



# The Intrinsic Distribution of Ly $\alpha$ Halos

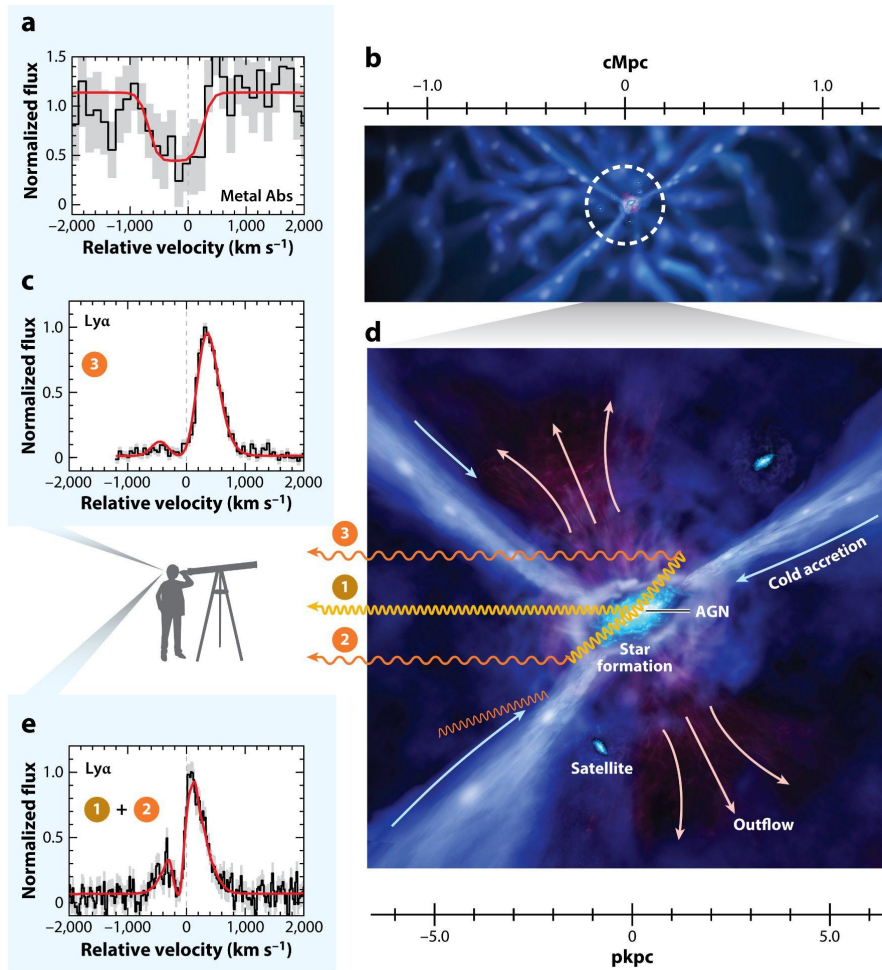
John Pharos, Lutz Wisotzki, Tanya Urrutia, and the AIP CGM Team

Contact: [jpharo@aip.de](mailto:jpharo@aip.de)

# Observing Ly $\alpha$ Halos

Ly $\alpha$  photons are produced inside galaxies, but escape through complicated CGM pathways.

This strongly affects Ly $\alpha$  observations, linking the emission line to CGM structure, the galaxy's internal processes, and interactions between them.



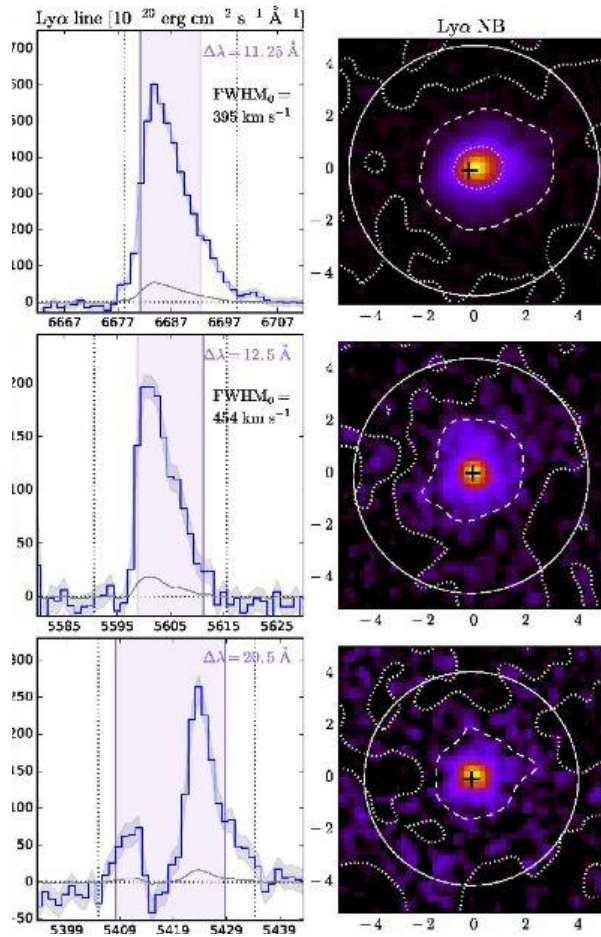
# Observing Ly $\alpha$ Halos

Integral field spectroscopy effectively captures the diversity of Ly $\alpha$  spatial/spectral profiles - see the UDF Mosaic.

This diversity is important for understanding the CGM.

But different spatial/spectral shapes also improve or reduce chances for detection...

To understand how Ly $\alpha$  relates to the CGM, we also need to understand this!



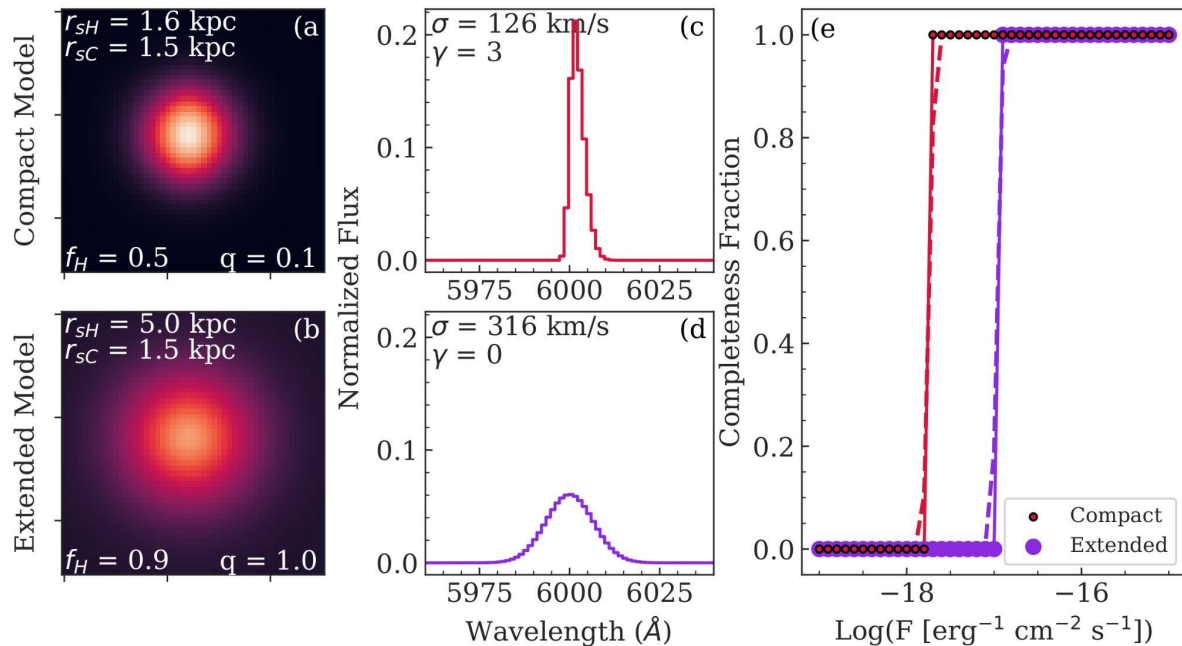
# Ly $\alpha$ Halo Selection Function

We make a 3D model with 6 spatial/spectral halo parameters:

- Compact and **halo exponential scale lengths**
- **Halo flux fraction** and ellipticity
- **Spectral line width** and skewness

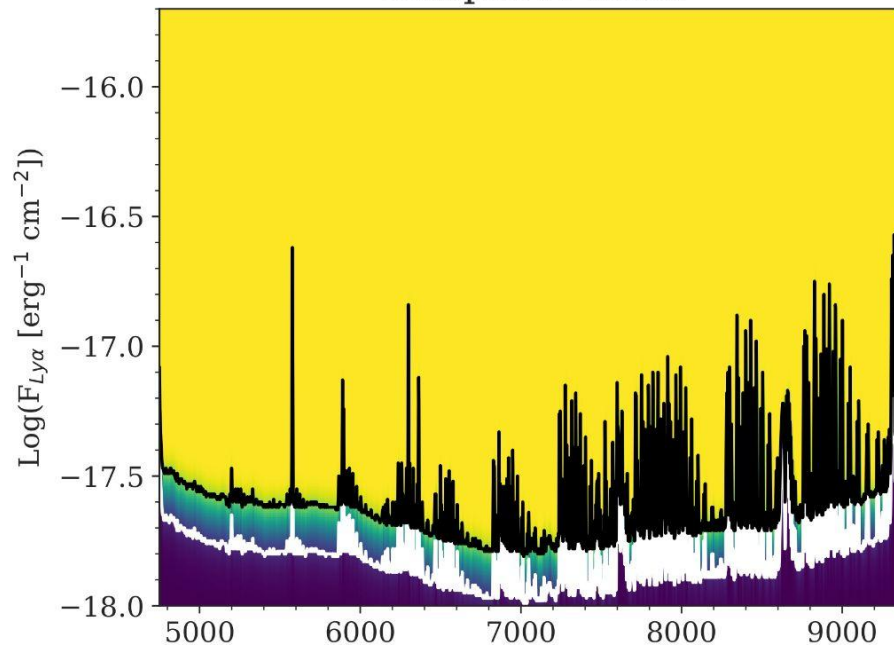
We insert the model into a MUSE-like datacube and test detection.

Example Lyman- $\alpha$  Halo Models in the UDF Mosaic

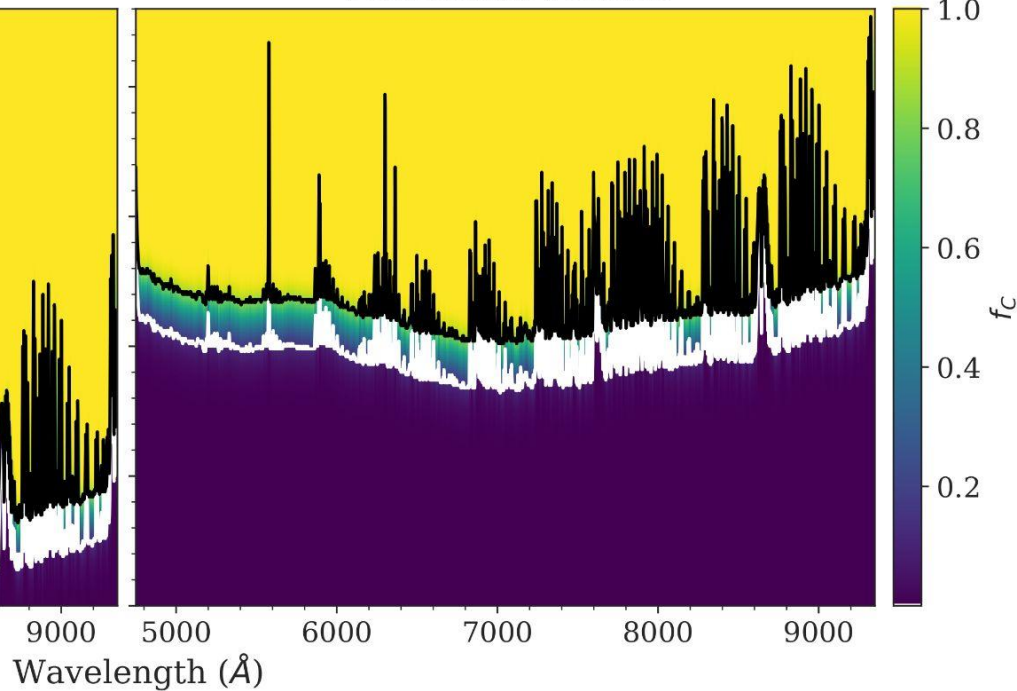


# Ly $\alpha$ Halo Selection Function

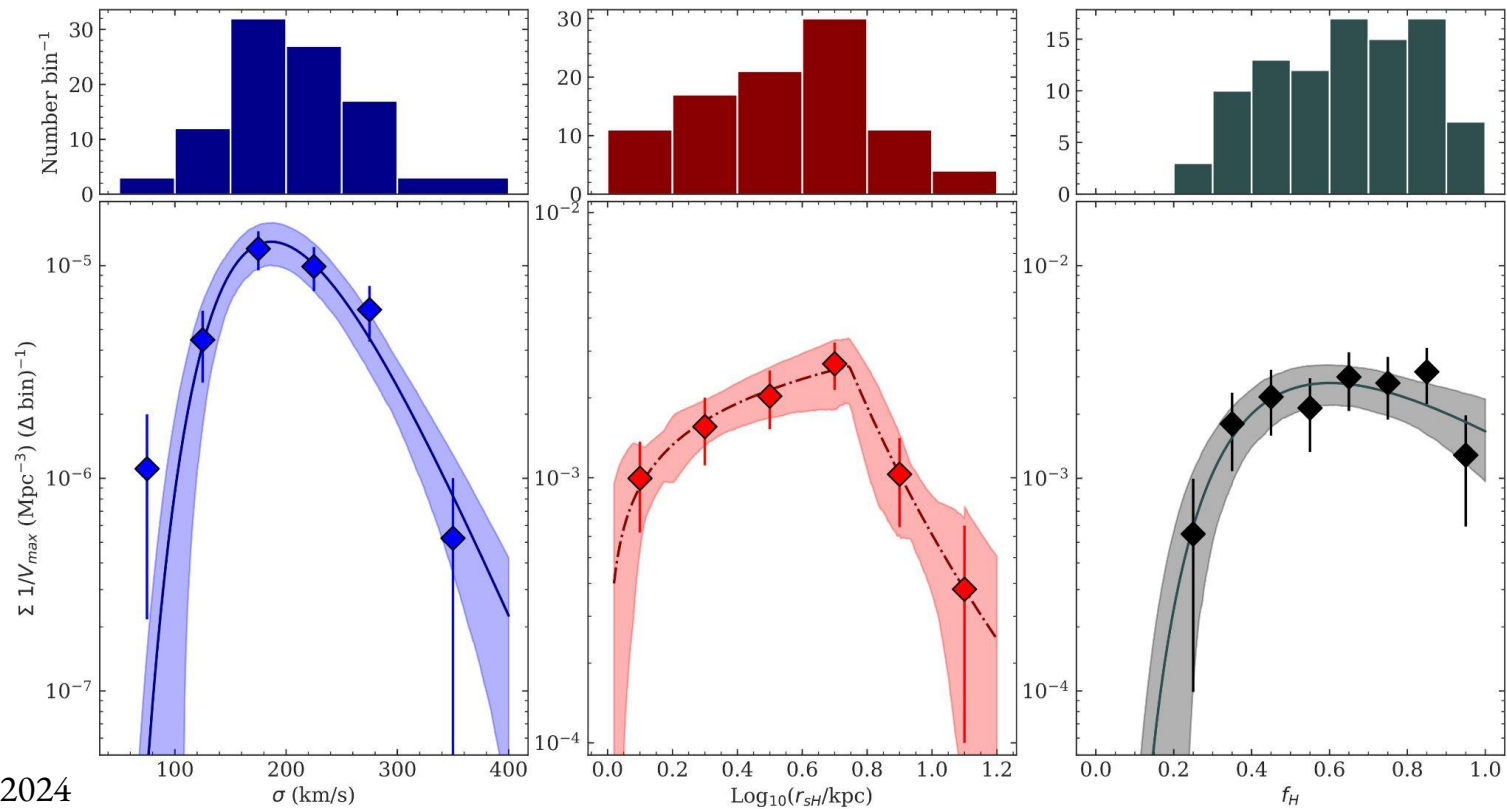
Compact Model



Extended Model



# The Intrinsic Distributions of Ly $\alpha$ Halo Properties



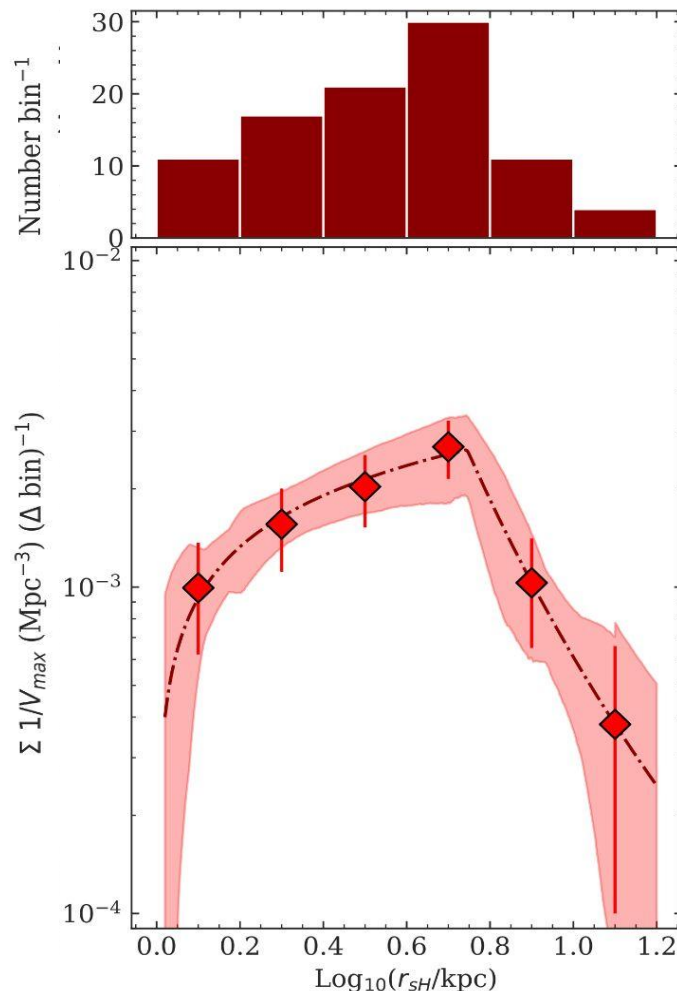
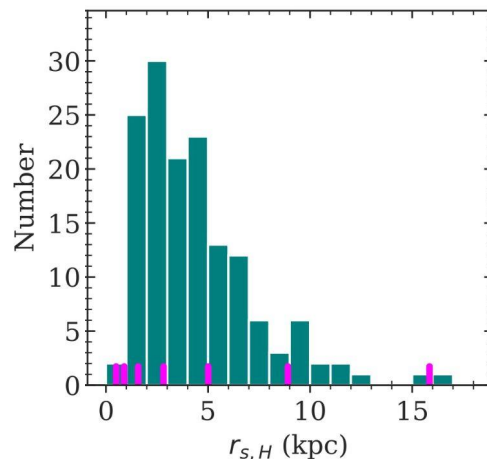
# The Halo Scale Length

The peak of the  $r_{sH}$  distribution is  $\sim 5$  kpc - larger than the observed sample!

**Extended halos are more common than we think!**



Read the paper at arXiv:  
2409.04537



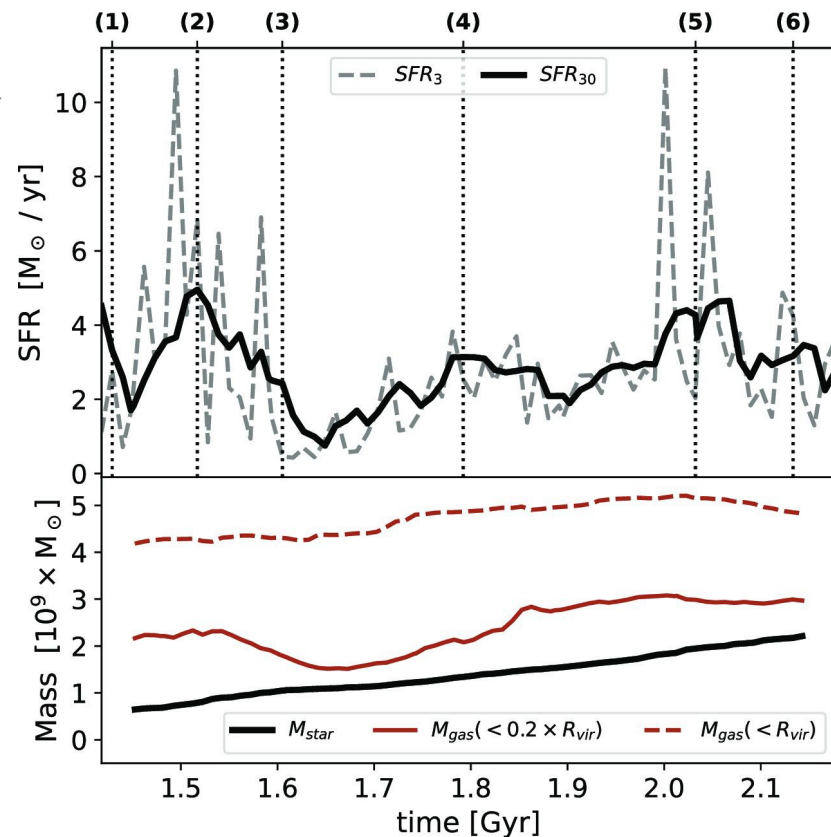


# Next Project: Selection Effects in Simulated Ly $\alpha$ Spectra

Can we apply our selection function to mock spectra and identify links between the host galaxy, Ly $\alpha$  emission, and Ly $\alpha$  detectability?

Blaizot+ 2023 simulate a low-mass, star-forming galaxy.

The galaxy evolves over  $z \sim 4.2$  to  $z \sim 3$ , with varying SFR generally consistent with Main Sequence.

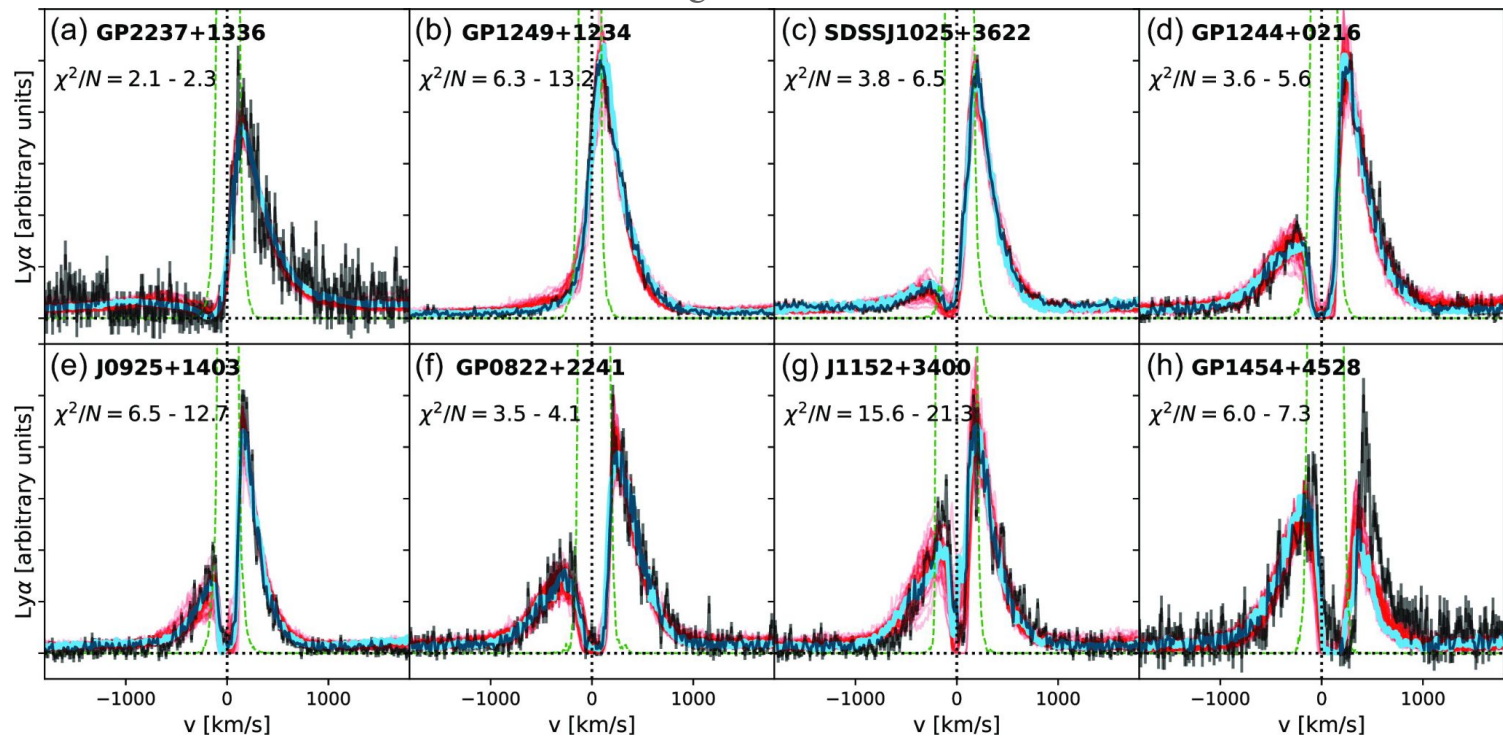


Blaizot et al. 2023

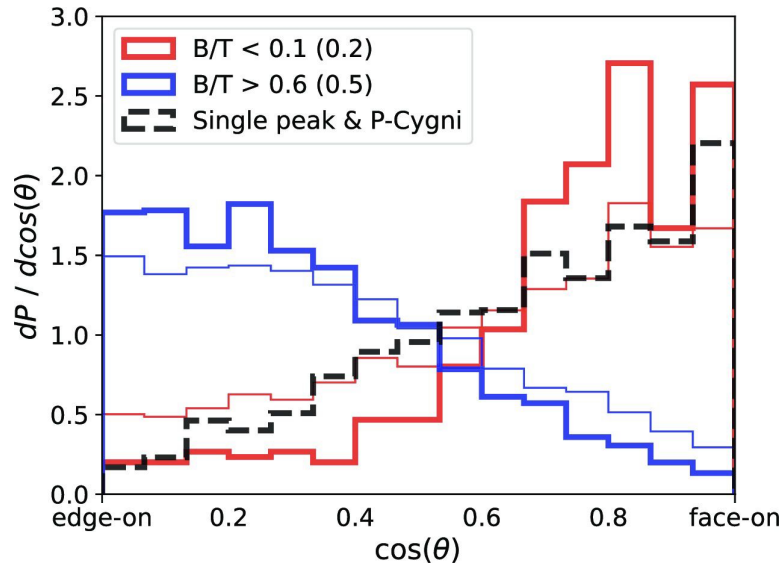


# Mock Spectra from Simulation

Blaizot+2023 derive  $\sim 22500$  mock Ly $\alpha$  emission spectra from the simulation timesteps and viewing orientations.



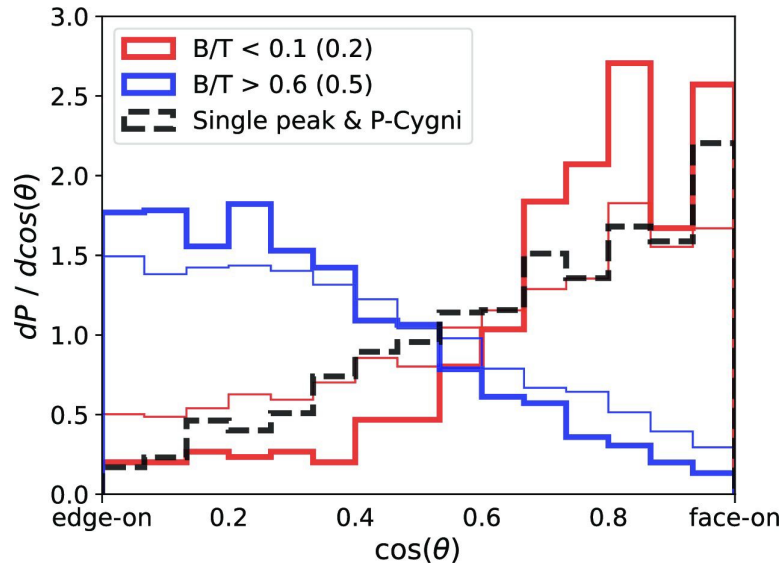
Blaizot et al.  
2023



# What Determines the simulated Ly $\alpha$ Line Shape?

The shape of the line depends on:

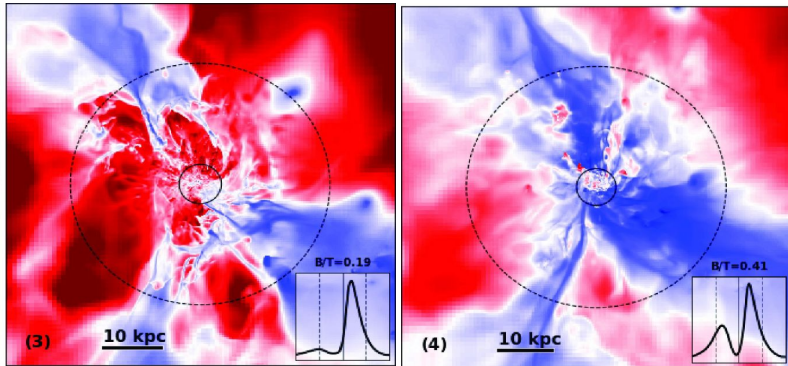
- (1) viewing direction

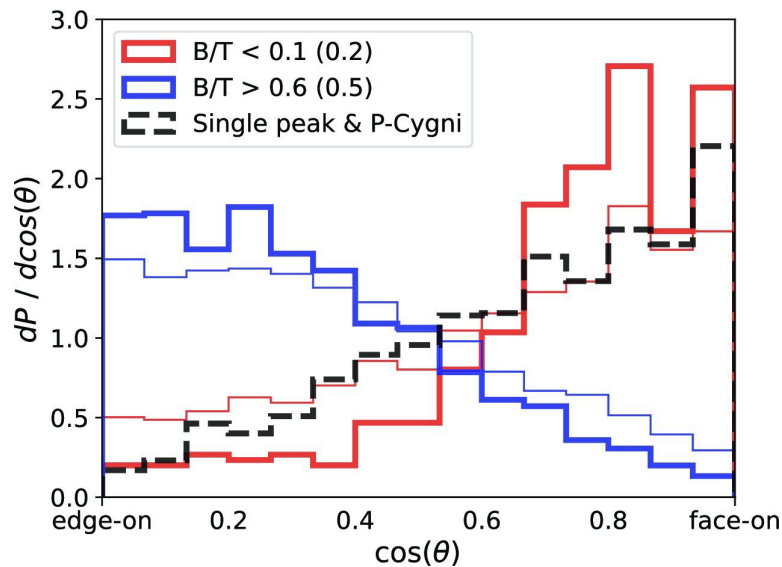


# What Determines the simulated Ly $\alpha$ Line Shape?

The shape of the line depends on:

- (1) viewing direction
- (2) gas flow phase

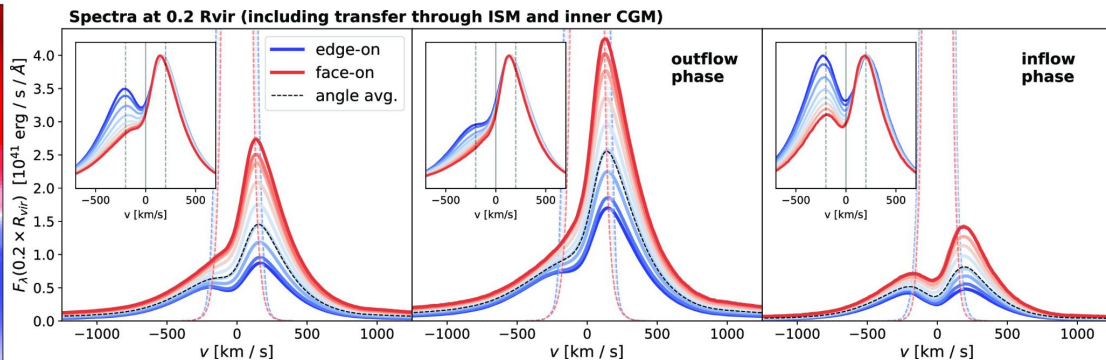
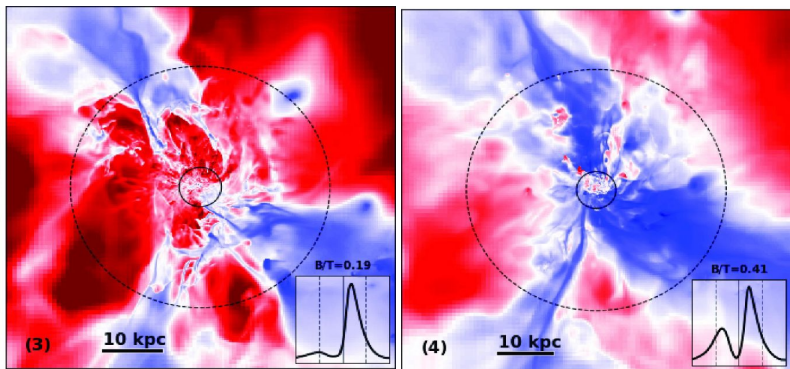




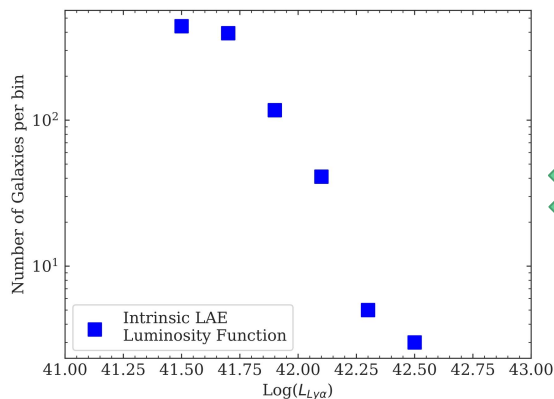
# What Determines the simulated Ly $\alpha$ Line Shape?

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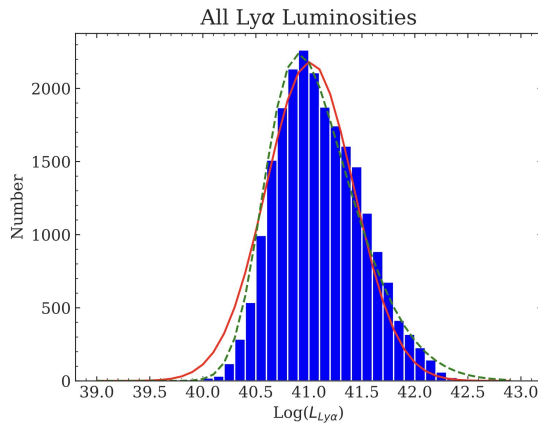
- (1) viewing direction
- (2) gas flow phase
- (3) propagation through ISM and/or CGM



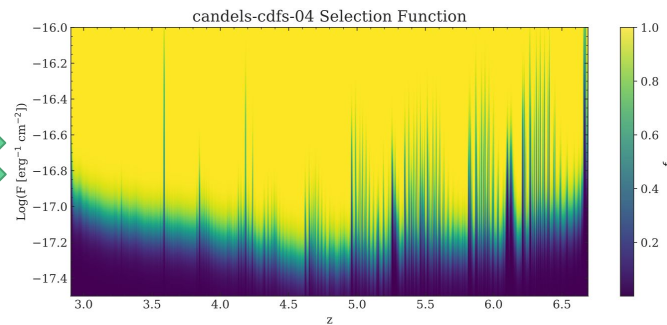
# An Experiment: a Mock LAE Population from One Galaxy



Draw  $N$  luminosities from LF



$M$  direction/time instance  
luminosities

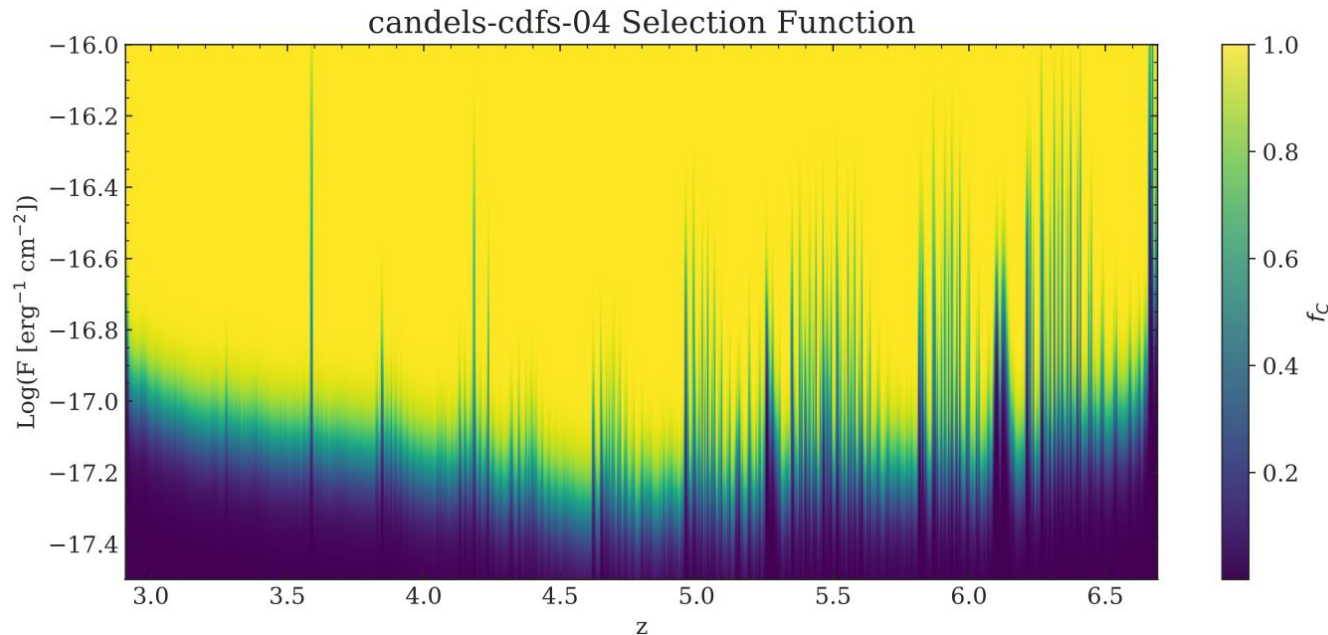


“Observe” galaxies with  
Selection Function

This gives a size  $N \times M$  ( $1000 \times 22500$ ) mock population spanning the range of observed luminosities and representing all simulated timesteps and viewing orientations

Then we have a size  $N \times M \times f_c(L)$  detected sample

# The Mock LAE Sample - the survey



Imagine we're observing our LAEs in MUSE-Wide - a single hour exposure.

For simplicity, pretend that the selection function for all MW fields can be represented by one pointing (CANDELS-CDFS-04).

Also assume all LAEs are at  $z=3.5$ .

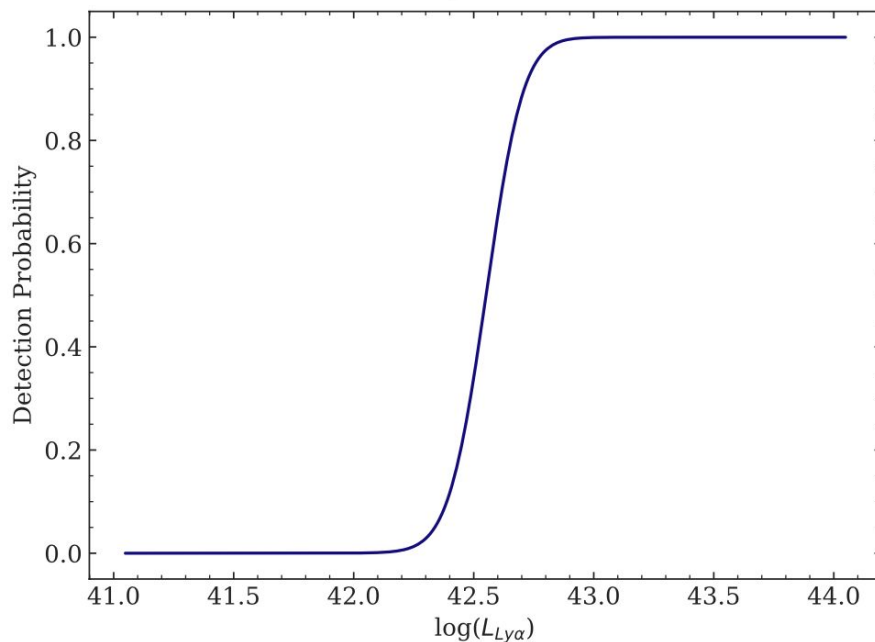
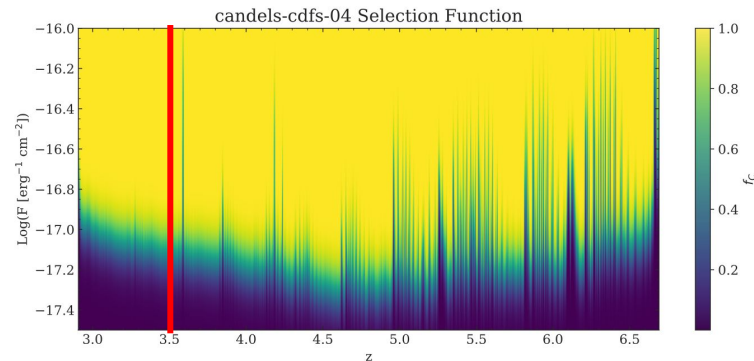
# The Mock LAE Sample - the survey

This gives a specific detection curve.

Each galaxy-instance has a specific detection probability.

Applying to the whole sample returns a mock observed sample similar to MUSE-Wide.

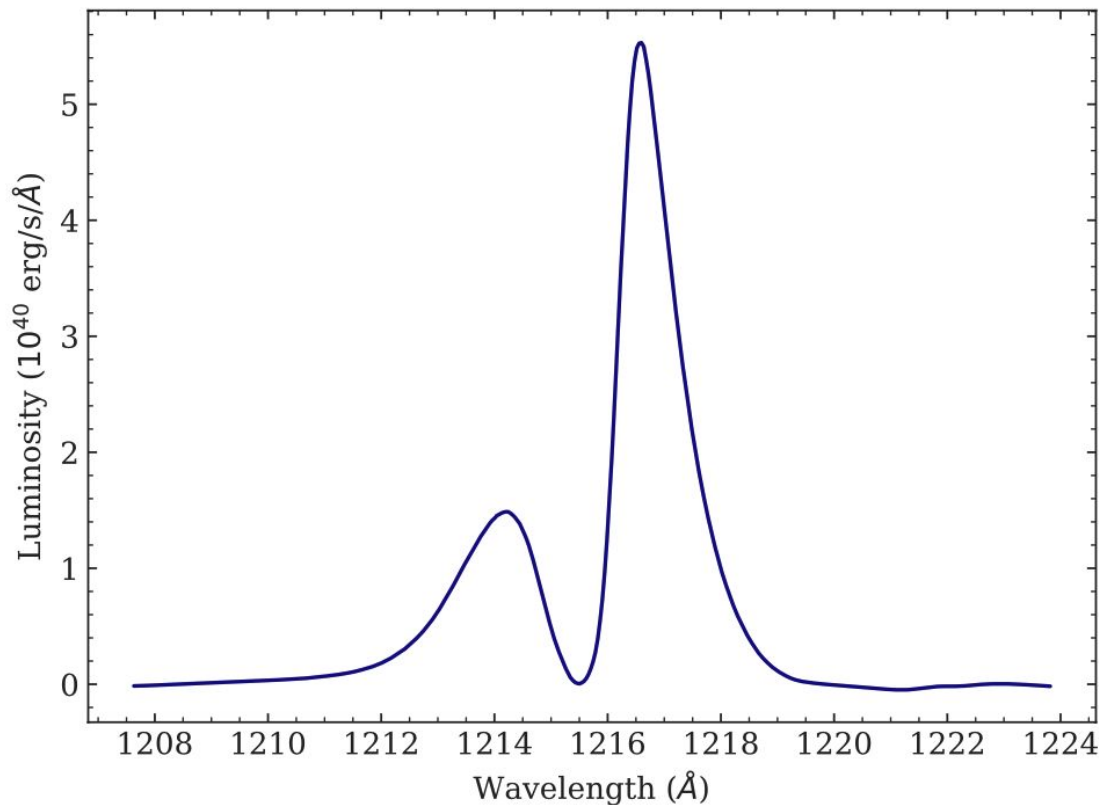
We detect  $\sim 11\%$  of the underlying population - what kind of galaxies made the cut?





# The Observed Sample - what does it look like?

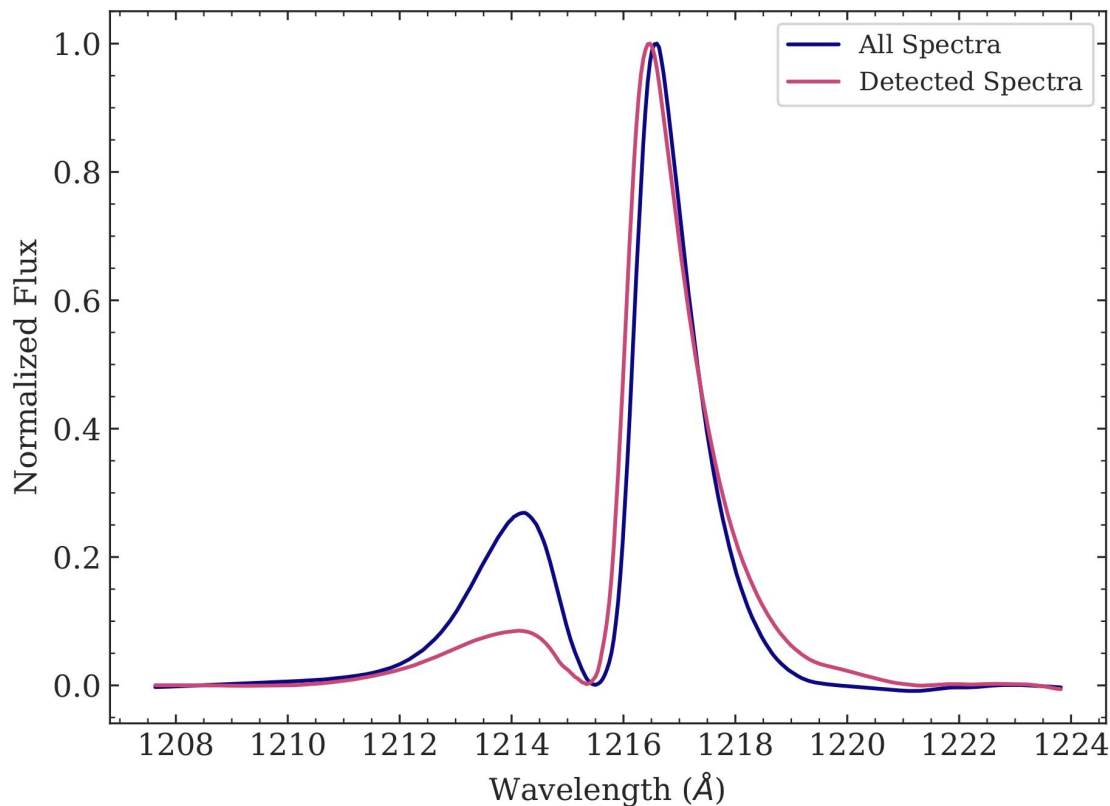
The median spectrum of all  $N \times M$  instances shows a very classic double-peaked profile.



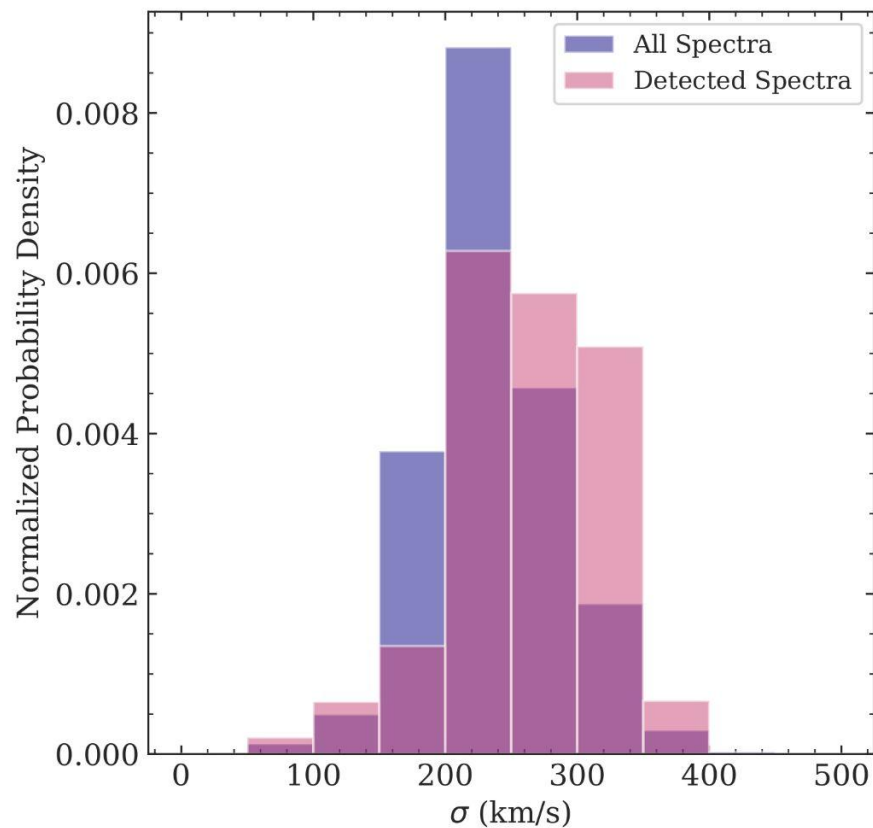
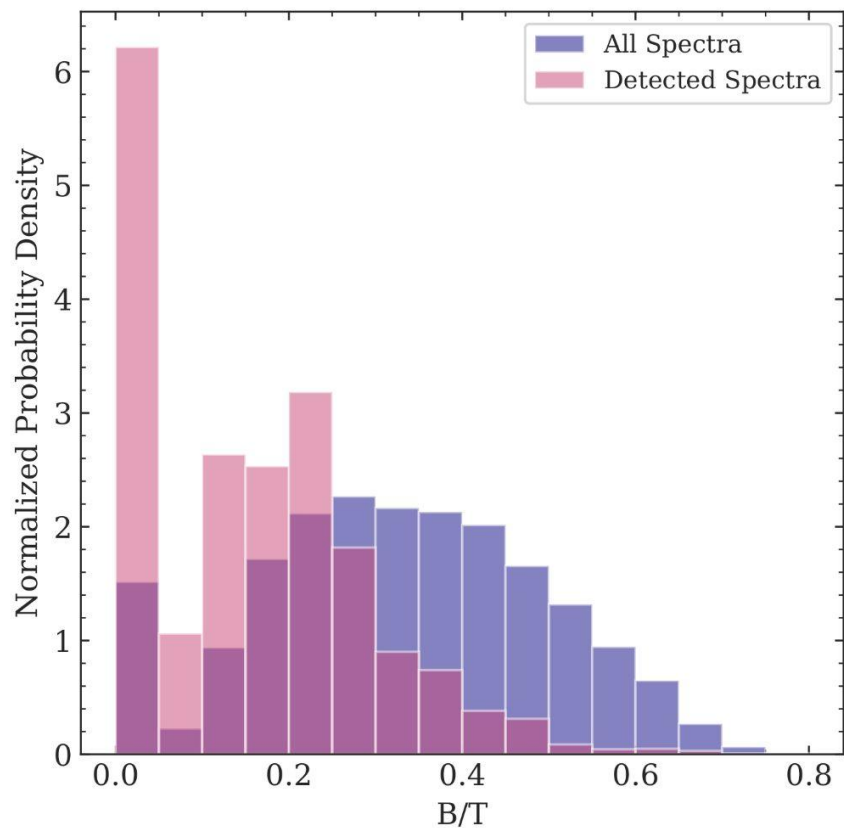
# The Observed Sample - what does it look like?

The median spectrum of all  $N \times M$  instances shows a very classic double-peaked profile.

But the median of the detected spectra looks different - the blue peak is much weaker!



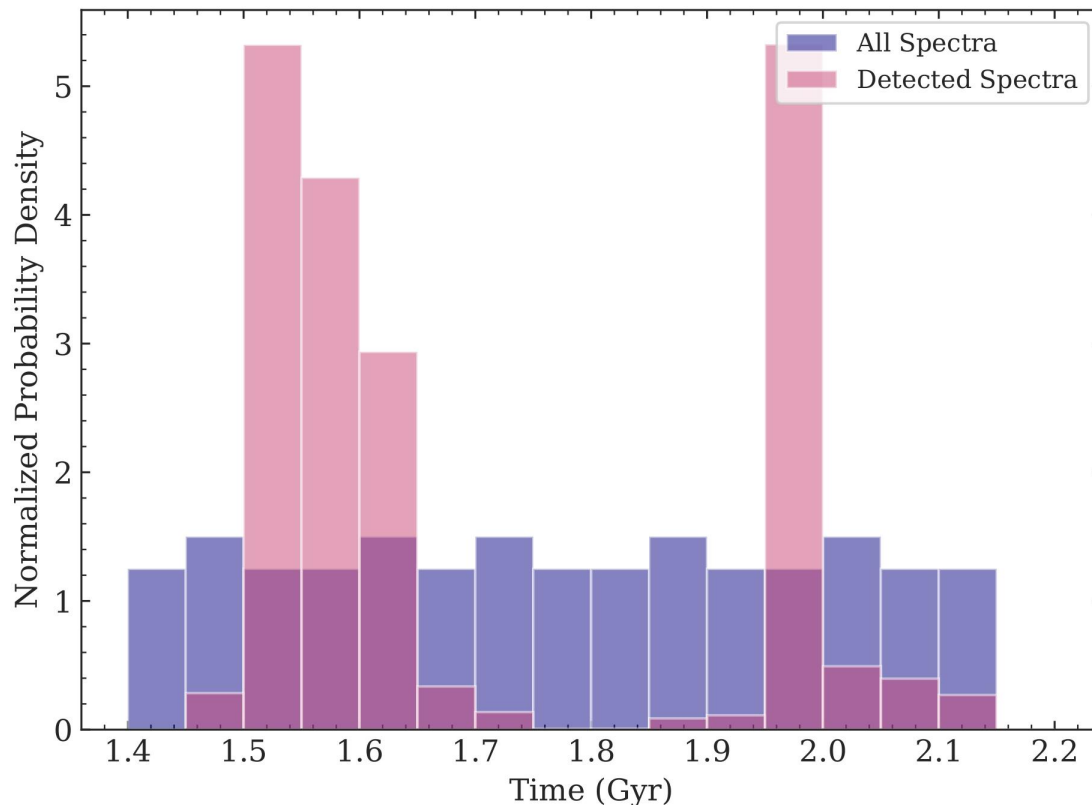
# Normalized Line Width and Blue Peak Distributions



# What other differences can we see?

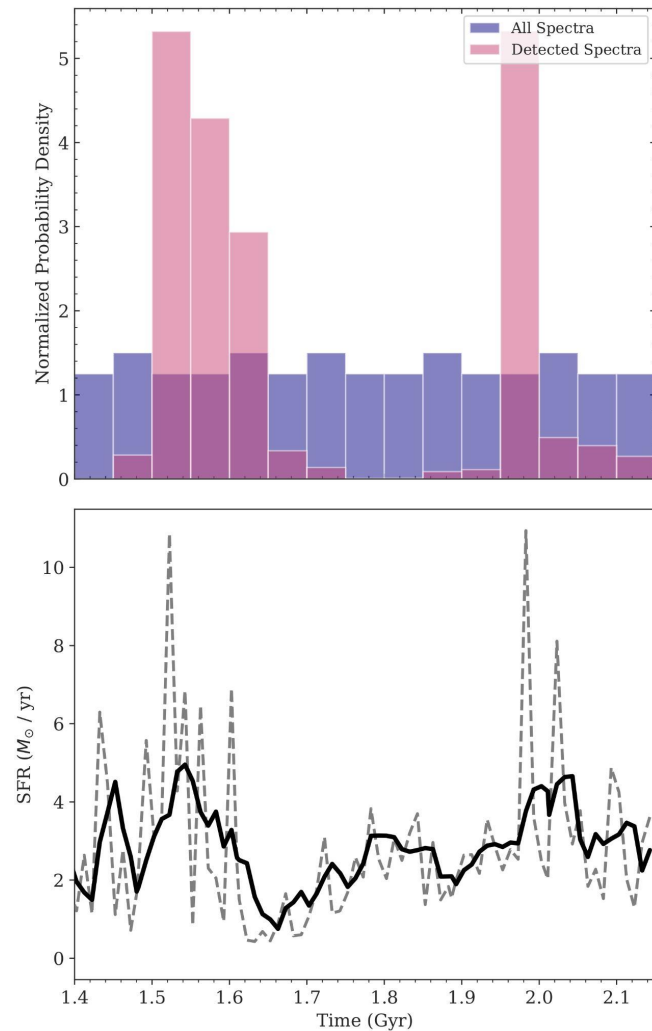
There's a clear selection on time, with two epochs ( $\sim 1.55$  Gyr and  $\sim 2$  Gyr) preferentially detected.

Does this pattern look familiar?



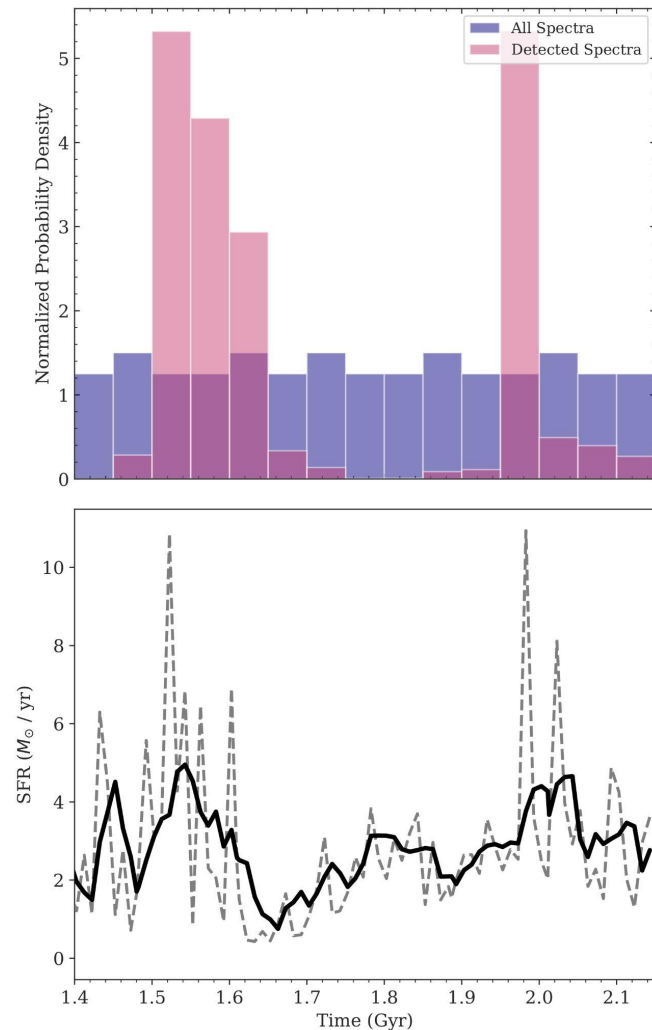
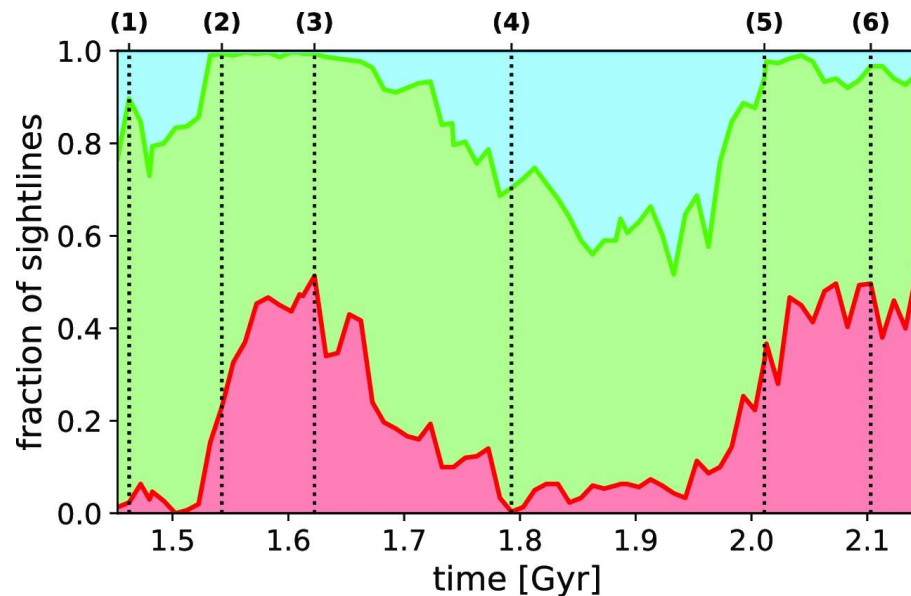
# Yes, it does

The preferred timesteps line up with periods of higher SFR.



# Preferred Detection Times

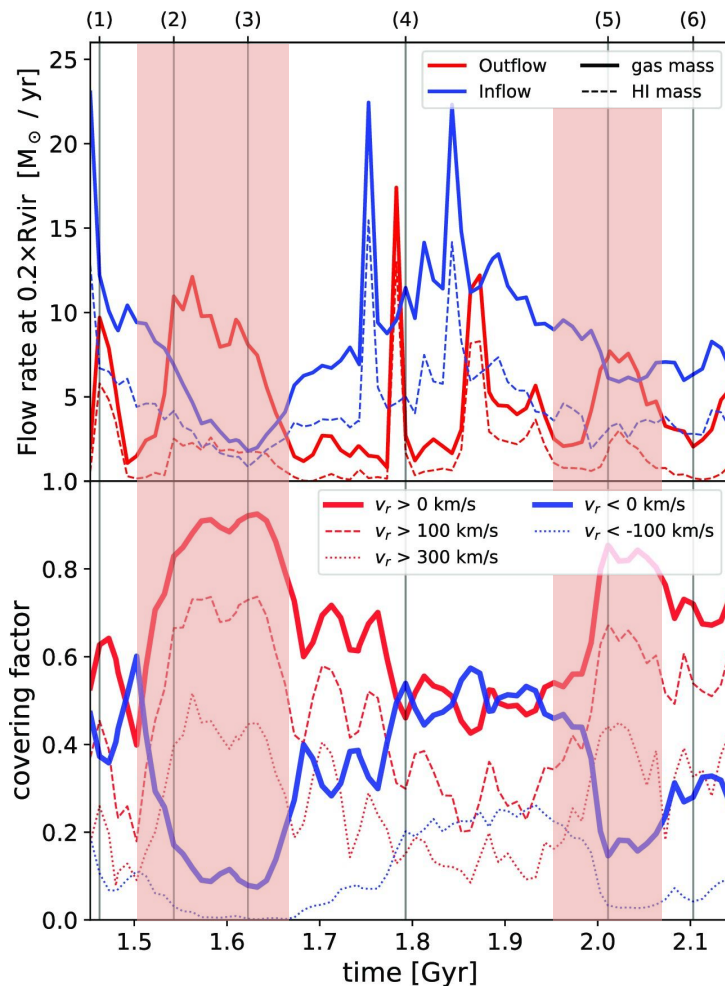
They also line up with red-peak-dominated times.



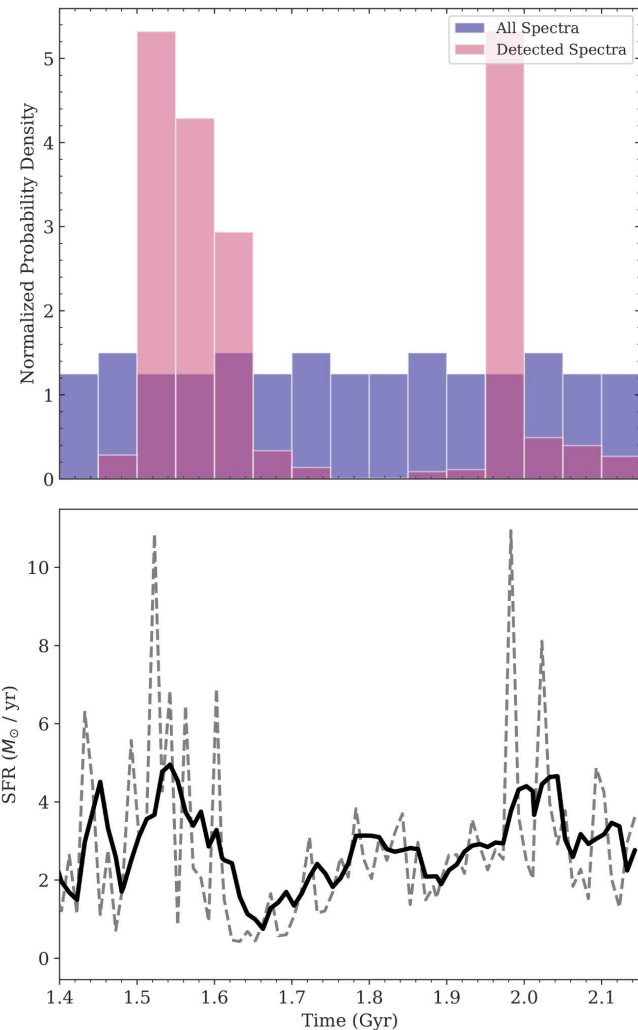
# Preferred Detection Times

And match outflow-dominated times.

**Conclusion:**  
detected LAEs will be strongly selected in favor of galaxies in outflow-dominated stages of their star formation history



Blaizot et al. 2023







# Summary and Future Steps

**We model LAHs in MUSE to test halo detectability, make selection functions, and recover intrinsic halo parameter distributions.**

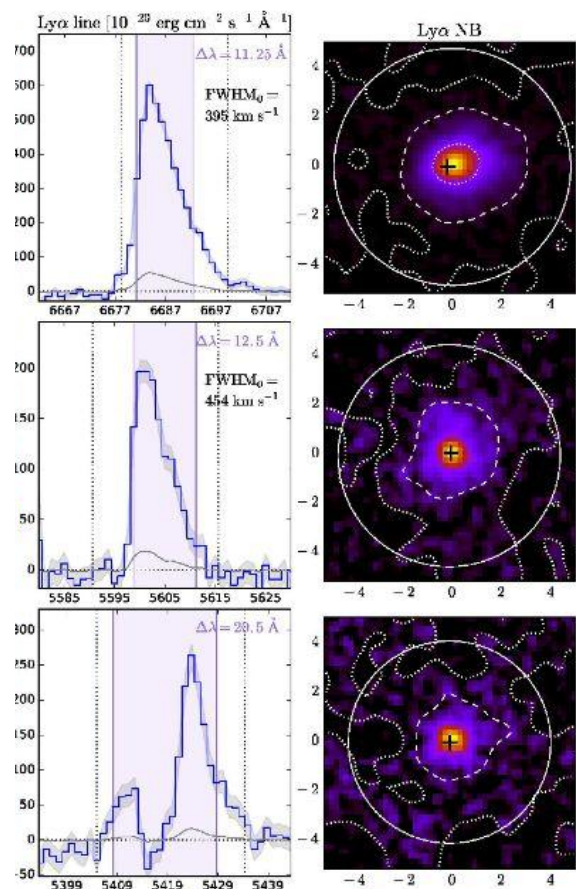
We find that **extended halos ( $r_{sH} > 5$  kpc) are more common than detected.**

Applying a **MUSE-Wide selection function** to a mock LAE population generated from simulated spectra **shows that outflow-dominated stages in the galaxy's star formation history are favorably detected.**

Future applications of this model and selection function:

- Improve Ly $\alpha$  luminosity functions with better completeness correction
- Test simulated galaxy spatial characteristics
- Compare intrinsic parameter distributions with host galaxy properties observed in other data (e.g. from HST/JWST)

# Extra Slides



Leclercq et al. 2017

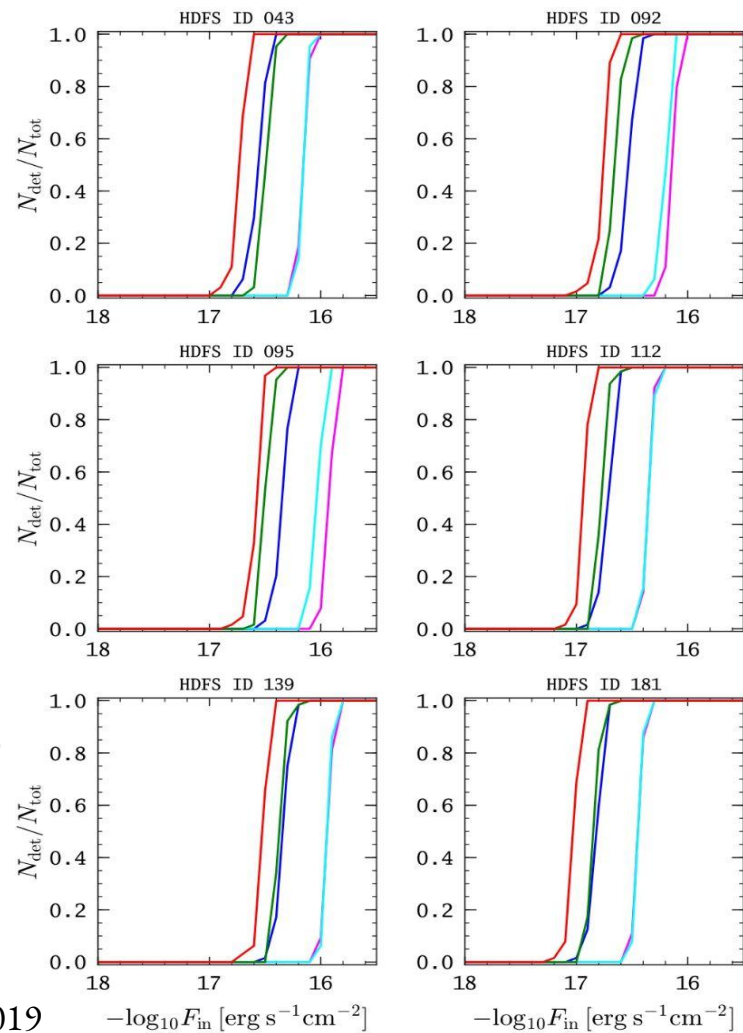
# Observing Ly $\alpha$

Ly $\alpha$  spatial/spectral profiles  
vary dramatically.

This diversity is important for  
understanding the CGM.

But different spatial/spectral  
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To understand how Ly $\alpha$  relates  
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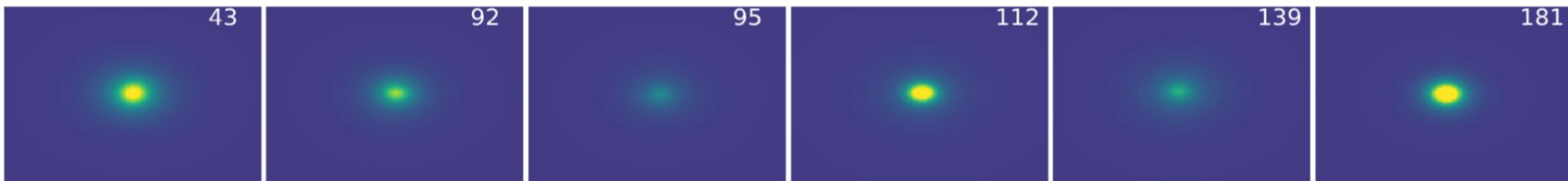
Herenz et al. 2019

# LAH Selection Function - the LAH Spatial Model

We model the spatial profile as a 2-component exponential disk

$$F(r) = \Sigma_C(r) + \Sigma_H(r) = \Sigma_{C0}e^{-r/r_{sC}} + \Sigma_{H0}e^{-r/r_{sH}}$$

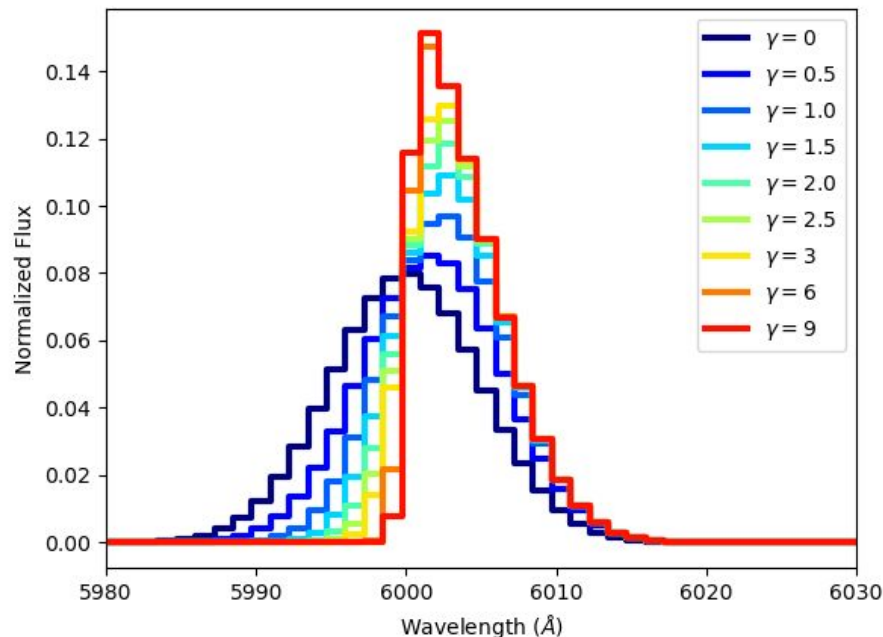
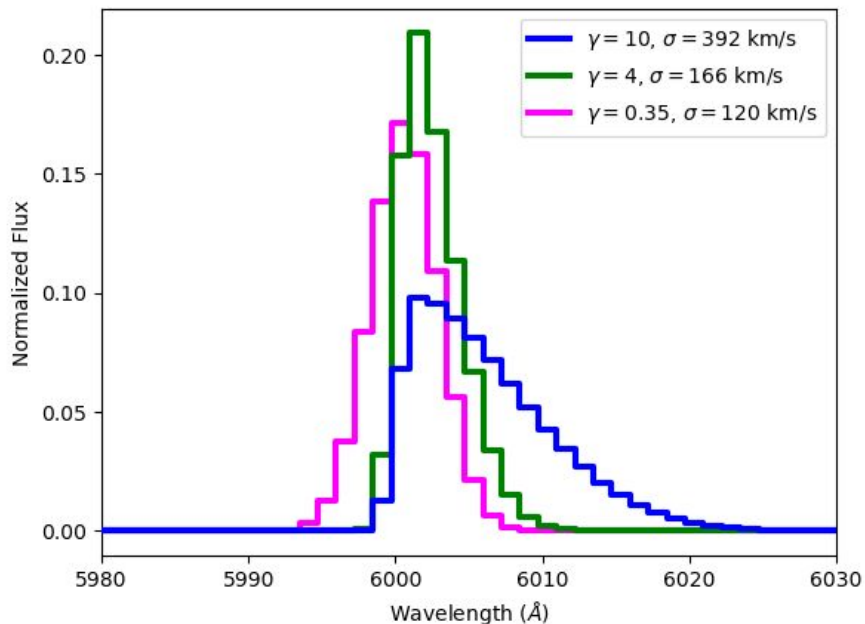
Halo flux fraction:  $f_H = \frac{F_H}{F_H + F_C}$  Ellipticity  $q$



# LAH Selection Function - the LAH Spectral Model

We model the spectral profile as a skewed Gaussian

$$f(x; A, \mu, \sigma, \gamma) = \frac{A}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \left\{ 1 + \operatorname{erf} \left[ \frac{\gamma(x-\mu)}{\sigma\sqrt{2}} \right] \right\}$$

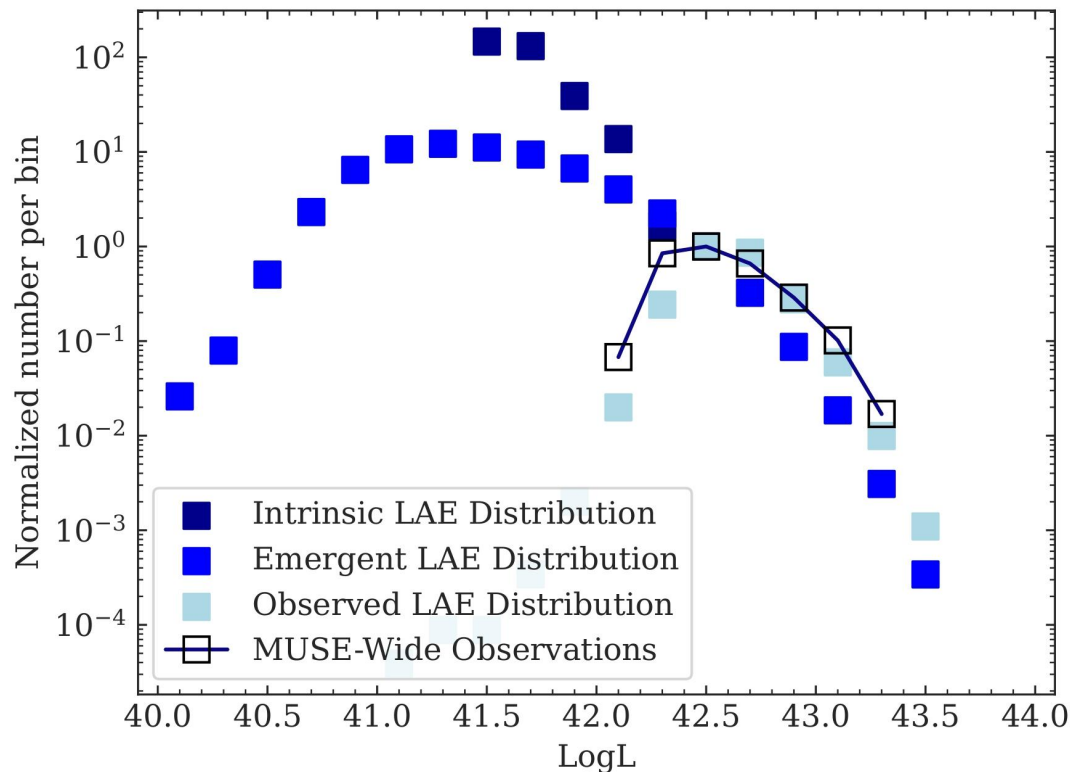


# Luminosity Functions

Intrinsic LF: Schechter function  
with  $\log L^* = 42.1$ ,  $\alpha = -1.84$

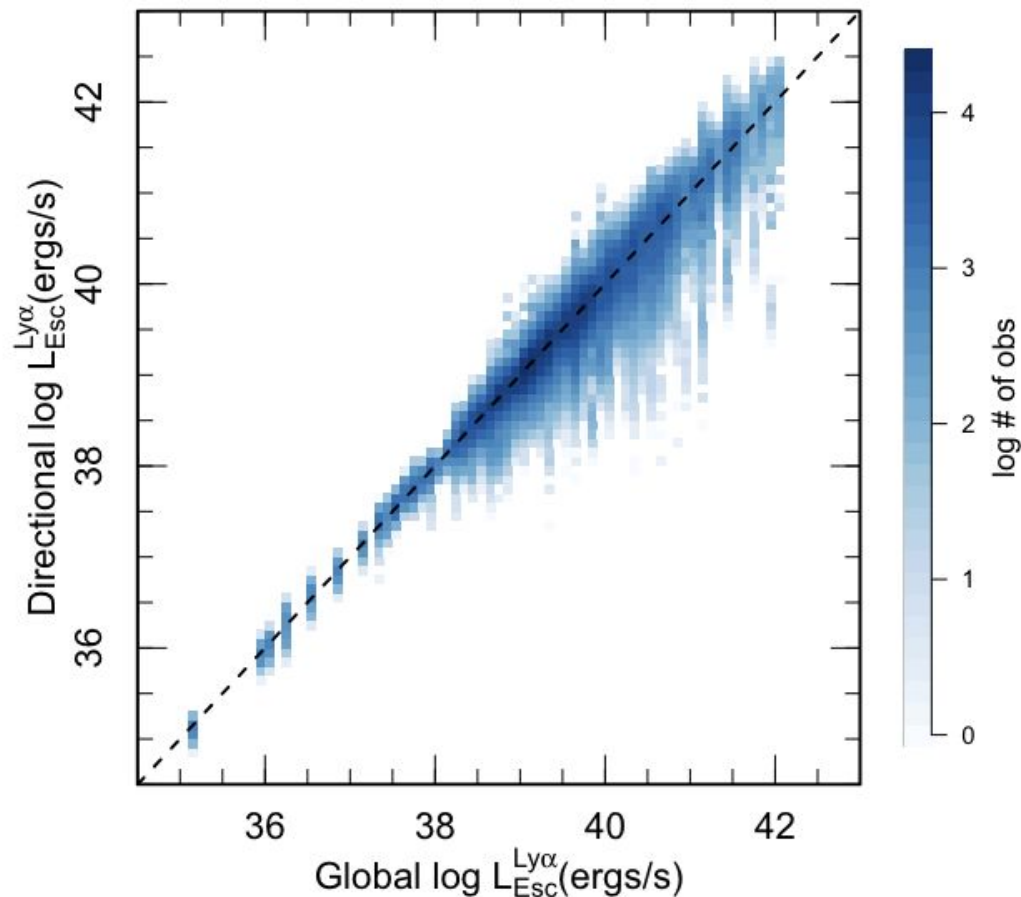
Intrinsic luminosities drawn from  
range  $41.5 < \log L < 43.5$

Chosen to try to replicate shape of  
observed LAE counts in  
Herenz+2019



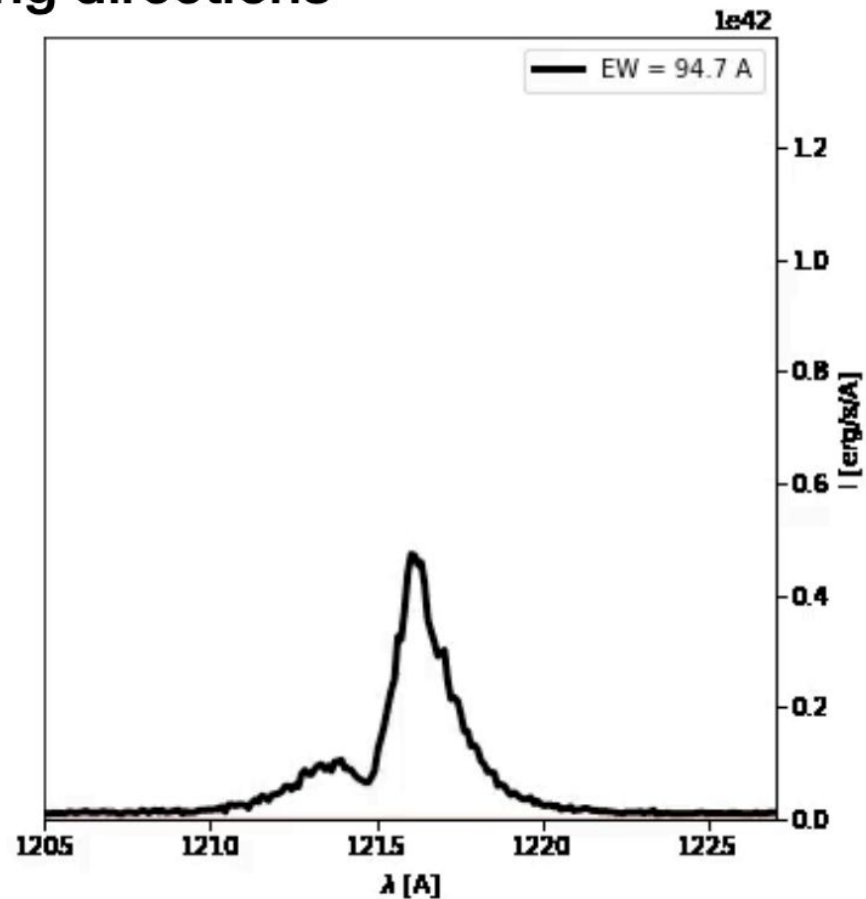
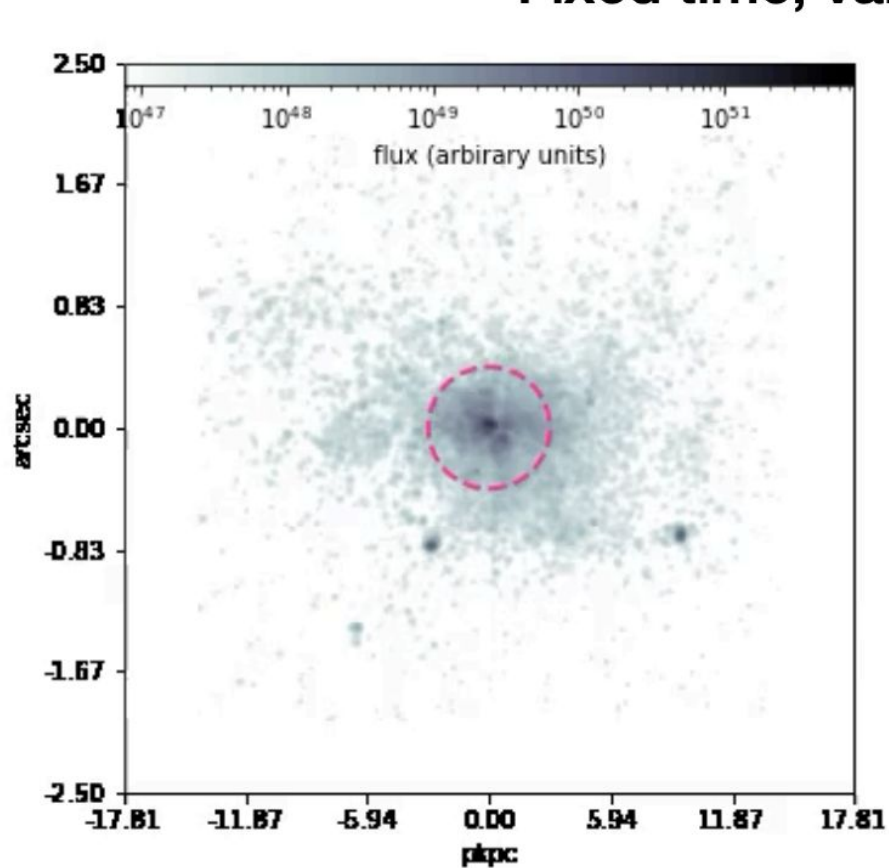
## Caveat: Global vs Directional Luminosity

- Paper by Moupiya Maji 2022 simulating Ly $\alpha$  and LyC escape in SPHINX galaxies

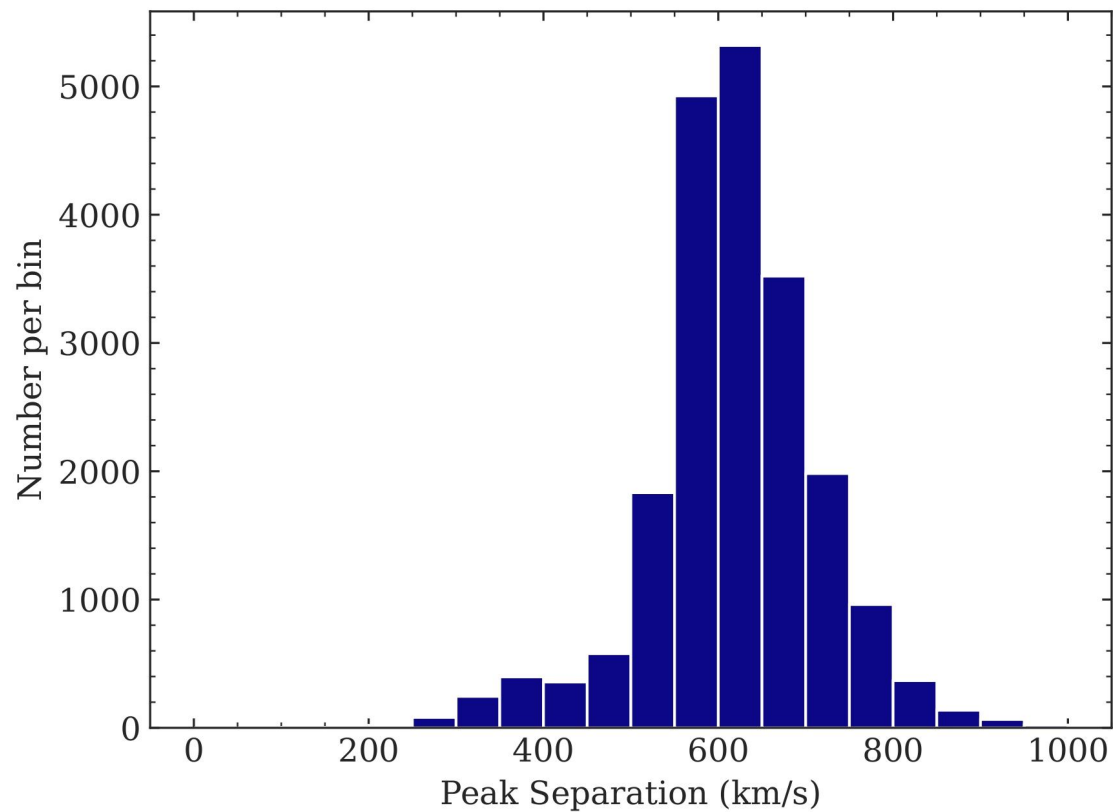


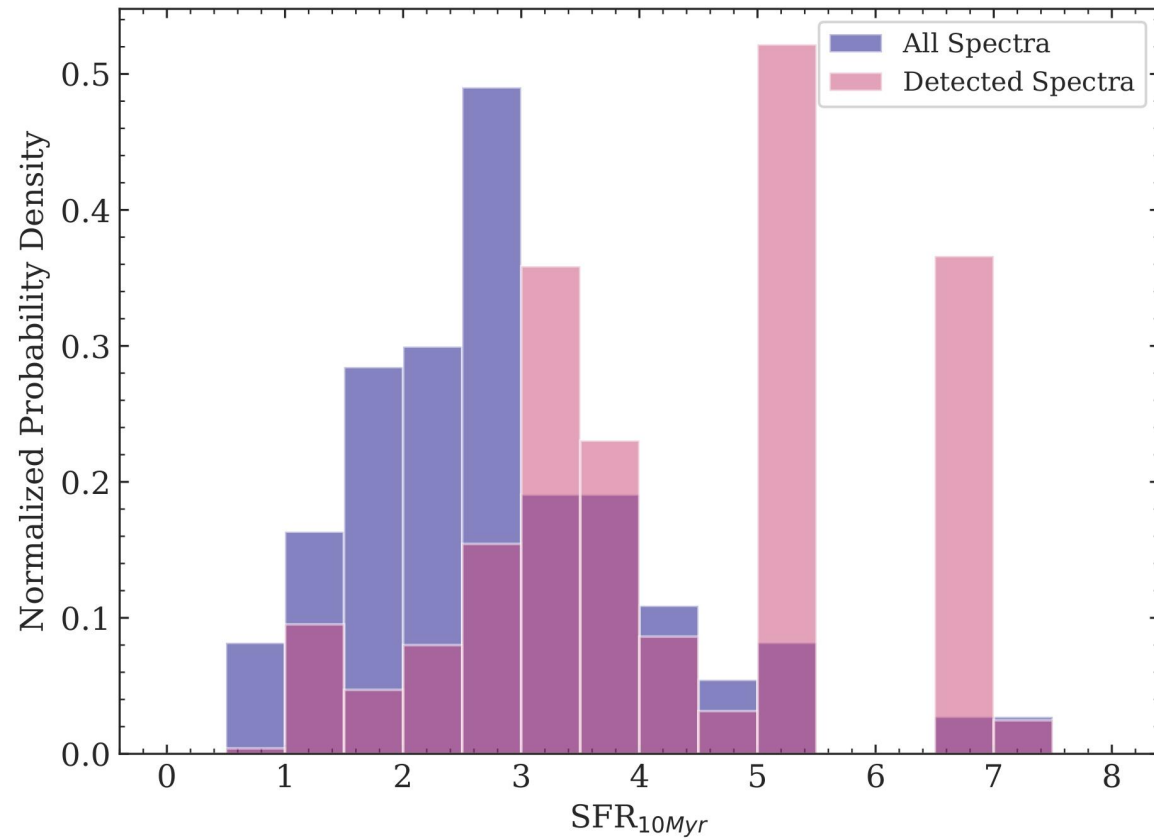


## Fixed time, varying directions



# Blue and Red Peak Separations

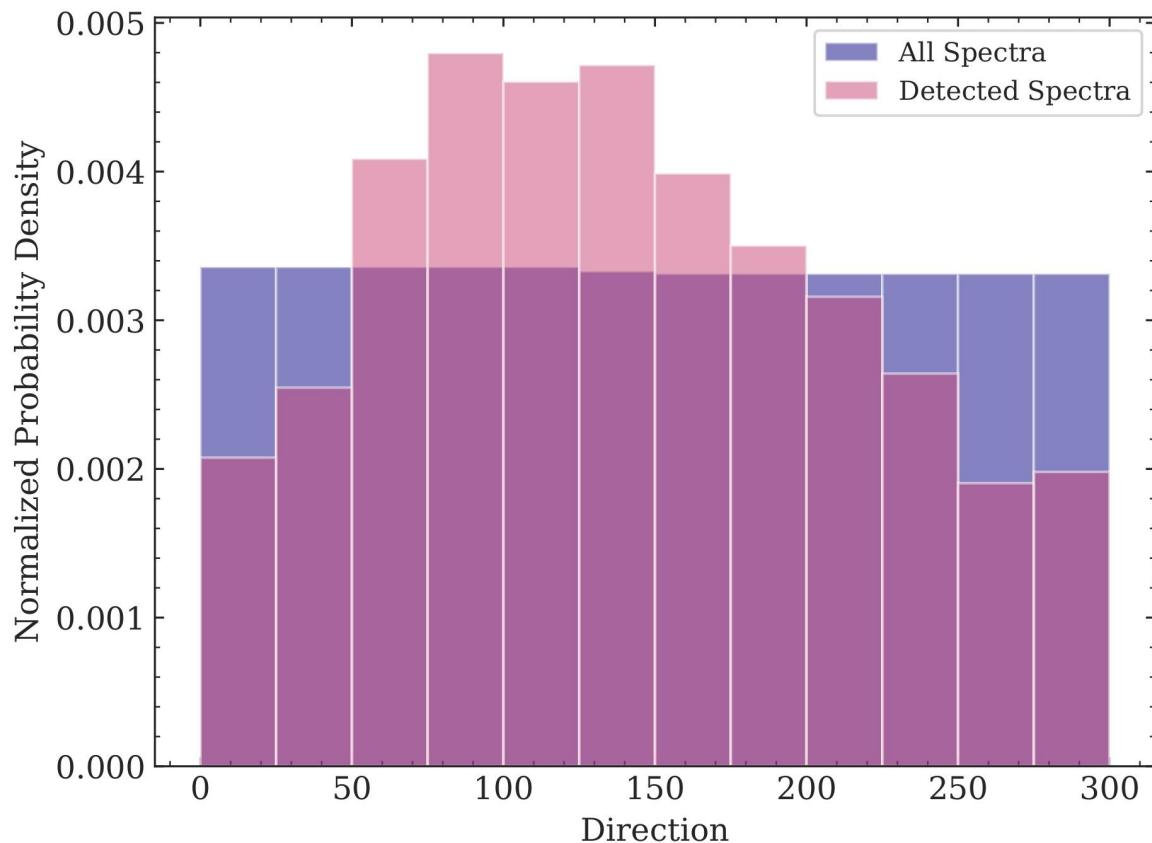




# Direction Dependence?

There's definitely some selection on viewing orientation, but I need to know the mapping to inclination to properly interpret.

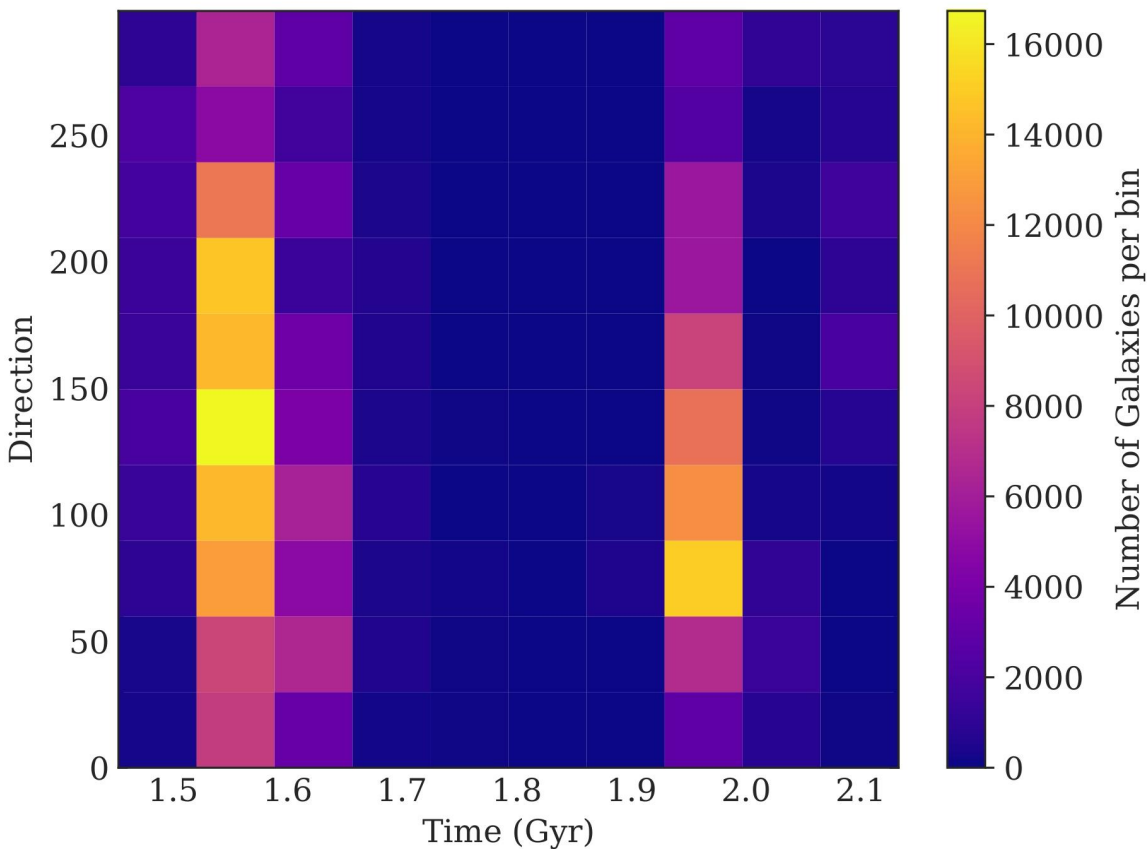
Also, binning could be smoothing over more specific differences.



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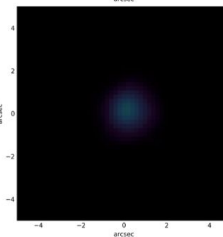
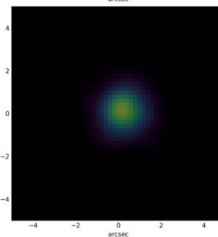
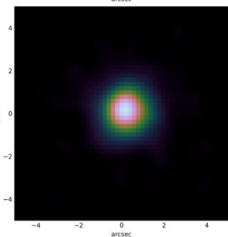
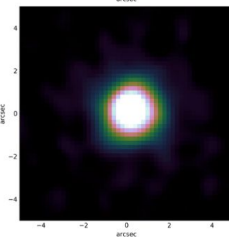
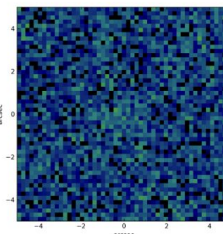
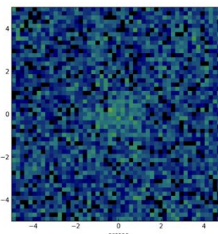
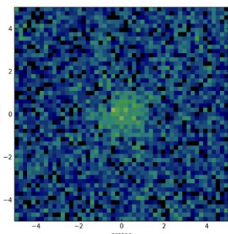
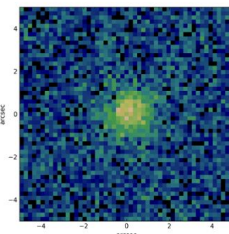
Also, binning could be smoothing over more specific differences.



**Real  
galaxy,  
typical  
Ly $\alpha$  halo**

Flux

S/N



$f$  [erg s $^{-1}$  cm $^{-2}$ ] =

$4 \times 10^{-17}$

$2 \times 10^{-17}$

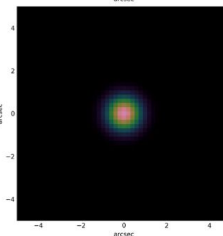
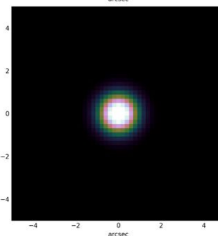
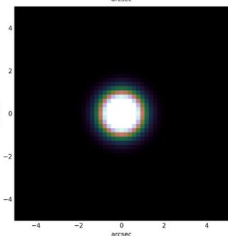
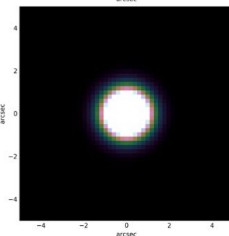
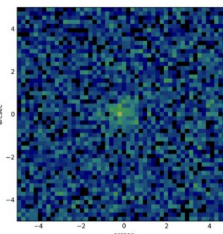
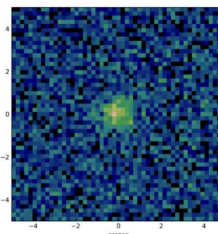
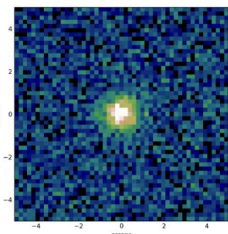
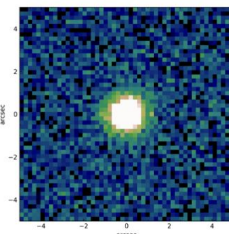
$1 \times 10^{-17}$

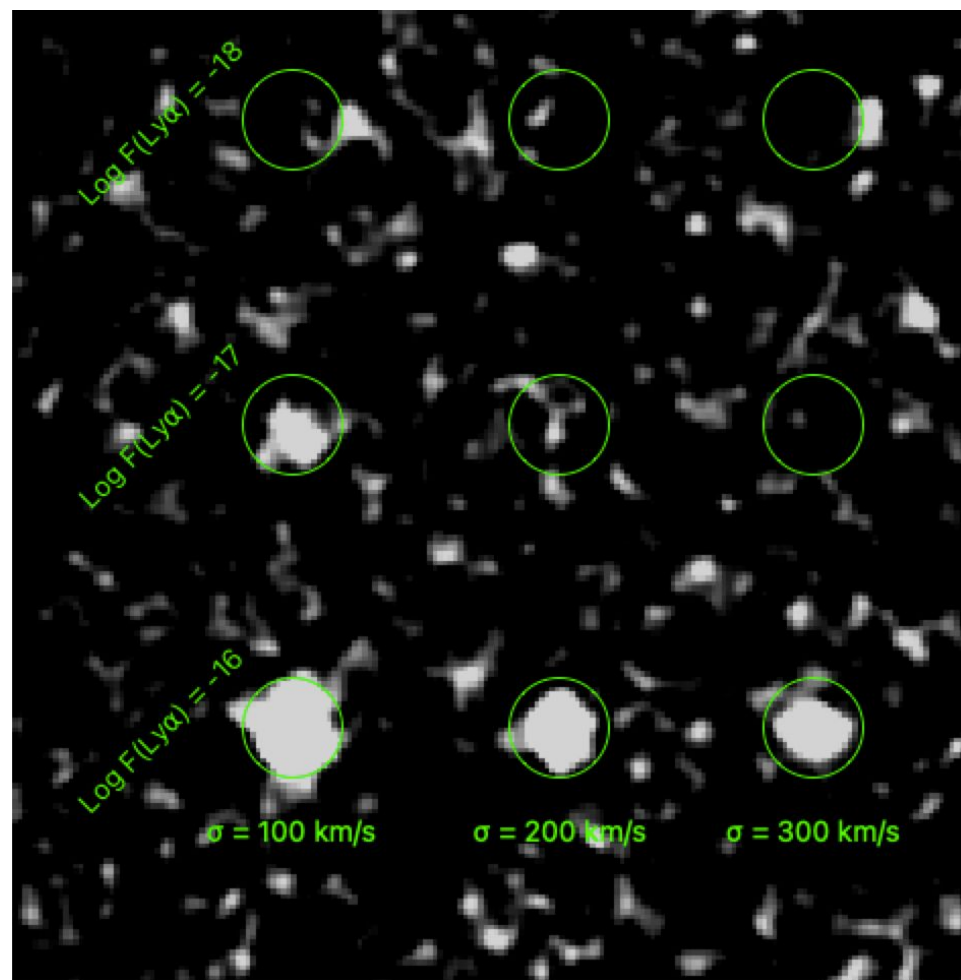
$5 \times 10^{-18}$

**Point  
source**

Flux

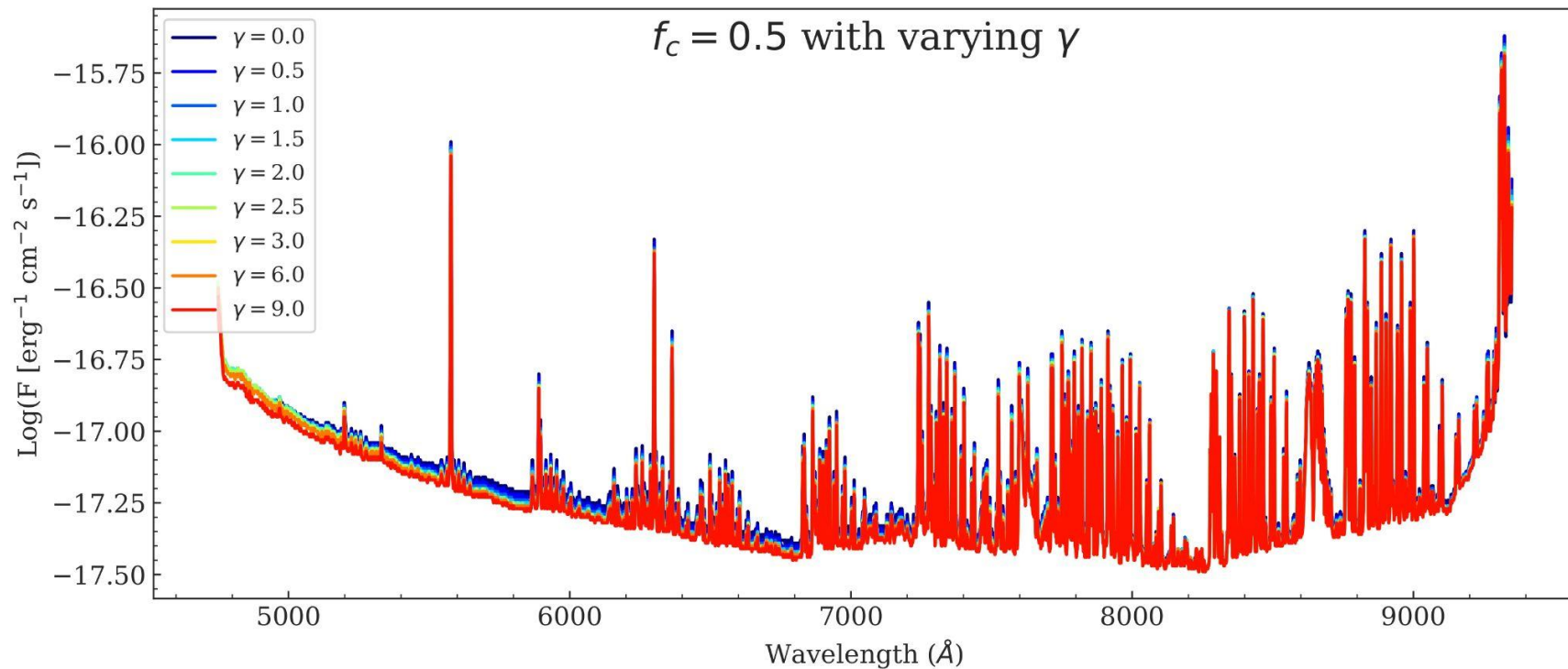
S/N



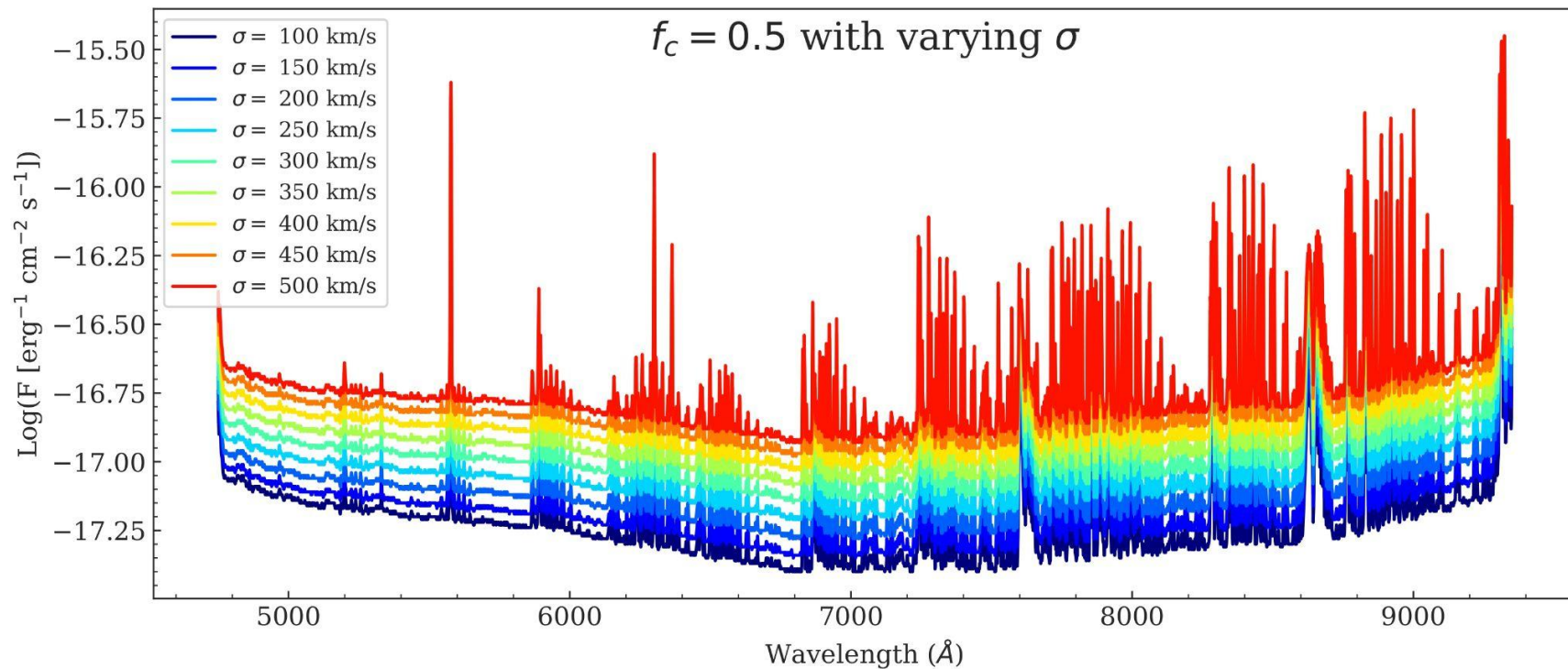




# LAH Selection Function - Parameter Tests



# LAH Selection Function - Parameter Tests



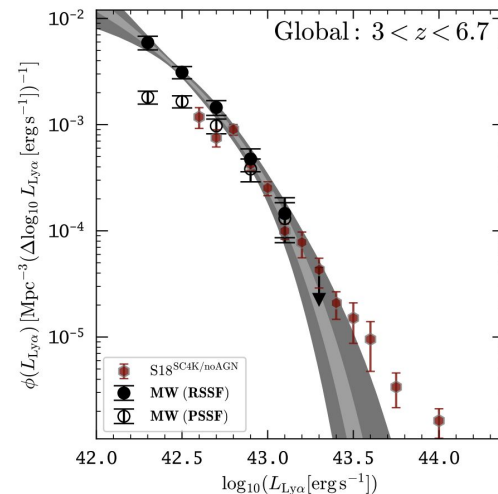
# Recovering the LAH Distribution - the $1/V_{\max}$ Estimator

We then correct the UDF distribution by measuring  $V_{\max}$  for each LAH in the sample, using a form that incorporates the completeness fraction  $f_c$ .

$$V_{\max,i} = \omega \int_{z_{\min}}^{z_{\max}} f_c(L_{Ly\alpha}, z) \frac{dV}{dz} dz$$

$$\phi_{1/V_{\max}}(\langle X_k \rangle) = \frac{1}{\Delta X_k} \sum_i \frac{1}{V_{\max,i}}$$

Then to estimate the corrected distributions, we bin measures of  $1/V_{\max}$  in each of the three main parameters:  $\sigma$ ,  $r_{\text{SH}}$ , and  $f_{\text{H}}$ .



Herenz et al. 2019

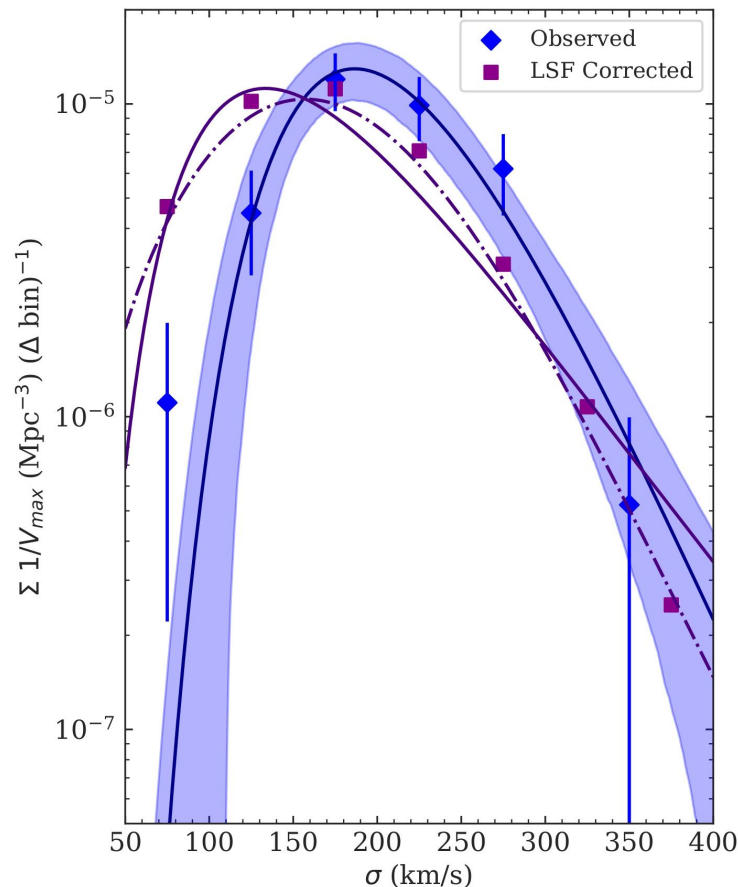
# The Intrinsic Line Width Distribution

We used observed (LSF-convolved)  $\sigma$  for the intrinsic distribution. Can we recover deconvolved line widths? ( $\sigma_0$ )

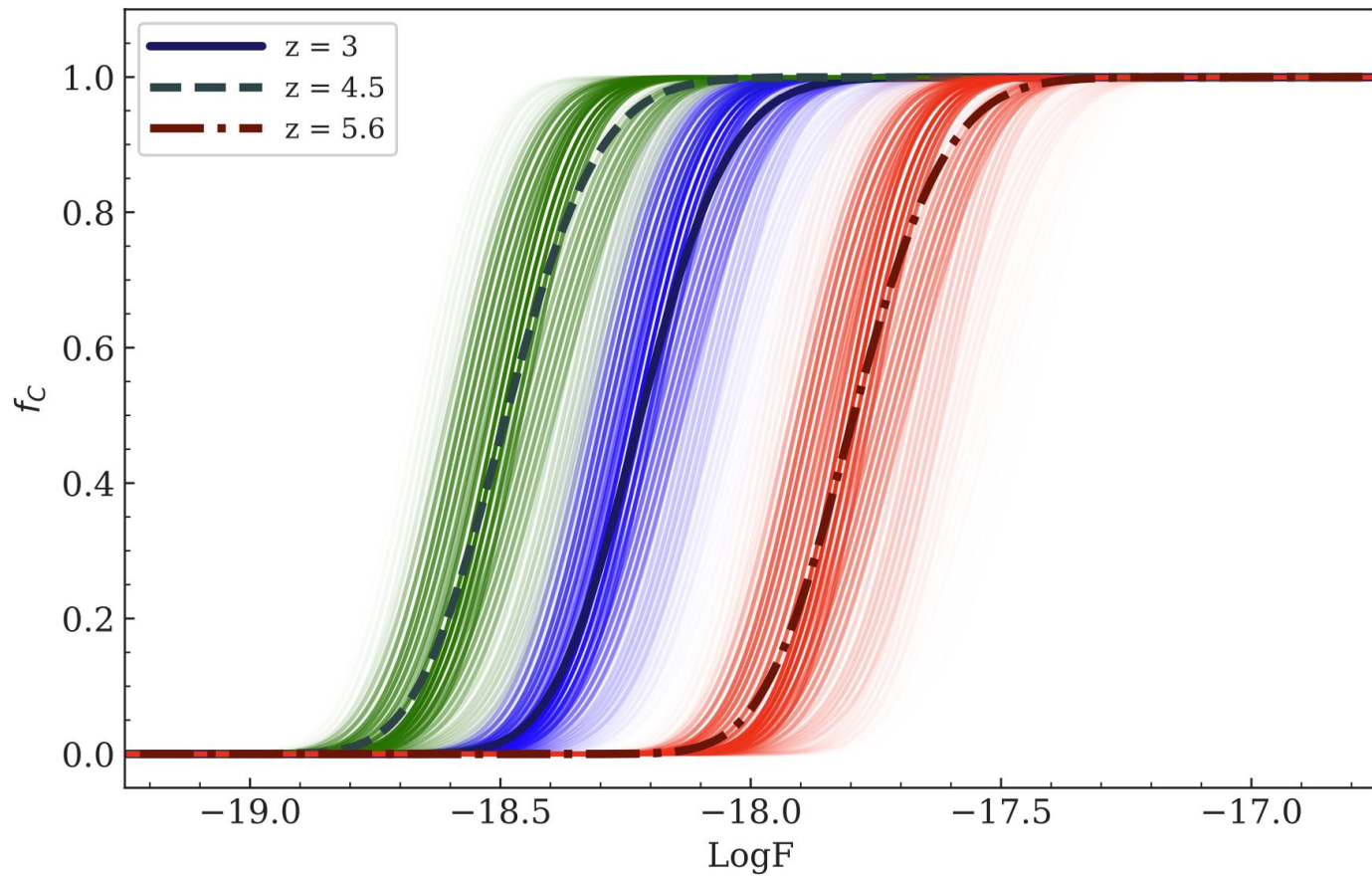
We construct a large mock sample matching  $z$  and  $\sigma$  distributions, then do the deconvolution.

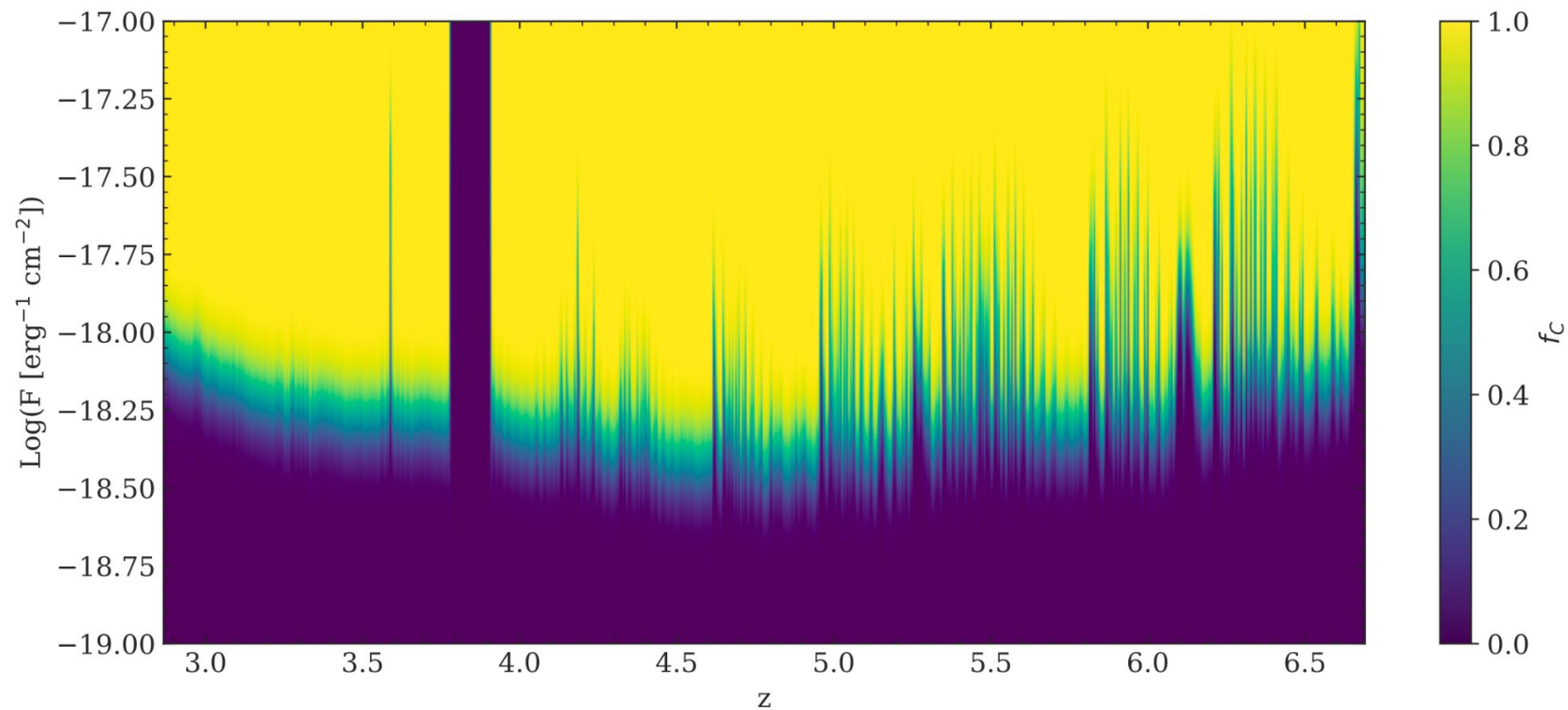
This shifts the peak width lower by  $\sim 30$  km/s, comparable to Claeysens+2024.

Distribution of  $\sigma$  might have implications for shell model, evidence of ionization channels, spatial extent of halo.



# MXDF Selection Functions





# Results So Far and Further Questions

We model Ly $\alpha$  Halos and test their detectability: key parameters are line width ( $\sigma$ ), halo scale length ( $r_s H$ ), and halo flux fraction ( $f_H$ )

With a model grid, we develop selection functions that finds the completeness fraction for halos at varying redshift and intrinsic line luminosity.

We use this to determine corrected halo parameter distributions - extended halos ( $r_s H > 5$  kpc) are more common than detected!

Can we relate these observed properties to more fundamental characteristics of LAE galaxies?

Read the paper at arXiv: 2409.04537





# Summary and Future Steps

We use a spatial/spectral model of LAHs to test halo detectability, make selection functions for MUSE observations, and recover intrinsic distributions of halo parameters.

This shows that extended halos ( $r_{sH} > 5$  kpc) are more common than detected.

We apply a MUSE-Wide selection function to a mock LAE population generated from spectra of a simulated star-forming galaxy at  $z \sim 3.5$ .

The selection shows that certain time periods in the galaxy's star formation history will be favorably detected - primarily those where outflows are dominating.

There are many future applications of this model and selection function:

- Test spatial characteristics of simulated galaxy
- Produce Ly $\alpha$  luminosity functions with improved completeness correction
- Compare our intrinsic parameter distributions with host galaxy properties observed in rest optical/infrared with data from HST/JWST