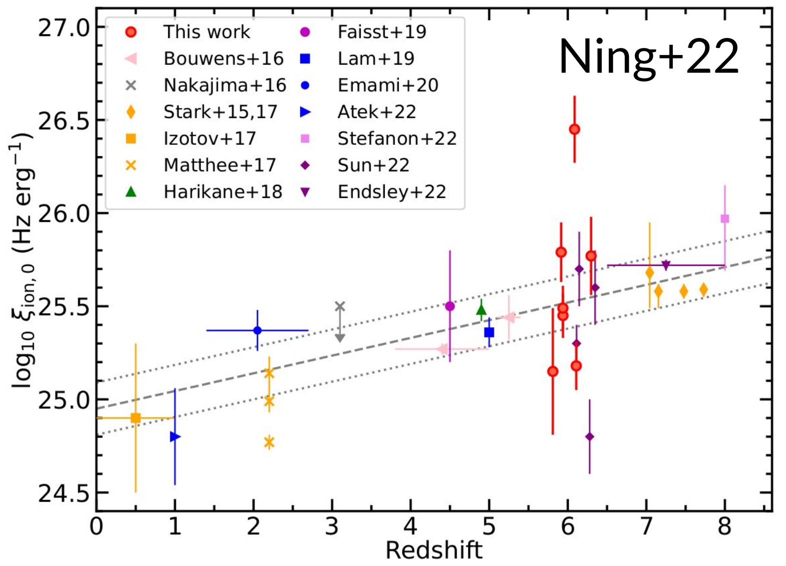
from SED fitting

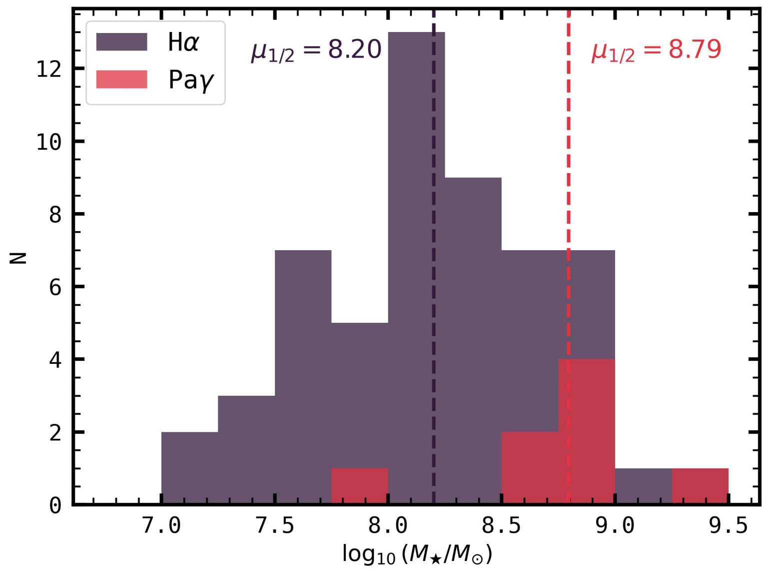
ξ_{ion} for Lyα+Paγ-emitters (T=10^4K):

$$\epsilon_{\mathrm{H}\alpha} / \epsilon_{\mathrm{Pa}\gamma} = 31.63$$

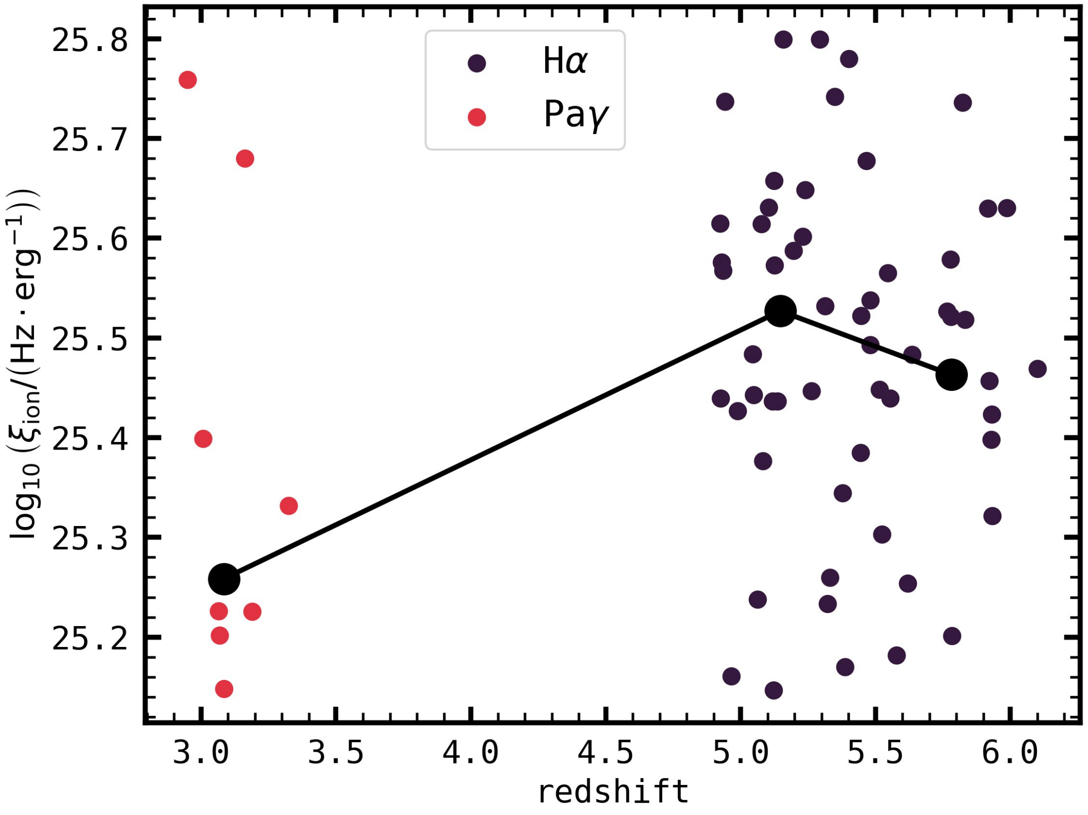
$\xi_{\rm ion}$ vs. Redshift

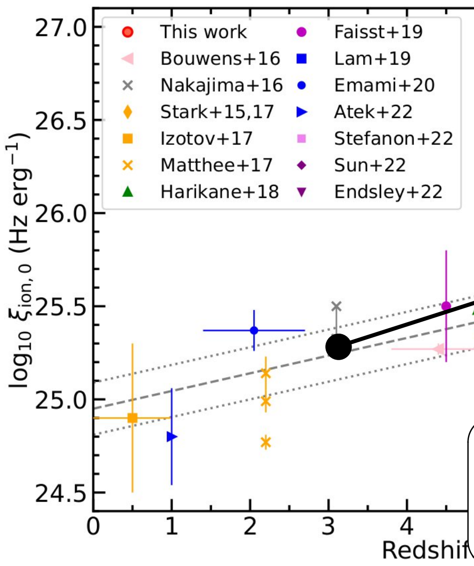




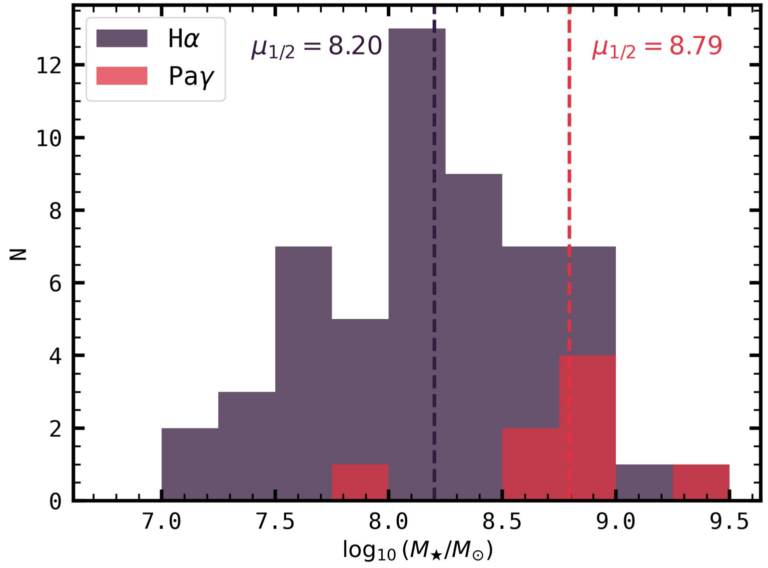


$\xi_{\rm ion}$ vs. Redshift

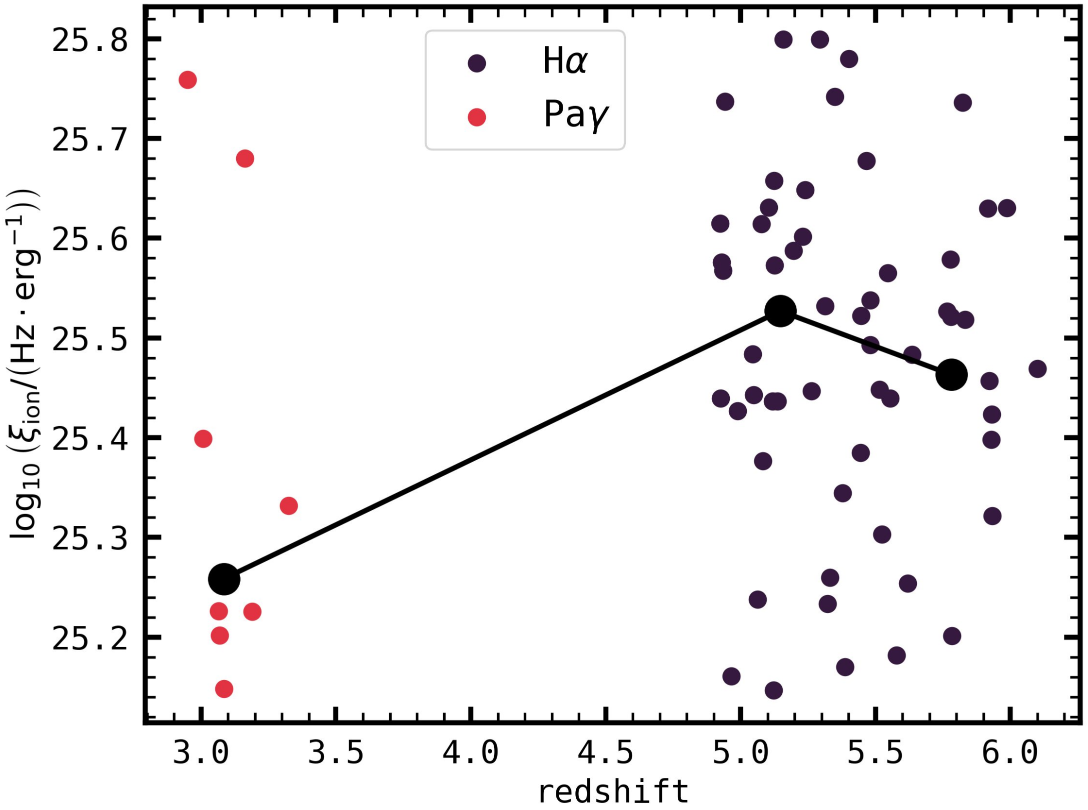


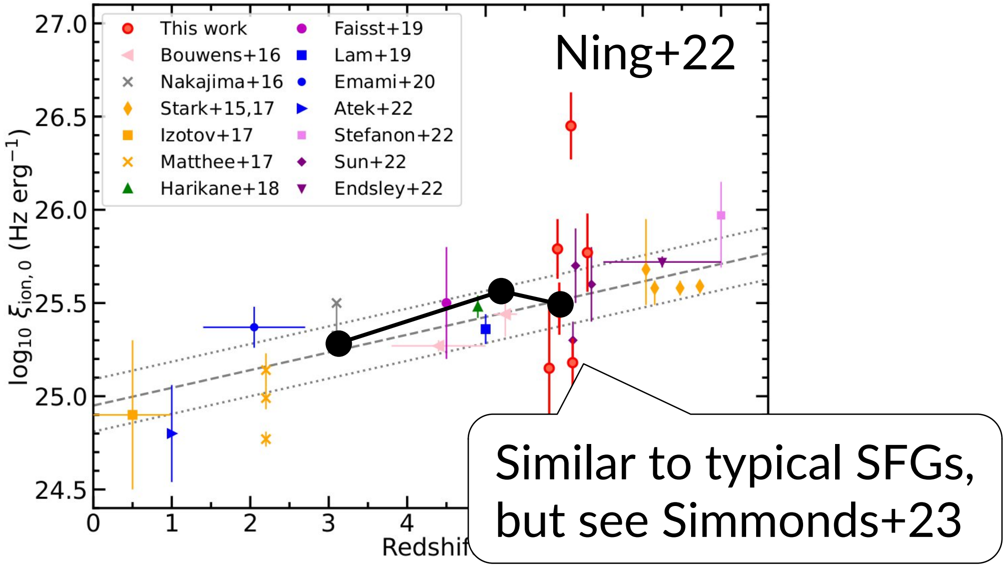


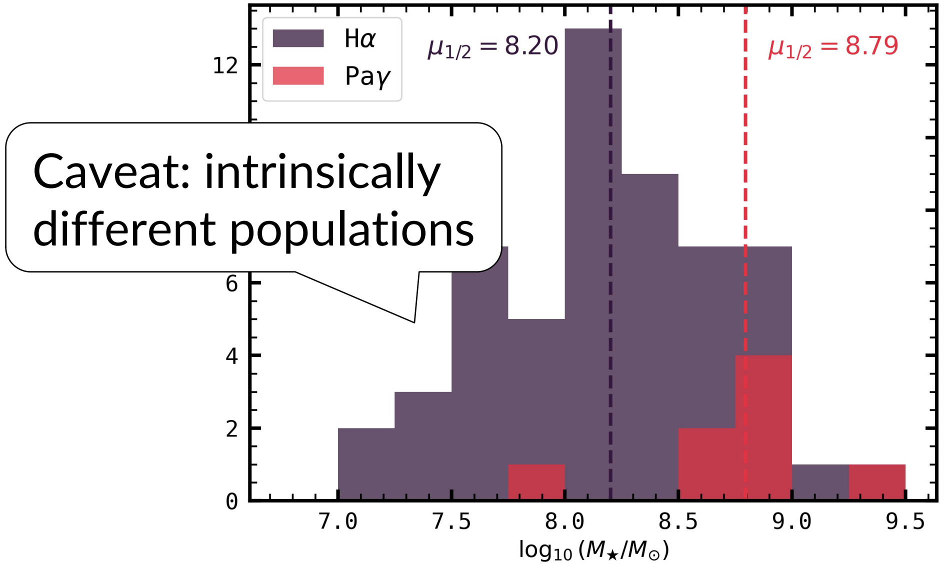
Similar to typical SFGs, but see Simmonds+23



$\xi_{\rm ion}$ vs. Redshift

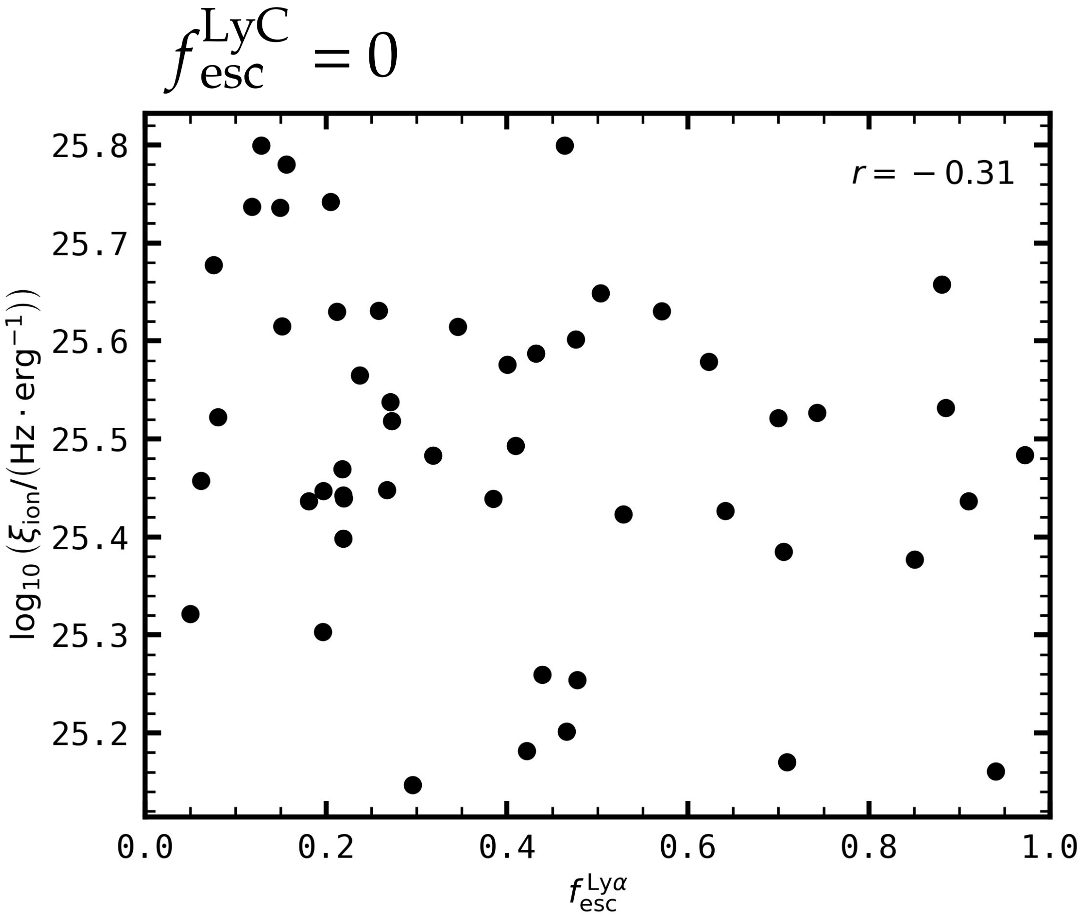


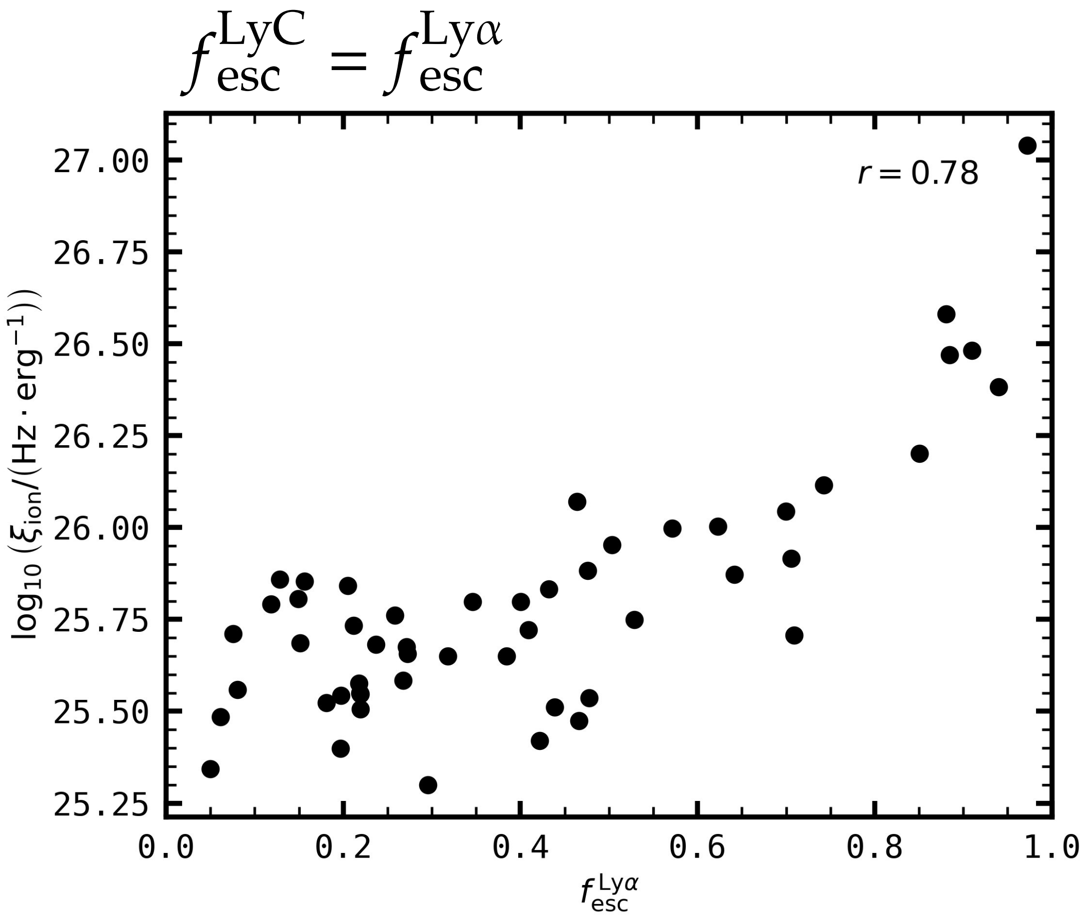




$$\xi_{\rm ion} = \frac{N(H^0)}{L_{1500}} \sim \frac{L({\rm H}\alpha)}{(1 - f_{\rm esc})} \frac{1}{L_{1500}}$$

Production & Escape: $\xi_{\rm ion}$ vs. $f_{\rm esc}^{\rm Ly\alpha}$

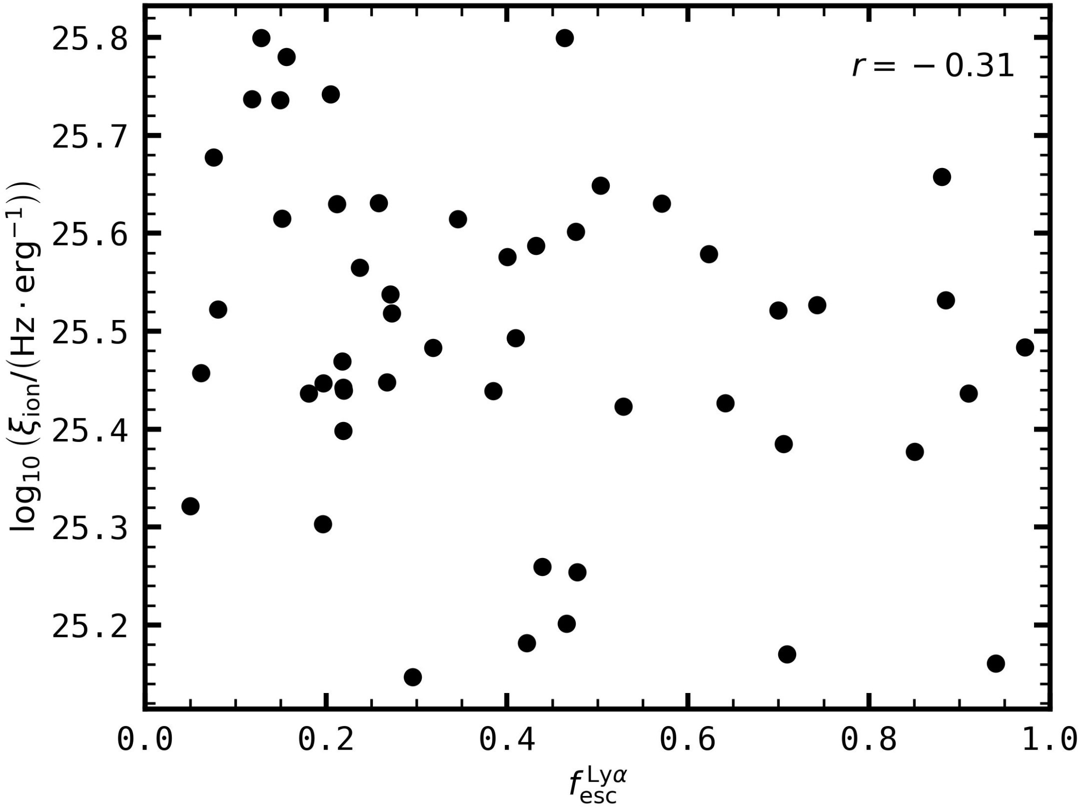




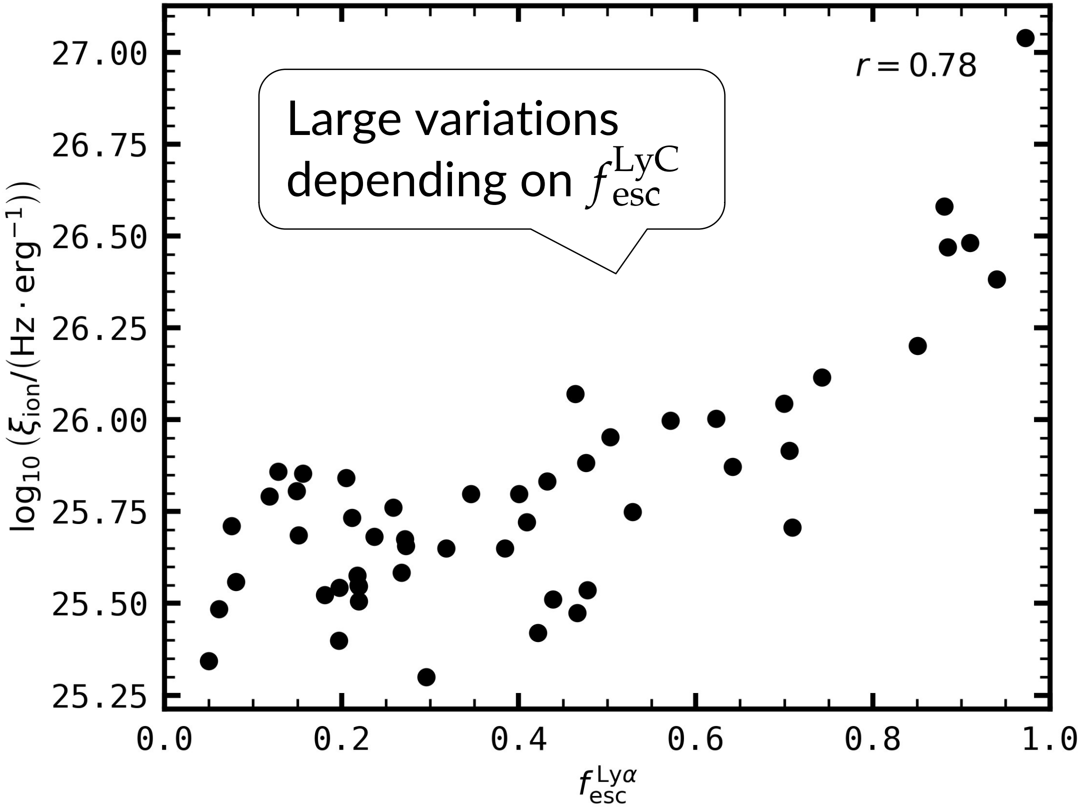
Production & Escape: ξ_{ion} vs. $f_{\text{esc}}^{\text{Ly}\alpha}$

$$\xi_{\text{ion}} = \frac{N(H^0)}{L_{1500}} \sim \frac{L(\text{H}\alpha)}{(1 - f_{\text{esc}})} \frac{1}{L_{1500}}$$

$f_{\text{esc}}^{\text{LyC}} = 0$

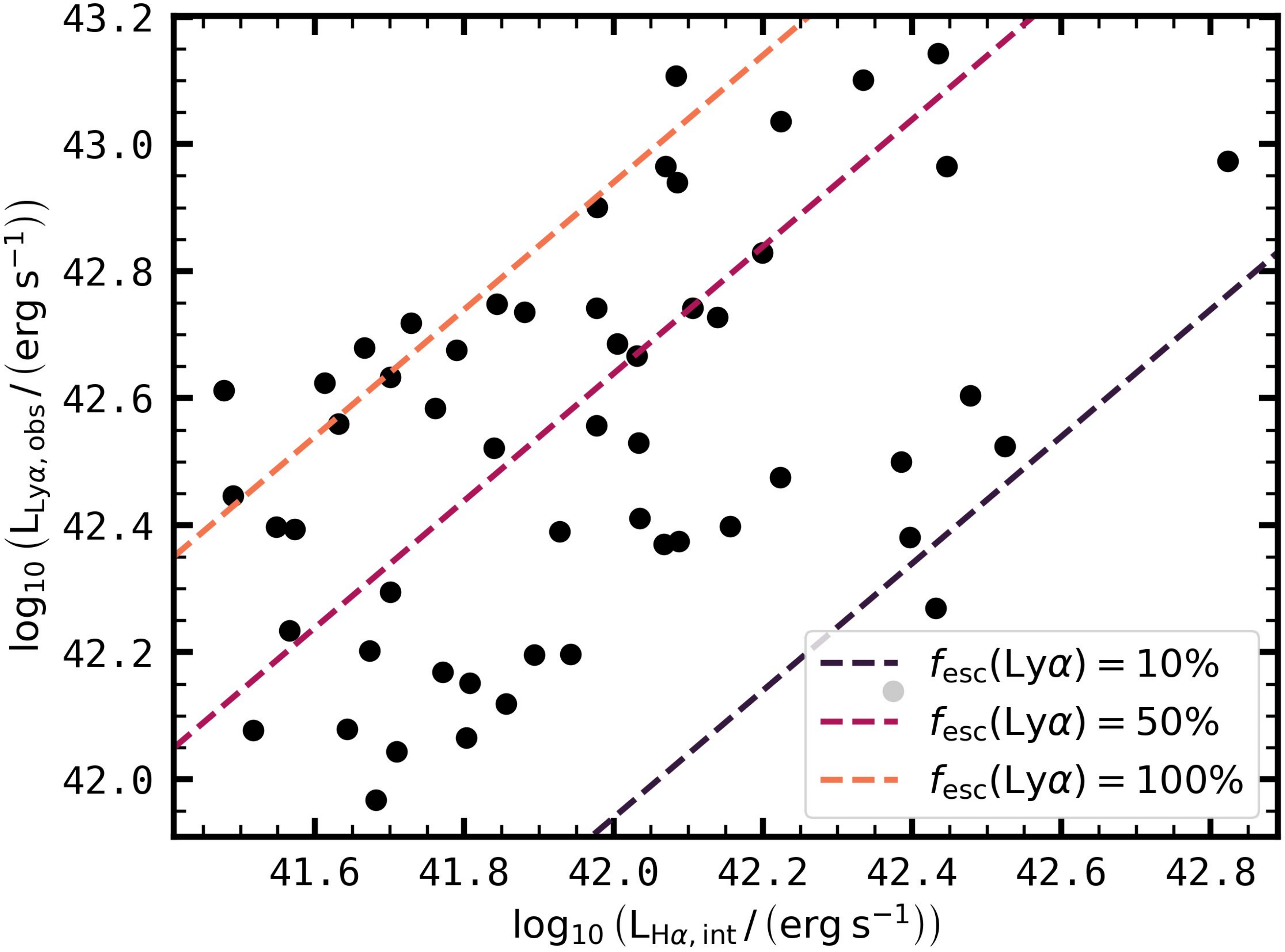


$f_{\text{esc}}^{\text{LyC}} = f_{\text{esc}}^{\text{Ly}\alpha}$



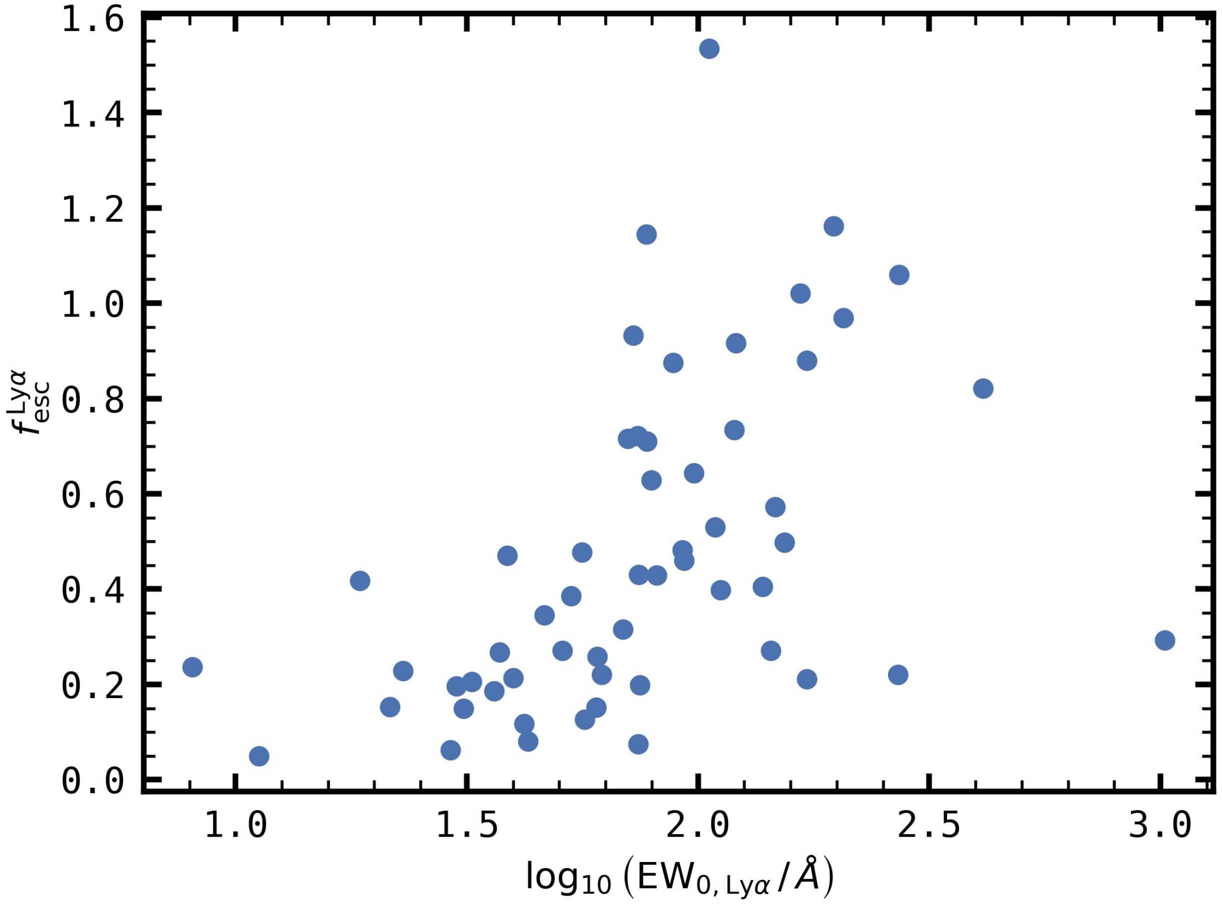
Summary

1) A typical Lyα velocity offset measured for 111 LAEs at $z \approx 3 - 6$ is around 200 km/s and does not evolve with redshift, in line with the absence of redshift evolution of several other fundamental properties of LAEs.
2) Half the bright ($L_{\mathrm{Ly}\alpha} > 10^{42.4}$ erg/s) LAEs at $z \approx 5 - 6$ have $f_{\mathbf{esc}}^{\mathbf{Ly}\alpha} > 50\%$, which makes them ideal candidates for the sources of LyC at the EoR.
3) The HI column density is a key physical parameter of the ISM controlling both the Lyα velocity offset and $f_{\mathbf{esc}}^{\mathbf{Ly}\alpha}$, although the latter also strongly depends on the amount of dust.
4) Constraining $f_{\mathbf{esc}}^{\mathbf{LyC}}$ as a function of $f_{\mathbf{esc}}^{\mathbf{Ly}\alpha}$ is necessary to determine the impact of the ionizing photon production efficiency ($\xi_{\mathbf{ion}}$) on Lyα photon escape ($f_{\mathbf{esc}}^{\mathbf{Ly}\alpha}$).

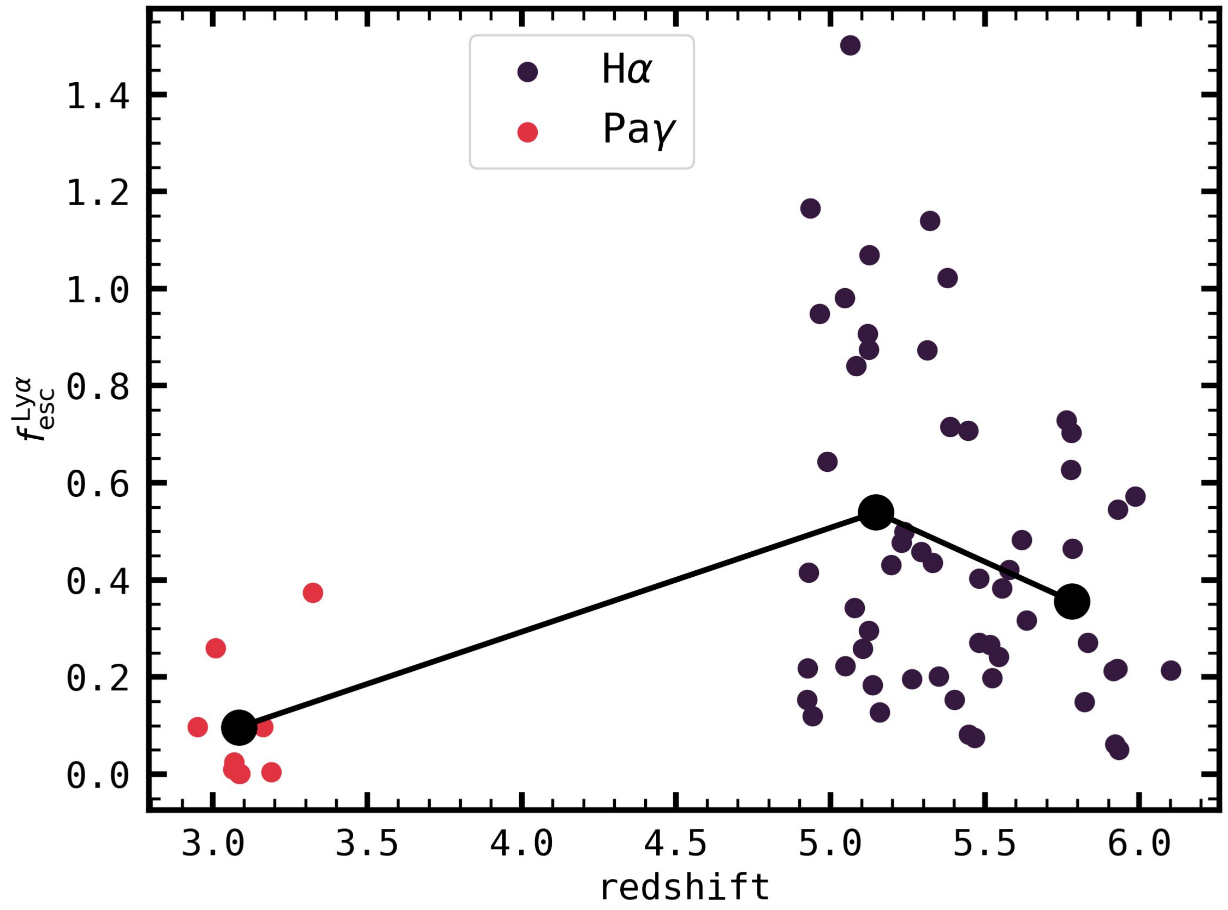


43.2
43.0
42.8
42.6
42.4
42.2
42.0
41.6
41.8
42.0
42.2
42.4
42.6
42.8
$\log_{10}(L_{Ly\alpha,obs}/(erg\,s^{-1}))$
$\log_{10}(L_{H\alpha,int}/(erg\,s^{-1}))$
$f_{esc}(Ly\alpha) = 10\%$
$f_{esc}(Ly\alpha) = 50\%$
$f_{esc}(Ly\alpha) = 100\%$

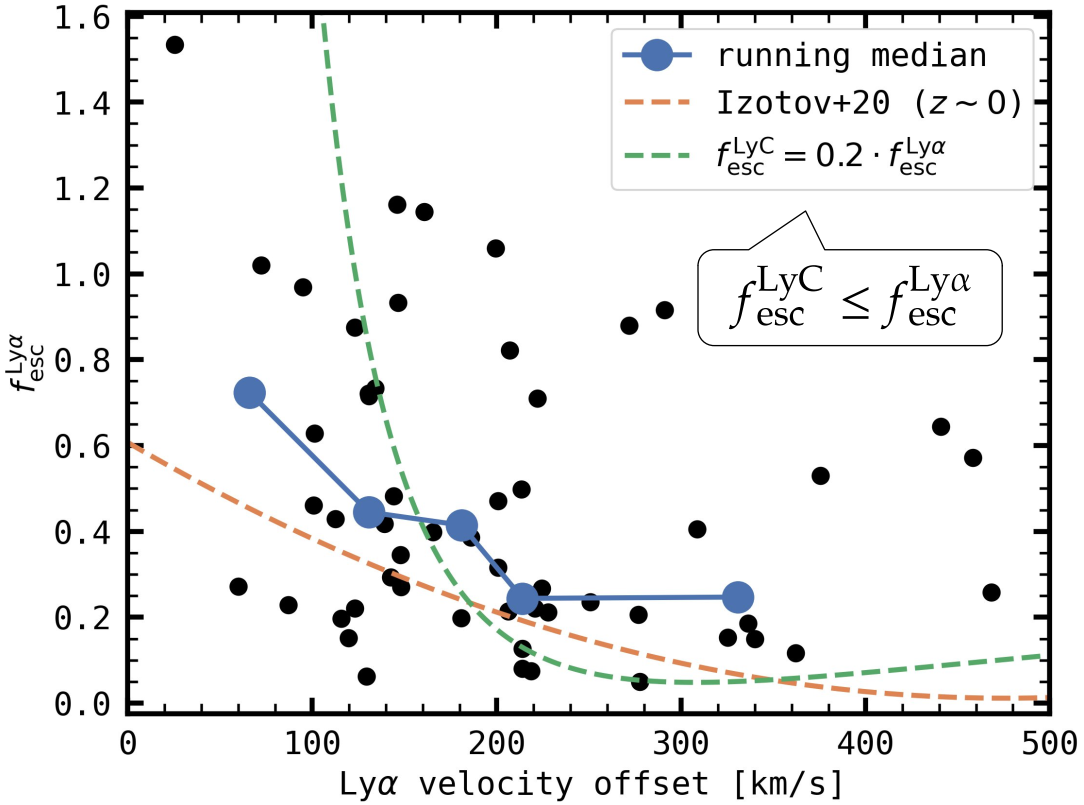
Lyα Escape Fraction vs. Lyα Equivalent Width



Lyα Escape Fraction vs. Redshift



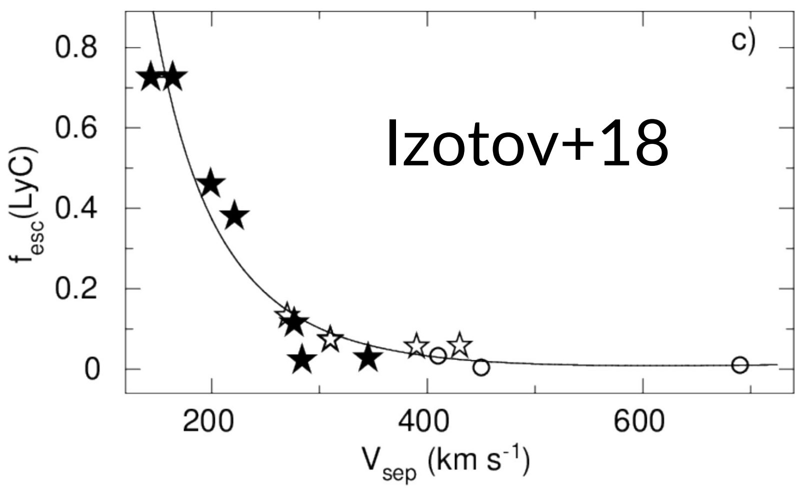
Lyα Escape Fraction vs. Lyα Velocity Offset

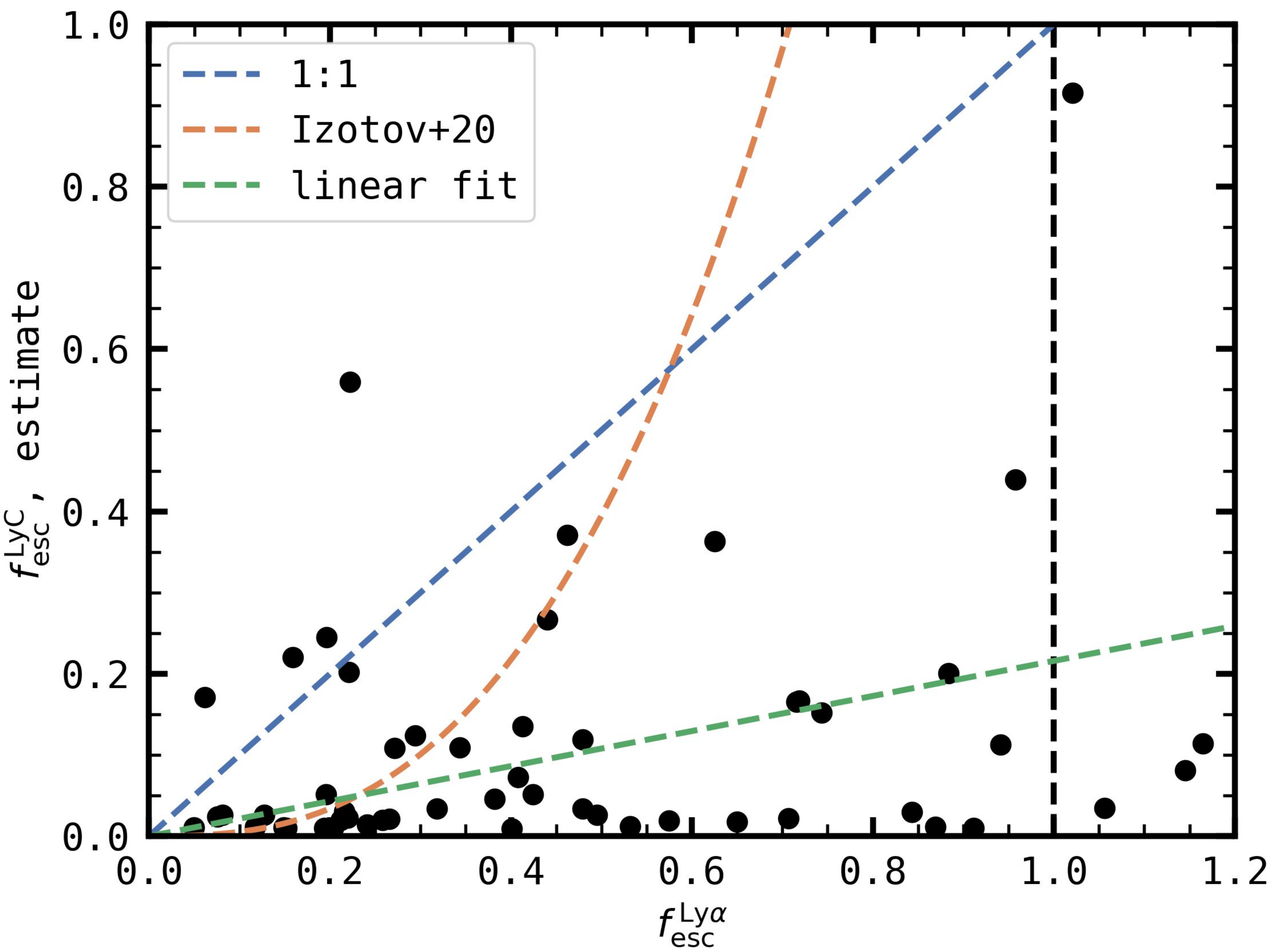


Connecting f_{esc}^{LyC} to $f_{esc}^{Ly\alpha}$

0th-order approx.: $f_{esc}^{LyC} \approx const \cdot f_{esc}^{Ly\alpha}$

$$f_{esc}(\mathrm{LyC}) = \frac{3.23 \times 10^4}{V_{sep}{}^2} - \frac{1.05 \times 10^2}{V_{sep}} + 0.095$$





1:1
Izotov+20
linear fit
f_{esc}^{LyC}, estimate
$f_{esc}^{Ly\alpha}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2