Cosmic Reionization proved by JWST observations of high-z galaxies

JWSTによる遠方銀河観測で探る宇宙再電離

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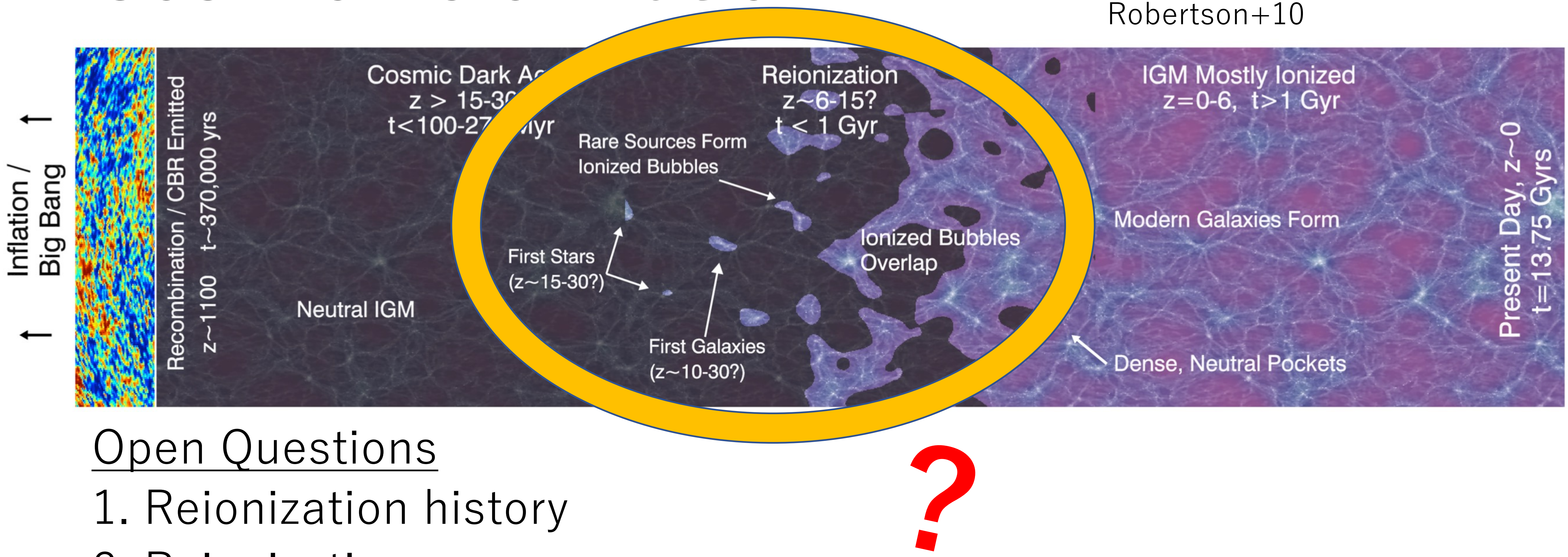
Cosmic Reionization

Robertson+10



Open Questions

1. Reionization history
2. Reionization source
3. Physical process

Cosmic Reionization History

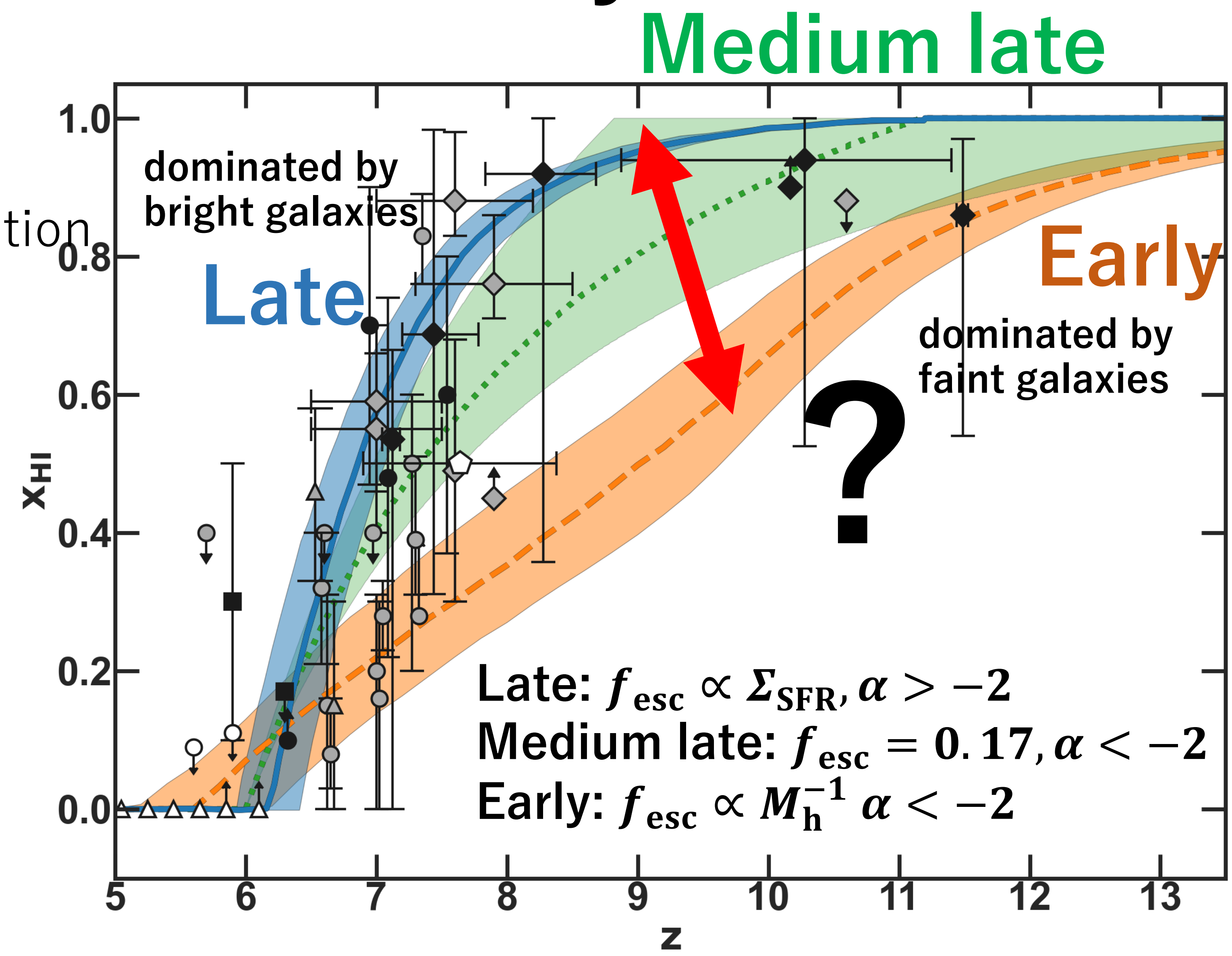
Reionization scenario

Redshift evolution of neutral fraction

$$x_{\mathrm{HI}} = \frac{n_{\mathrm{HI}}}{n_{\mathrm{HI}}+n_{\mathrm{HII}}}$$

- **Late** (Naidu+20)
- **Medium late** (Ishigaki+18)
- **Early** (Finkelstein+19)

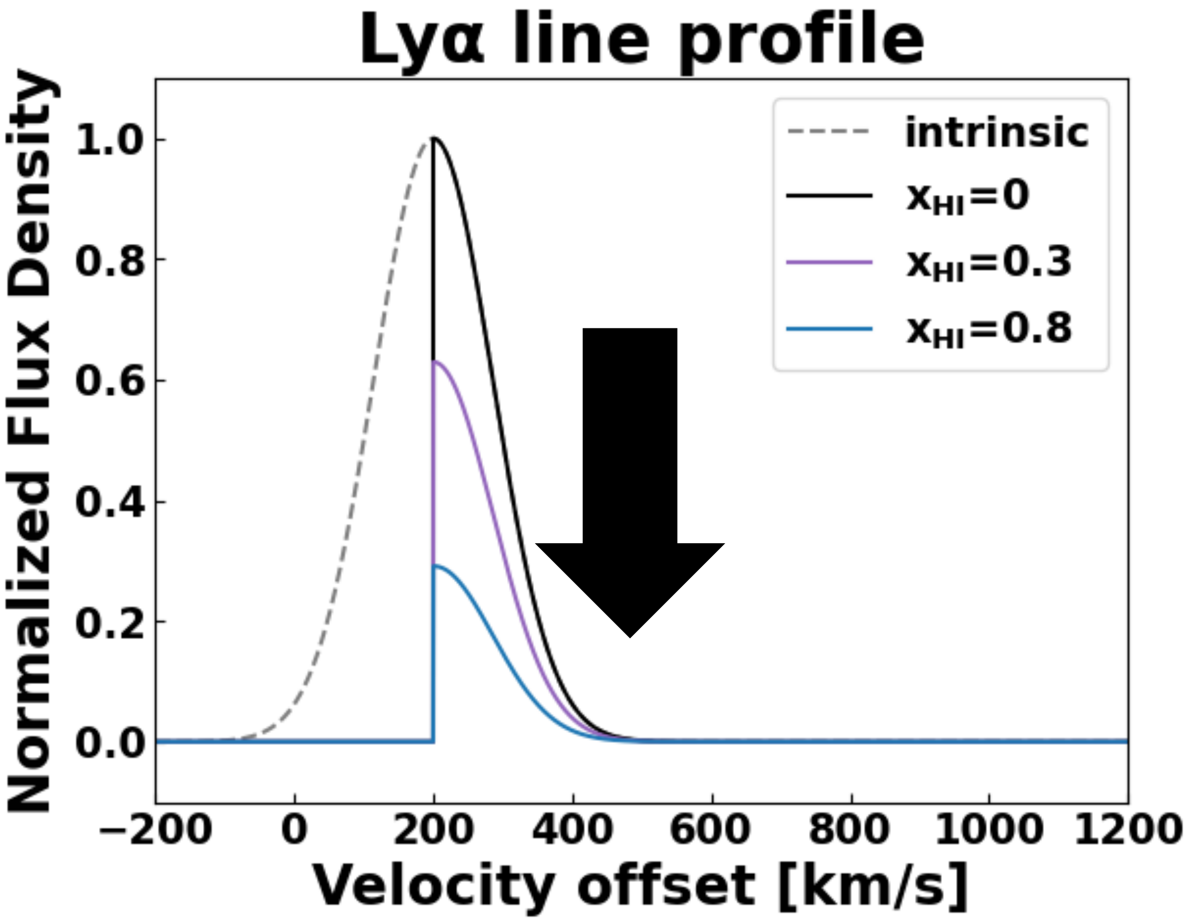
- Not strongly constrained



Lyα Emission

- Lyα emission line ($\lambda_{\mathrm{rest}} = 1216\text{Å}$) is strongly attenuated by HI in the IGM

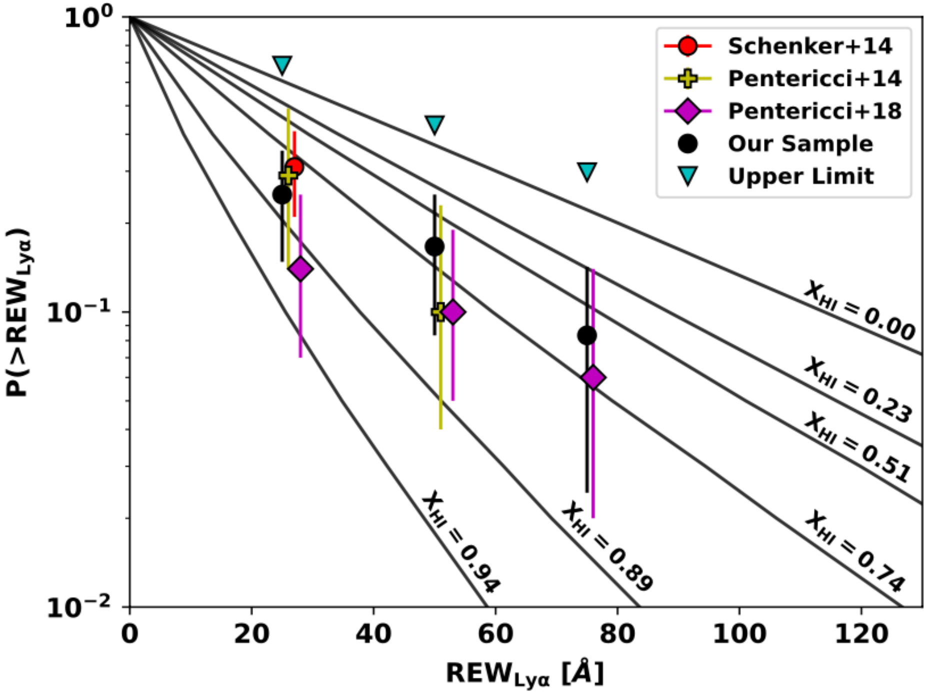
- Lyα EW is a good probe of x_{HI}



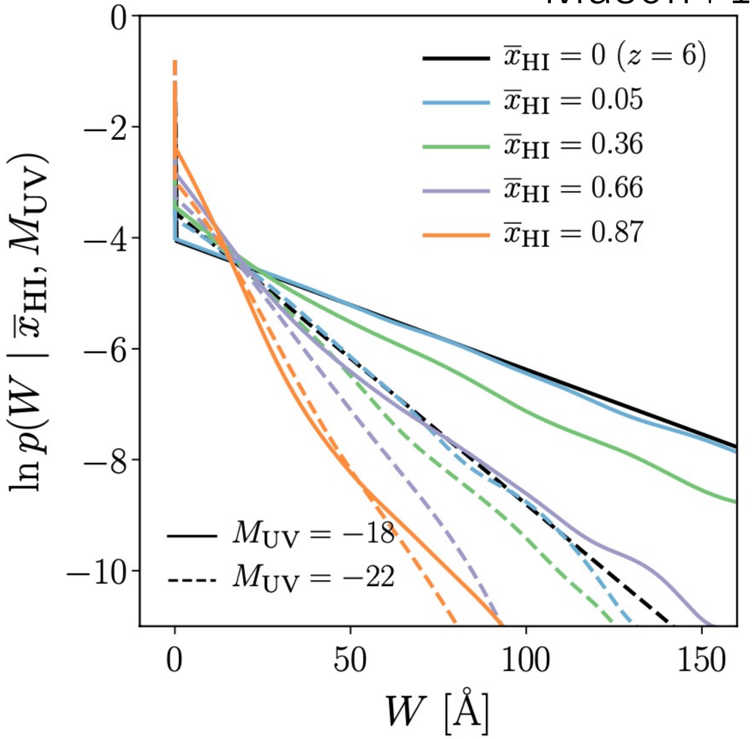
Ly α Equivalent Width

- Ly α fraction: the fraction of LAEs among LBGs
- Using full distribution of EW (Mason+18)

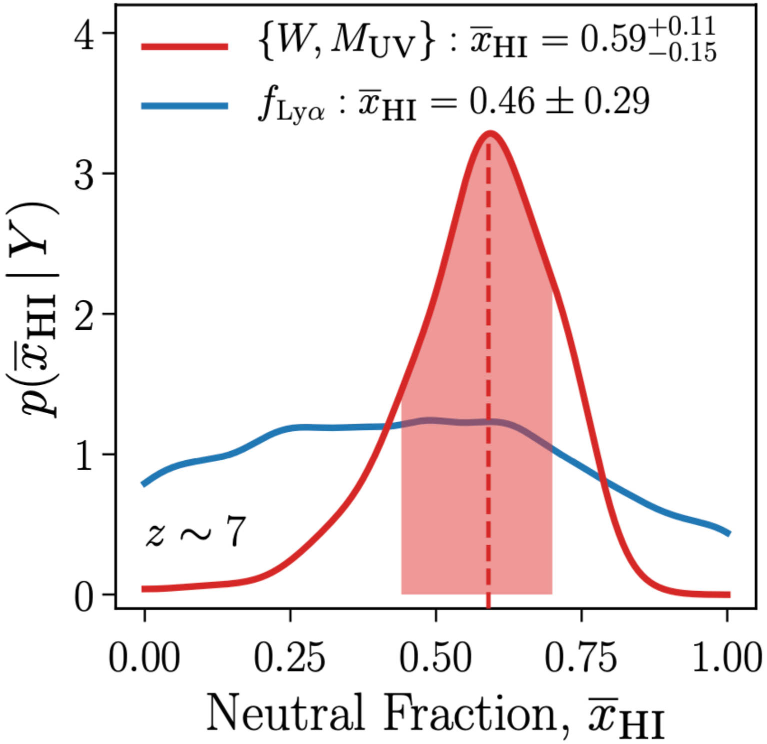
Jones+23



Mason+18

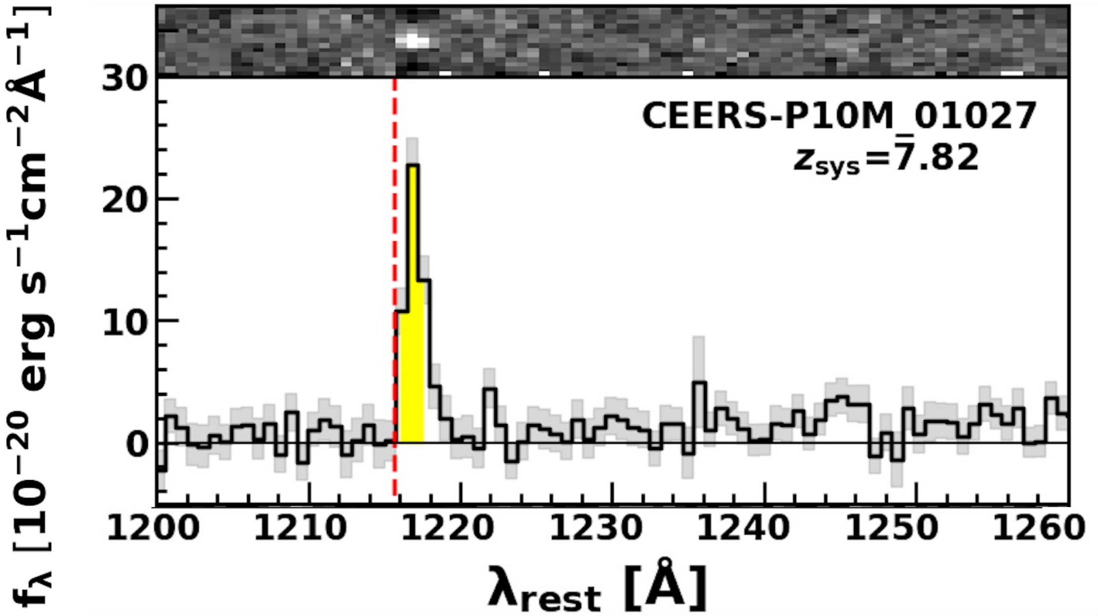


Mason+18

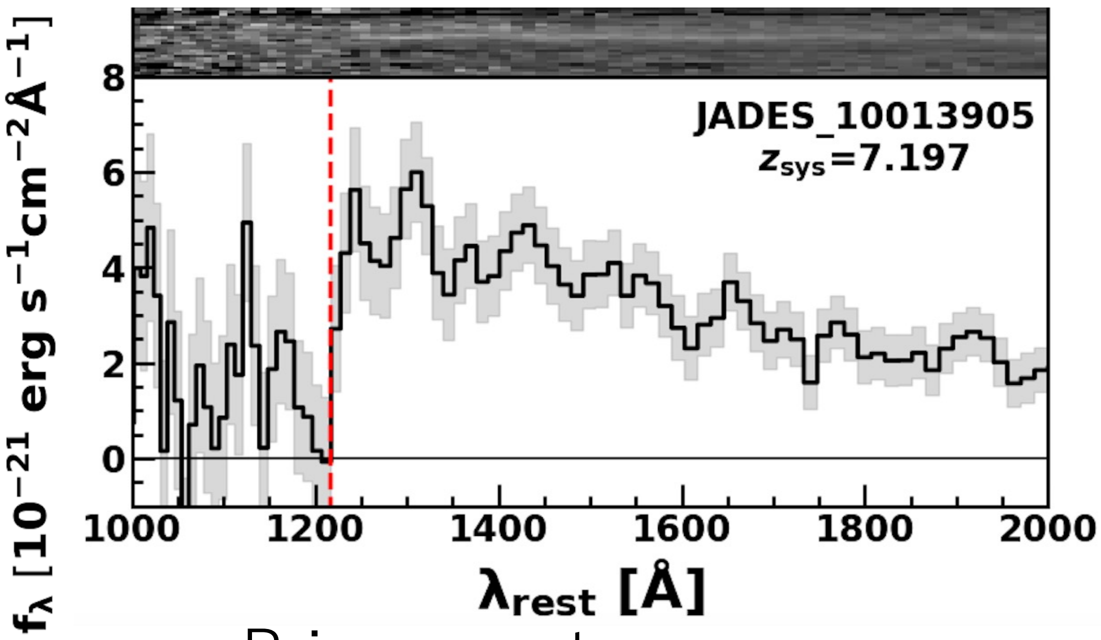


JWST Data

- JWST/NIRSpec observations
- ERS (GLASS, CEERS), GO, DDT, and GTO (JADES) programs
- High-resolution grating (R~2700), Medium-resolution grating (R~1000), and Prism (R~100) spectra



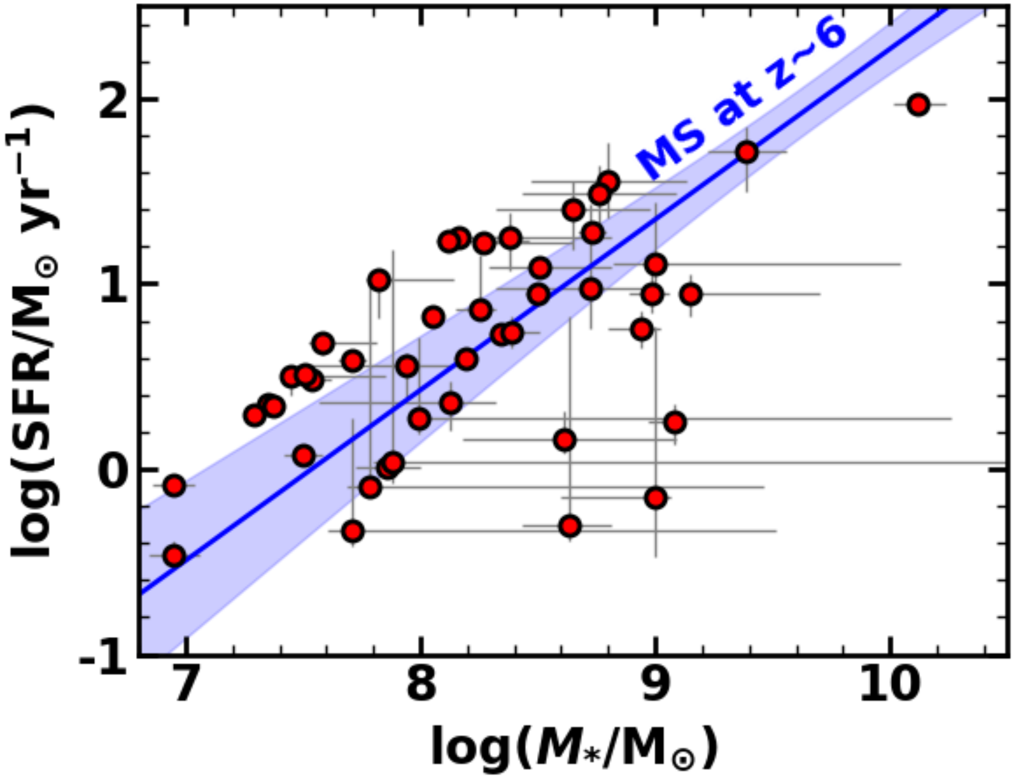
Medium-resolution spectrum



Prism spectrum

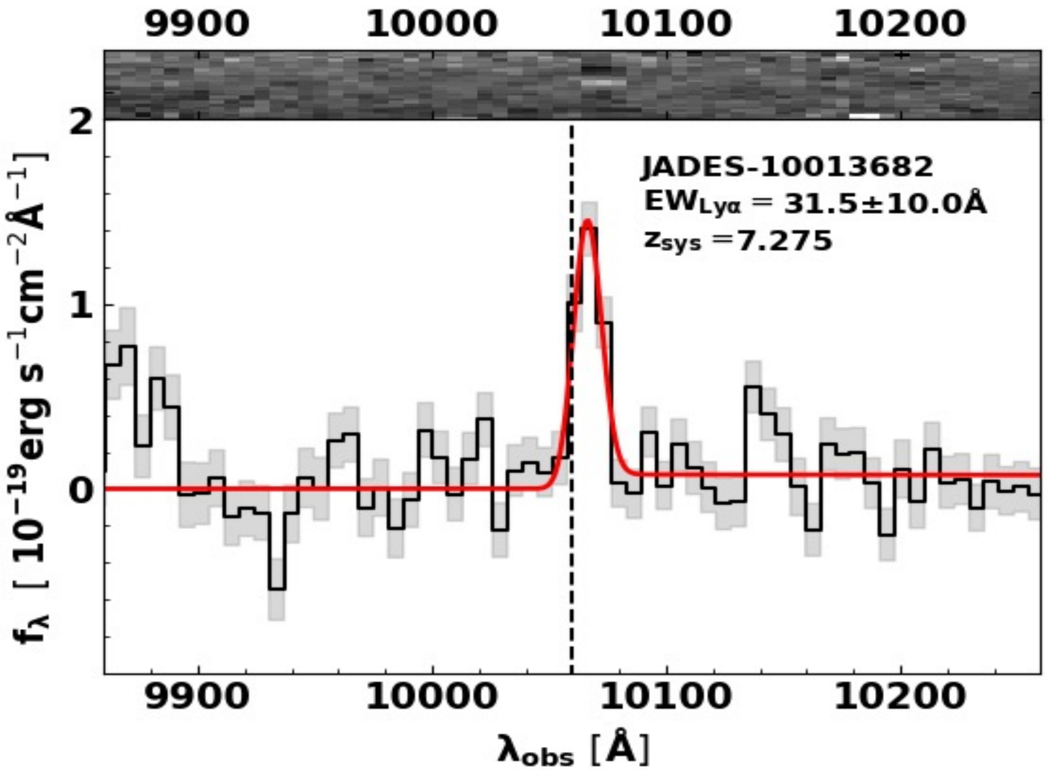
Sample Galaxies

- 54 galaxies at 6.6<z<13.2 with -22.5<$\mathrm{M_{UV}}$<-17.0
- Include GNz-11 at z~10.6 (Bunker+23)
- Redshifts are spectroscopically confirmed
- Fall on star-formation main sequence at z~6



Spectral Fitting

- Continuum + Ly α line + IGM absorption(Inoue+14)
- Convolved with LSF(Isobe+23)
- Ly α velocity offset, line width, and EW measurements



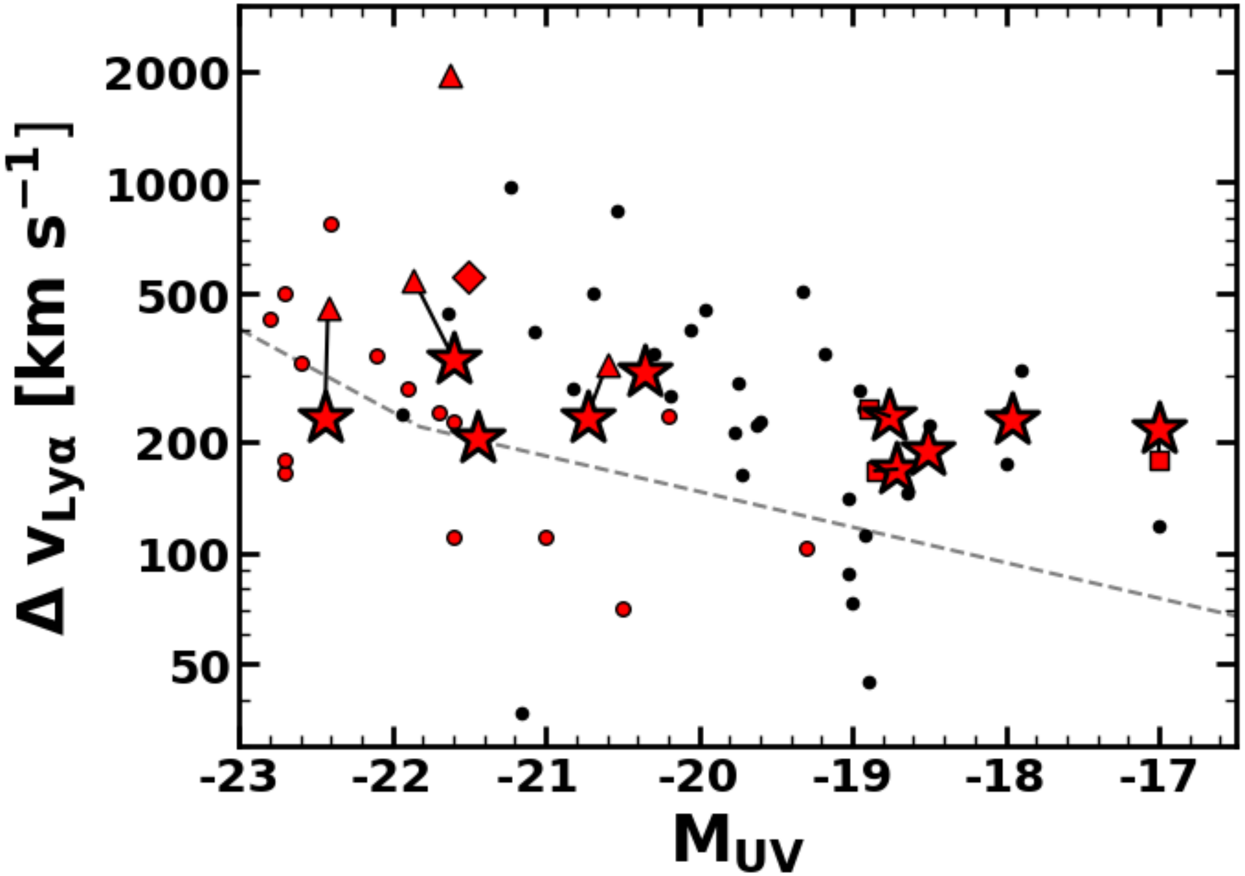
Ly α detections

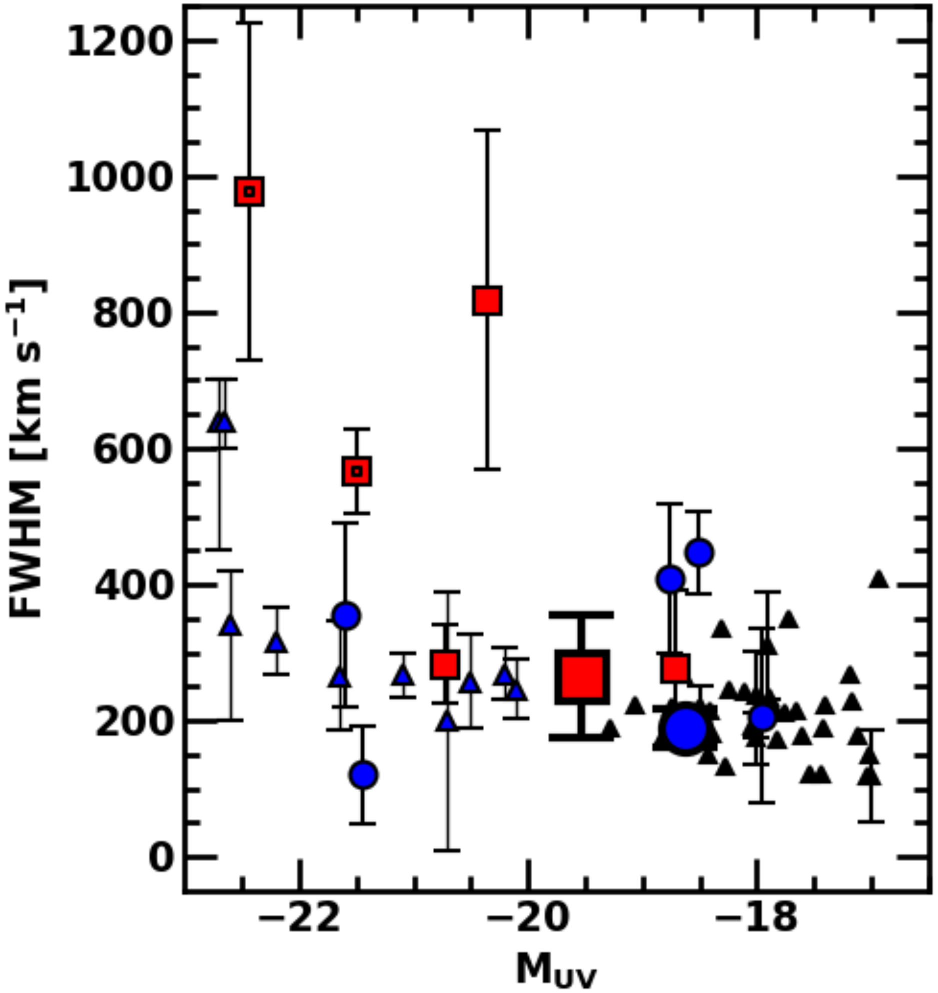
- 15/54 galaxies with Ly α detections (S/N>3)

ID	z_{sys}	$z_{\mathrm{Ly}\alpha}$	$\mathrm{EW}_{0,\mathrm{Ly}\alpha}$ [Å]	$\Delta v_{\mathrm{Ly}\alpha}$ [km s^{-1}]
(1)	(2)	(3)	(4)	(8)
JADES_00016625	6.631	6.637	26.6 ± 21.3	234 ± 31
JADES_00003334	6.706	6.712	16.5 ± 12.6	229 ± 113
JADES_00004297	6.713	6.718	36.6 ± 14.9	188 ± 54
CEERS_00044	7.104	–	62.6 ± 58.4	–
CEERS_00439	7.179	–	33.8 ± 23.9	–
JADES_10013682	7.275	7.281	31.5 ± 10.0	215 ± 23
GLASS_10021	7.286	7.292	3.2 ± 2.9	203 ± 32
CEERS_00698	7.471	7.480	5.4 ± 3.0	334 ± 64
CEERS_80239	7.487	–	105.3 ± 72.1	–
CEERS_00686	7.752	–	20.4 ± 19.9	–
CEERS_01027	7.821	7.828	17.9 ± 7.5	232 ± 56
GLASS_10000	7.881	7.890	7.5 ± 3.8	308 ± 102
JADES_00021842	7.98	7.985	18.8 ± 14.6	168 ± 91
CEERS_01019	8.679	8.686	3.4 ± 3.3	231 ± 54
GNz-11	10.603	10.624	18.0 ± 2.0	555 ± 32

Evolution of Lyα Properties

- No evolution of velocity offset and FWHM

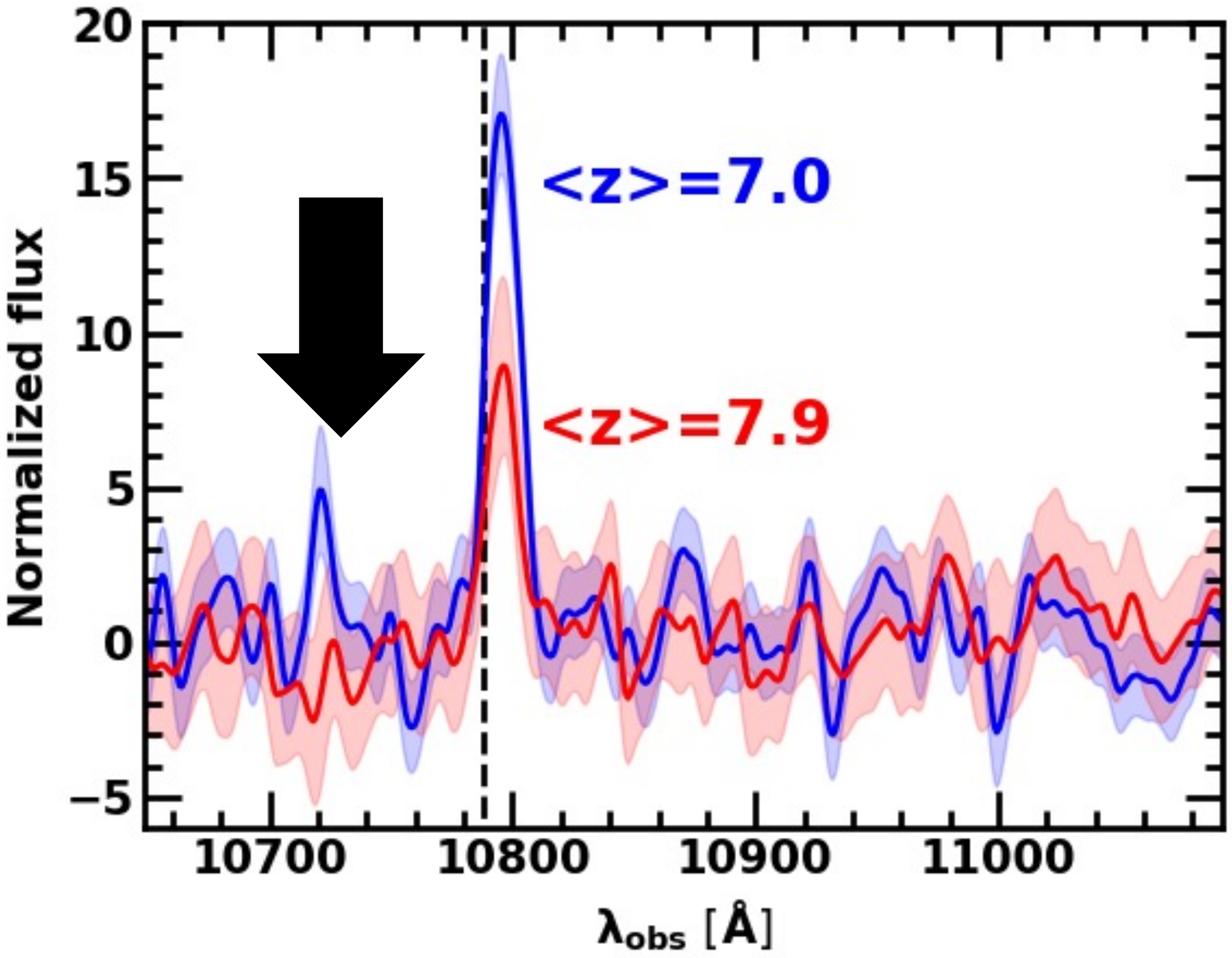




Composite Spectra

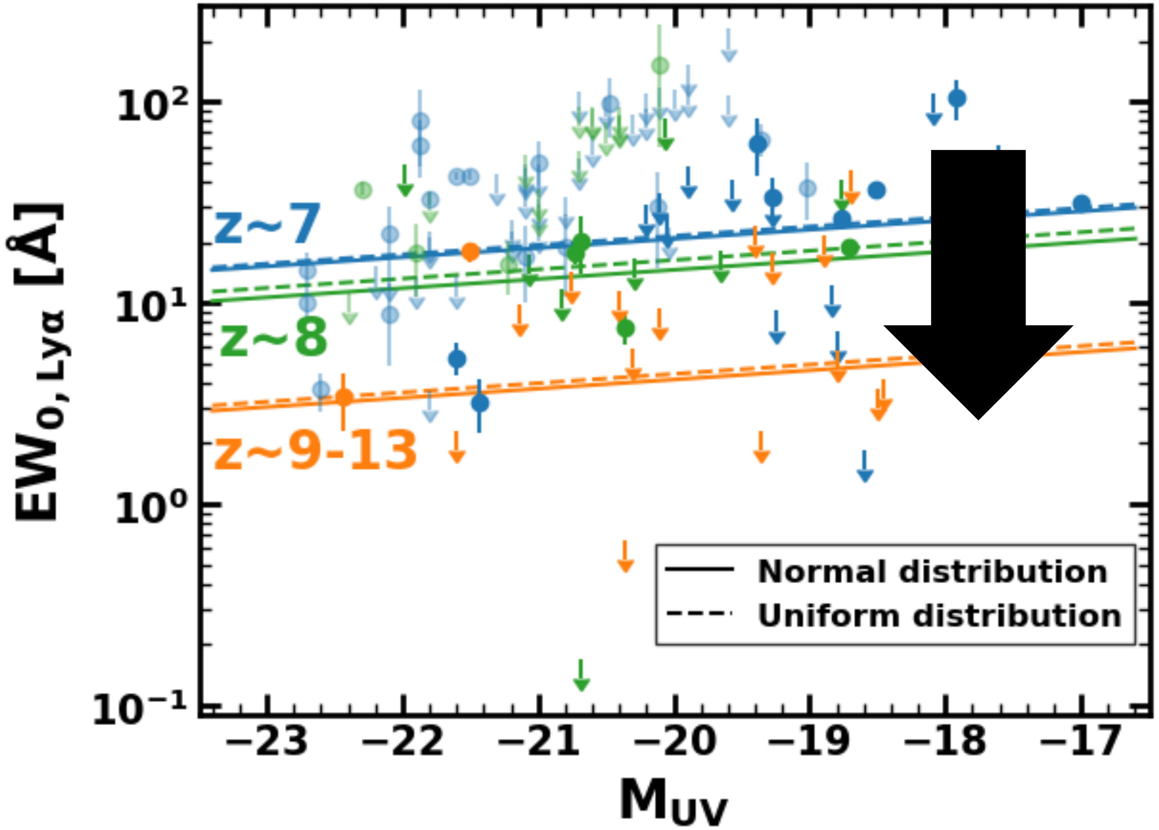
- Stacking spectra normalized with continuum fluxes

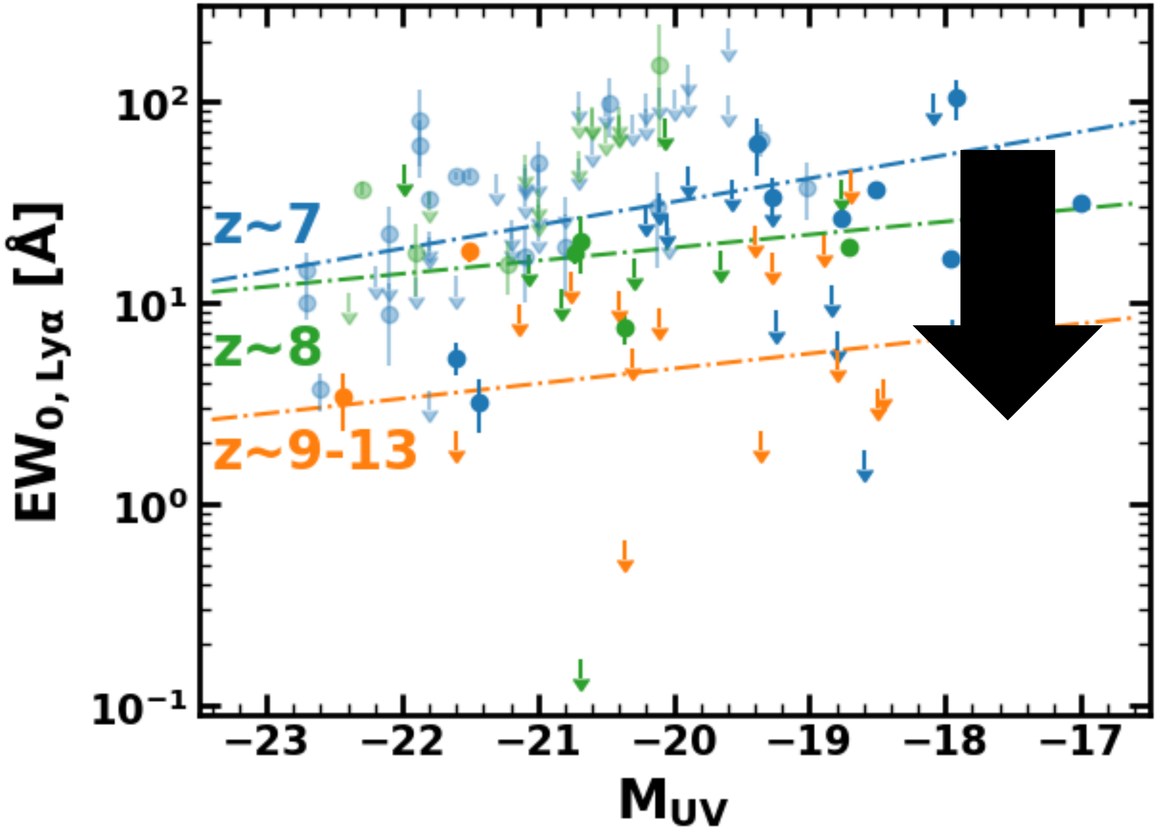
- Clear evolution of peak flux
→EW evolution



Evolution of Ly α EW

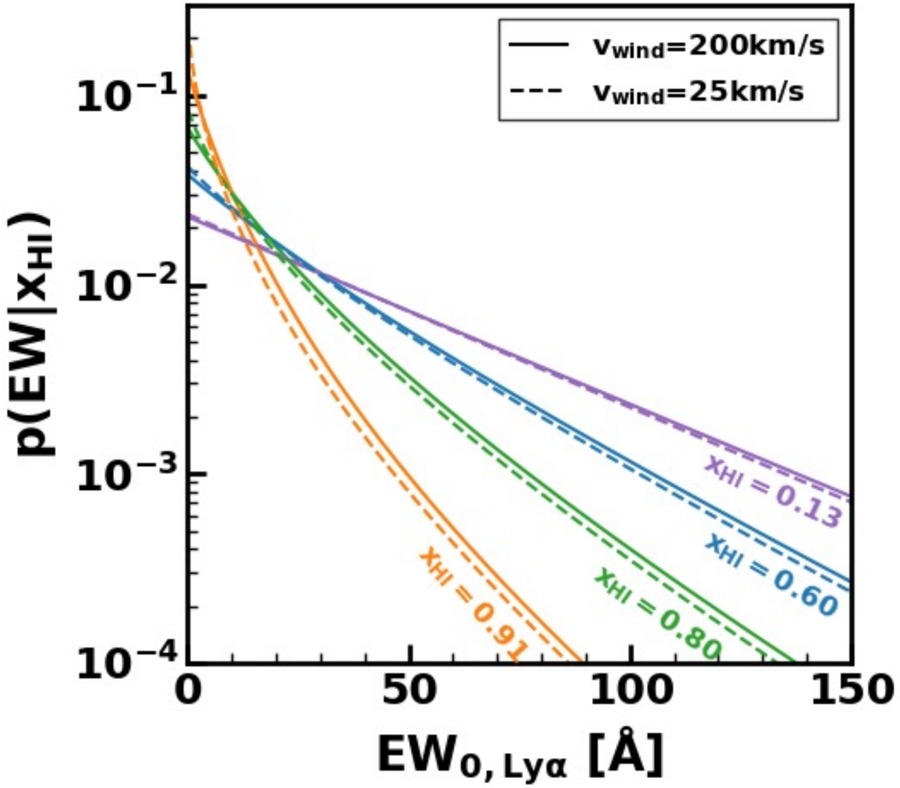
- Measurements of EW and 3 σ upper limits
- Evolution of Ly α EW → $x_{\rm HI}$ evolution

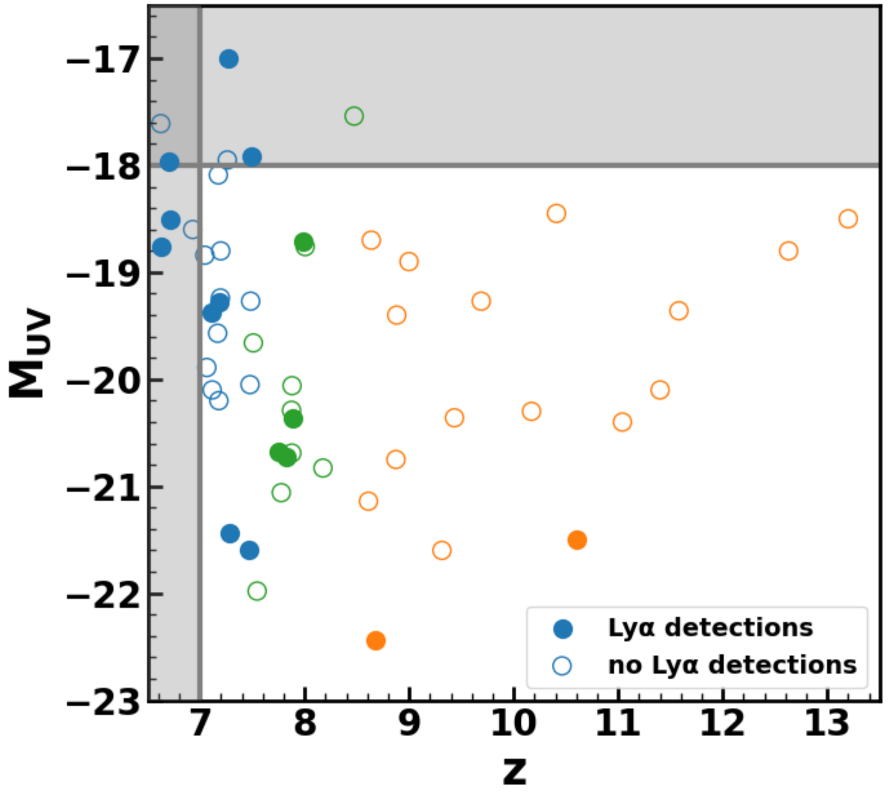




EW Distribution Model

- Comparing EW measurements with models
- Galactic wind model + reionization simulation (Dijkstra+11)
- Similar M_{UV} distribution at z~7, 8, and 9-13





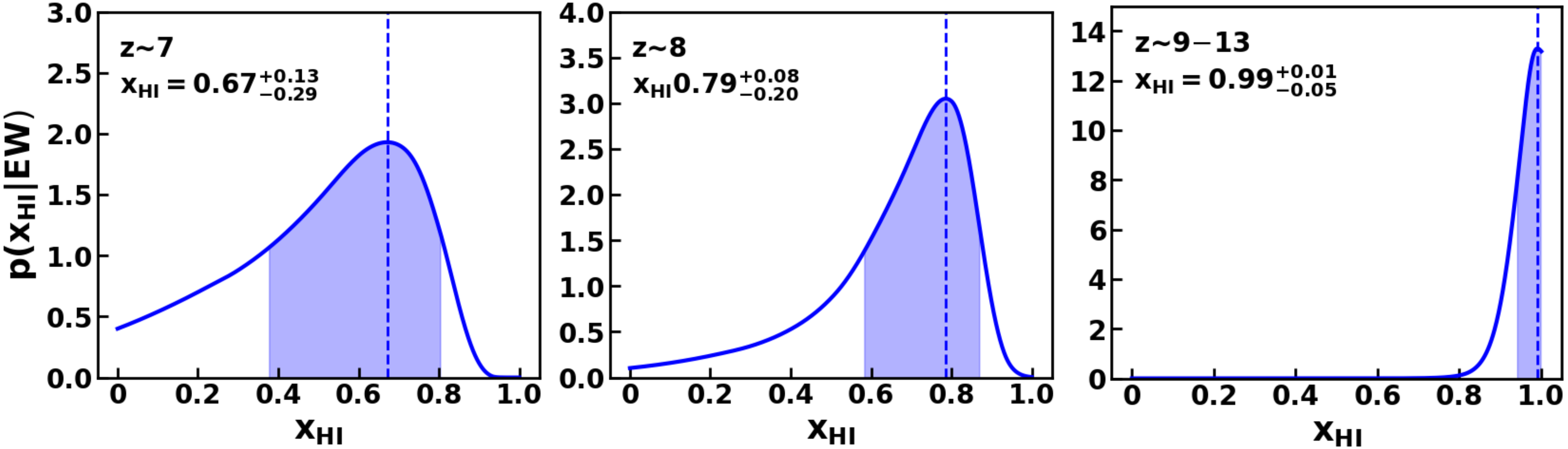
x_{HI} Estimates

- Bayesian inference based on Mason+18

$$p(x_{\mathrm{HI}}|\mathrm{EW}) \propto \prod_i \underline{p(\mathrm{EW}_i|x_{\mathrm{HI}})}\,\underline{p(x_{\mathrm{HI}})}$$

EW distribution model

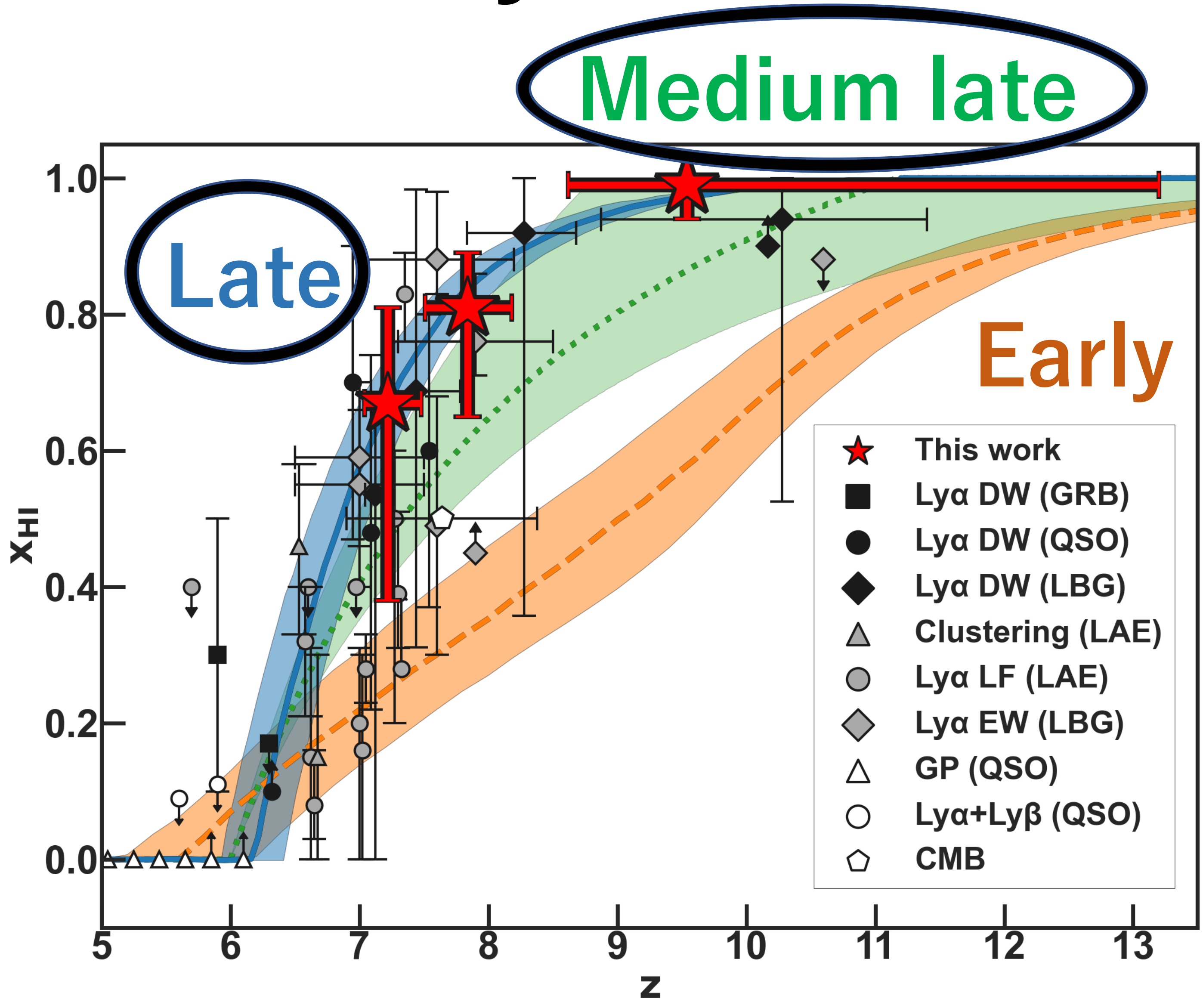
Uniform prior with $0<x_{\mathrm{HI}}<1$



Cosmic Reionization History

- Late or Medium late scenario

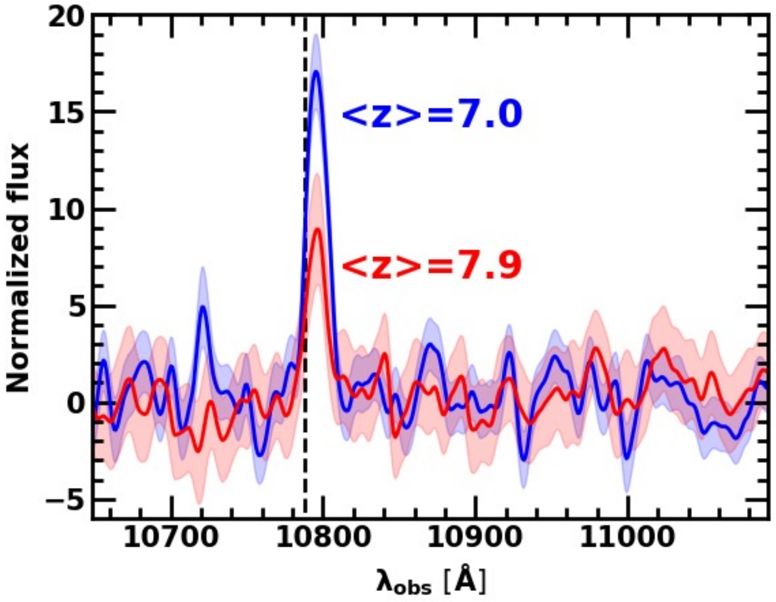
- Reionization source:
objects hosted by moderately massive halos

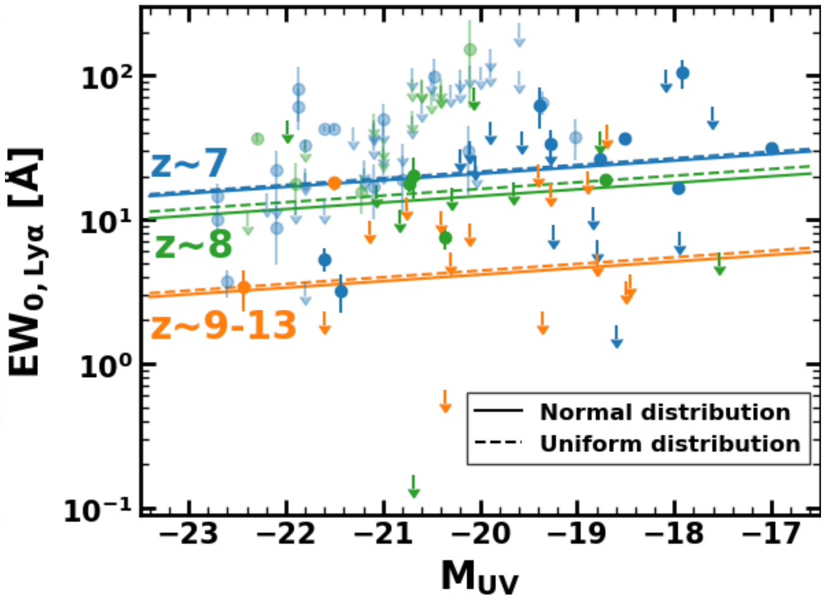


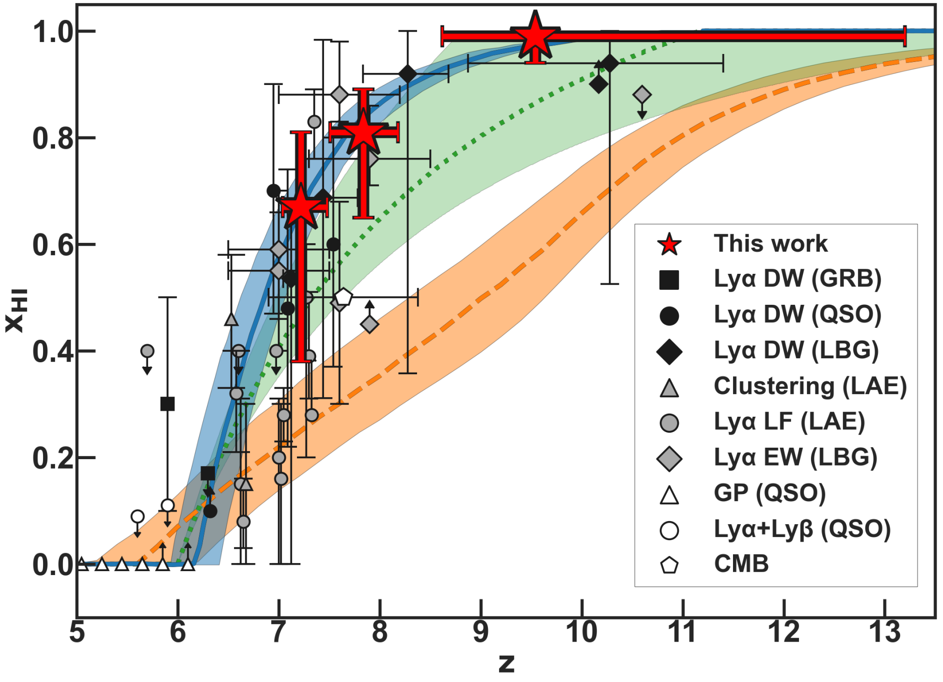
Summary

- Spectral analysis of 54 galaxies at z~7-13
- Clear signature of **Lyα EW evolution**
- x_{HI} estimates consistent with **late reionization history**

→Reionization source: objects hosted by moderately massive halos







Appendix

EW Distribution Model

EW distribution model (Dijkstra+11)

Galactic outflow model: intrinsic Lyα line scattered through the outflow

Reionization seminumeric simulation: IGM opacity

↓

$T_{\mathrm{IGM}}(x_{\mathrm{HI}})$: fraction of Lyα photons transmitted through the IGM

$$p_{\mathrm{z=6}}(\mathrm{EW}) \propto \exp(-\mathrm{EW}/\mathrm{EW_c})$$

$$p(\mathrm{EW}|x_{\mathrm{HI}}) = N \int_0^1 dT_{\mathrm{IGM}}\, P(T_{\mathrm{IGM}}) p_{\mathrm{z=6}}(\mathrm{EW}/T_{\mathrm{IGM}})$$

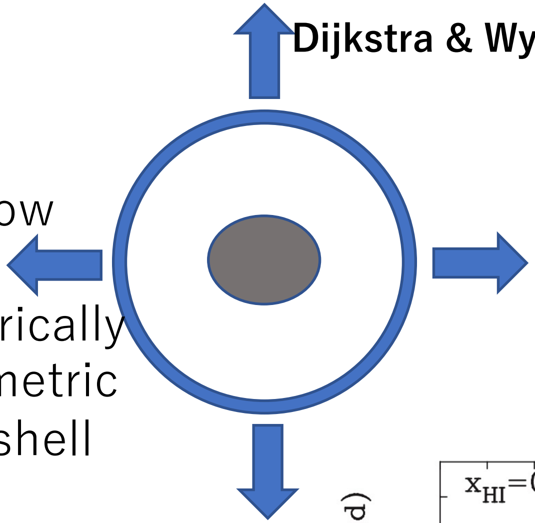
EW Distribution Model

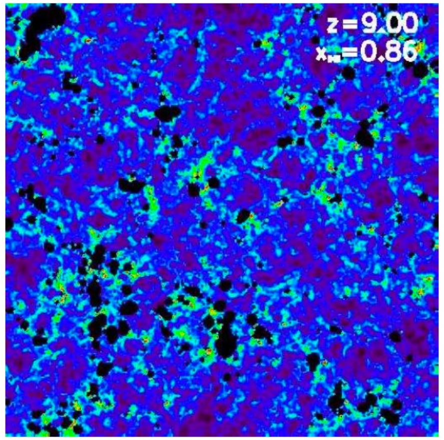
EW distribution model (Dijkstra+11)

Galactic outflow model + Seminumerical simulation

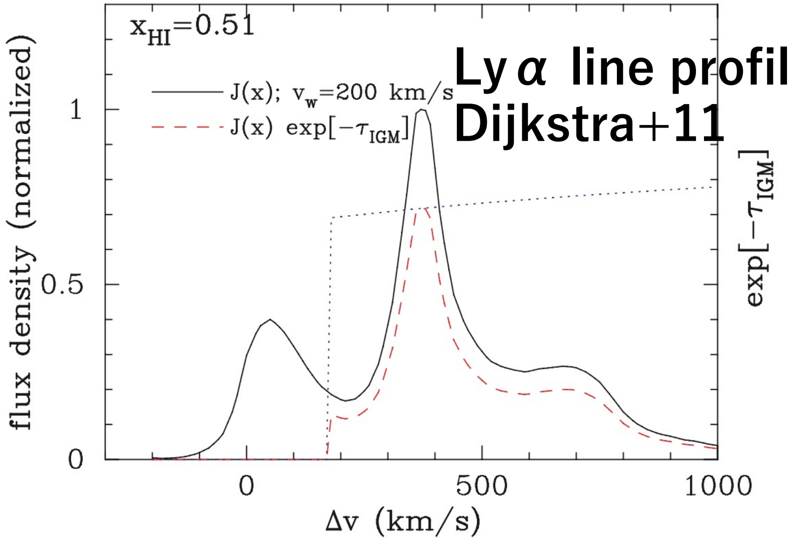
Dijkstra & Wyithe 10

outflow
↓
spherically symmetric thin shell



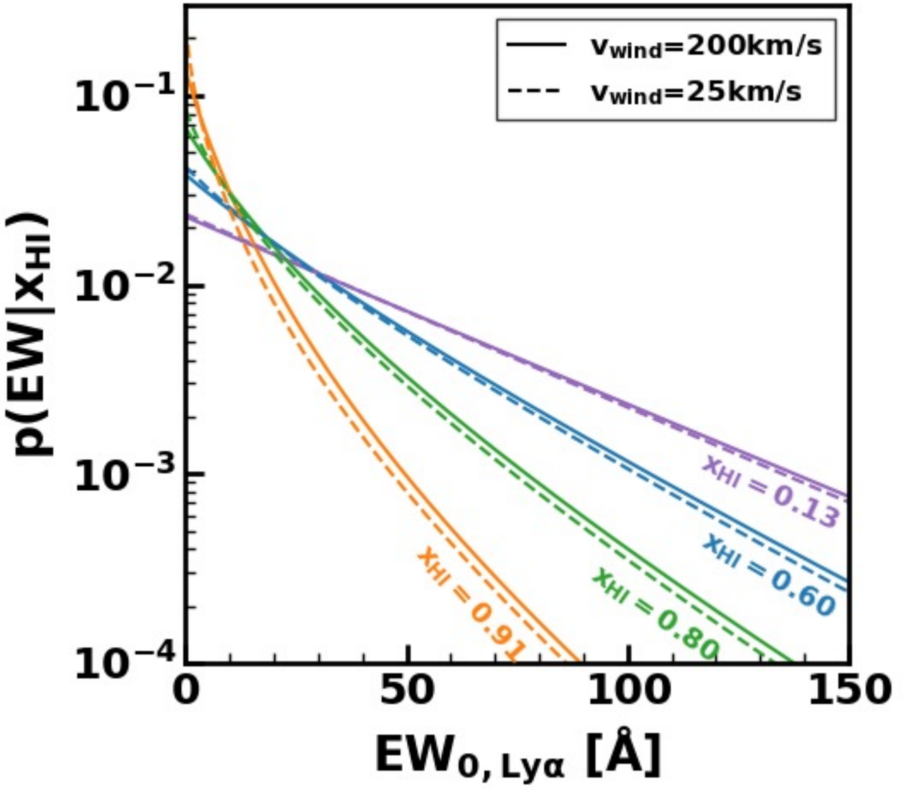


Mesinger+11



Lyα line profile
Dijkstra+11

Lyα EW probability distribution functions



Bayesian Inference

Bayesian Inference (Mason+18)

- For galaxies with Ly α detections:

$$p(\mathrm{EW}_i|x_{\mathrm{HI}}) = \int_0^\infty d\mathrm{EW}\ \frac{e^{-\frac{(\mathrm{EW}-\mathrm{EW}_i)^2}{2\sigma_i^2}}}{\sqrt{2\pi}\sigma_i} p(\mathrm{EW}|x_{\mathrm{HI}})$$

- For galaxies with no Ly α detections:

$$\begin{aligned} p(\mathrm{EW}_i < \mathrm{EW}_{\mathrm{lim}}|x_{\mathrm{HI}}) &= \int_{-\infty}^{\mathrm{EW}_{\mathrm{lim}}} d\mathrm{EW}\ p(\mathrm{EW}_i|x_{\mathrm{HI}}) \\ &= \int_0^\infty d\mathrm{EW}\ \frac{1}{2}\mathrm{erfc}\left(\frac{\mathrm{EW}-\mathrm{EW}_{\mathrm{lim}}}{\sqrt{2}\sigma_i}\right) p(\mathrm{EW}|x_{\mathrm{HI}}) \end{aligned}$$