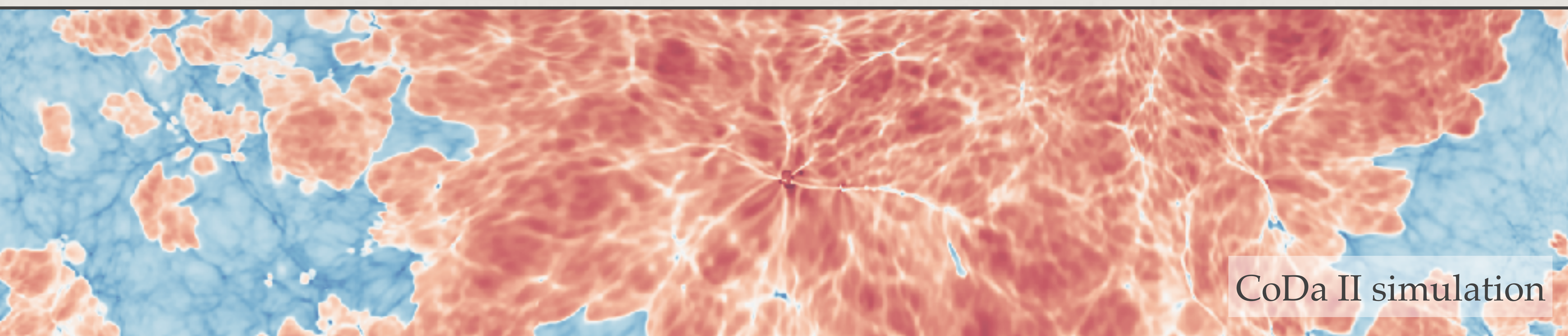
Kavli IPMU (Sep 2021)

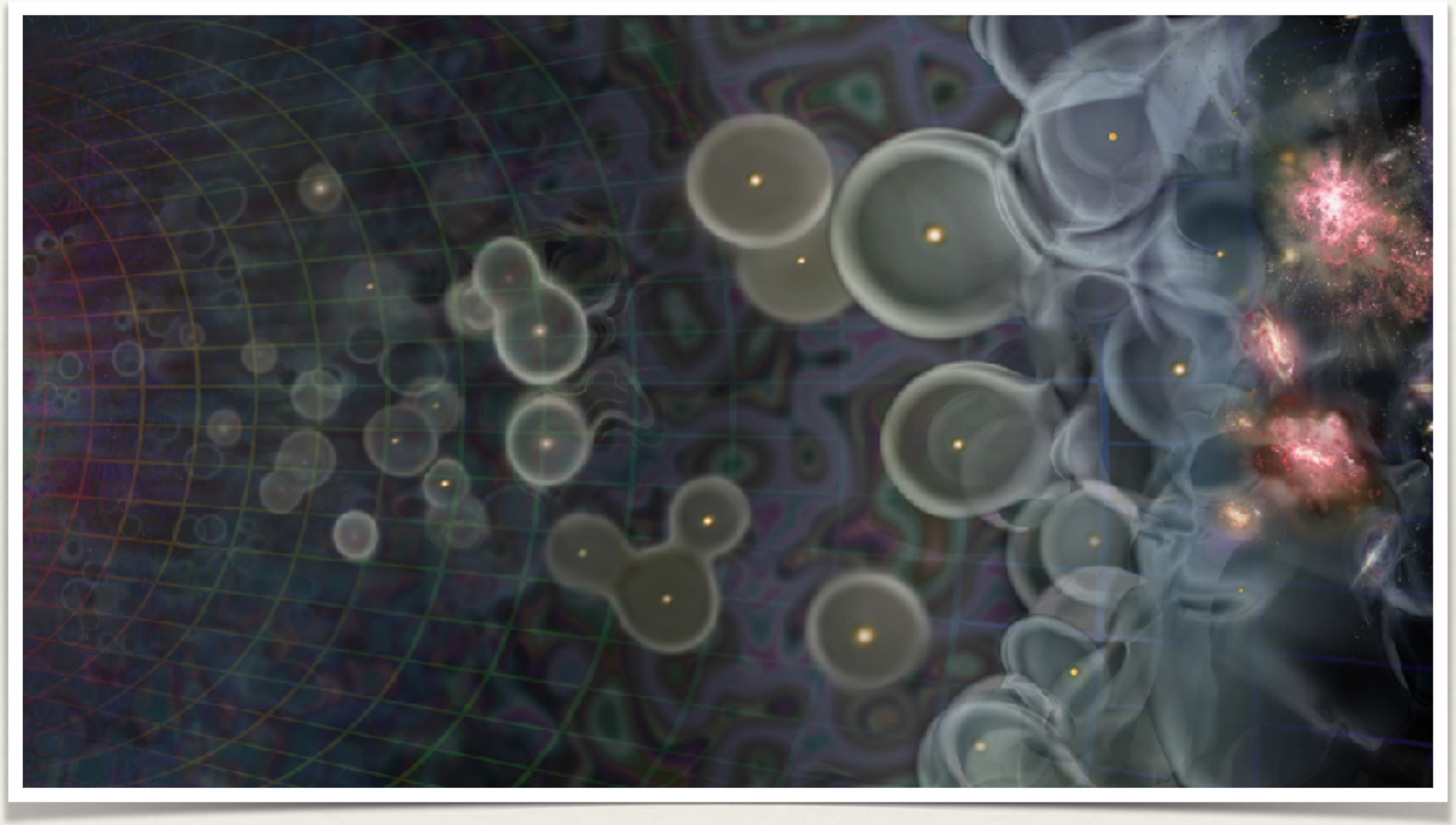
Lyα Transmission in the Reionizing Intergalactic Medium

Hyunbae Park (Kavli IPMU, Japan)
Intae Jung (NASA, USA)
Hyunmi Song (Yonsei U., Korea)
+ CoDa simulation Team

arXiv:2105.10770



Reionization Era

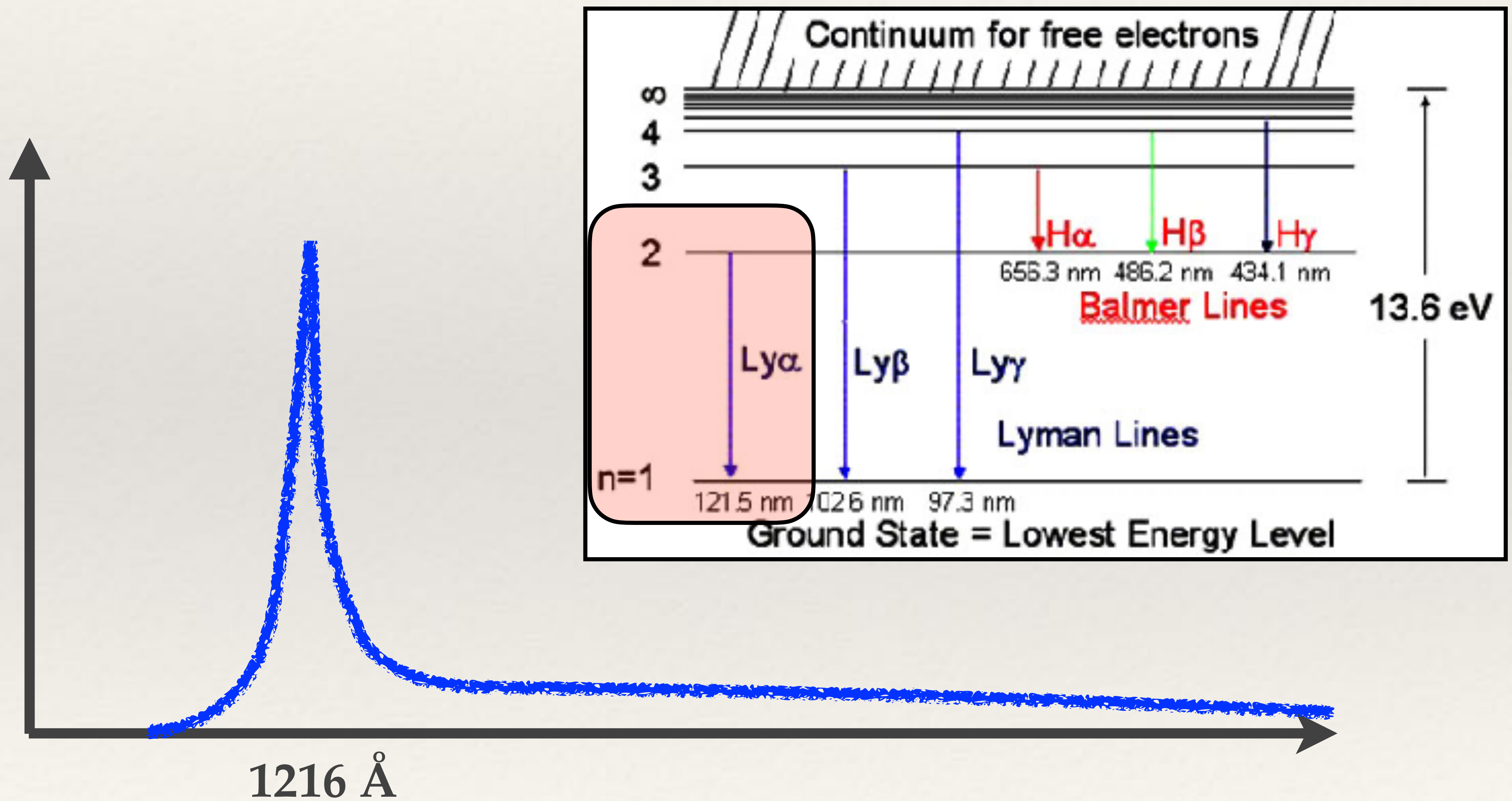


$z \sim 30$ $z \sim 6$

Early galaxies ionizing the intergalatic medium.

Lyman Alpha Emitter (LAE)

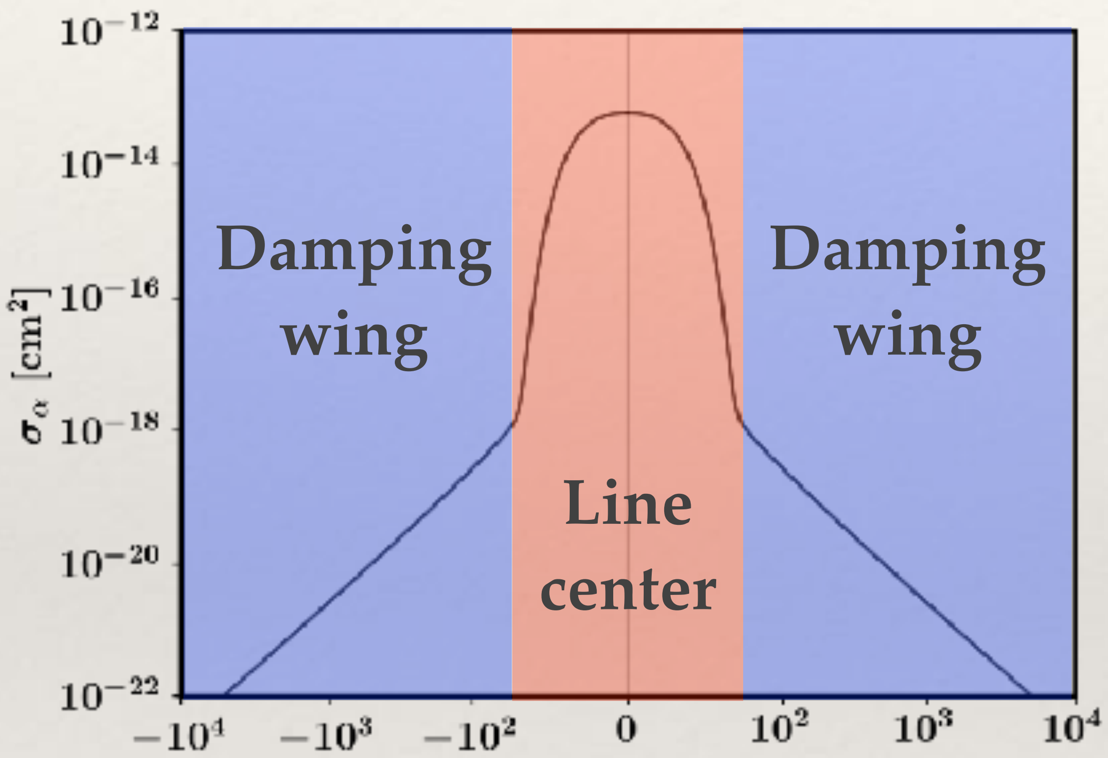
Galaxy with strong Lyα emission



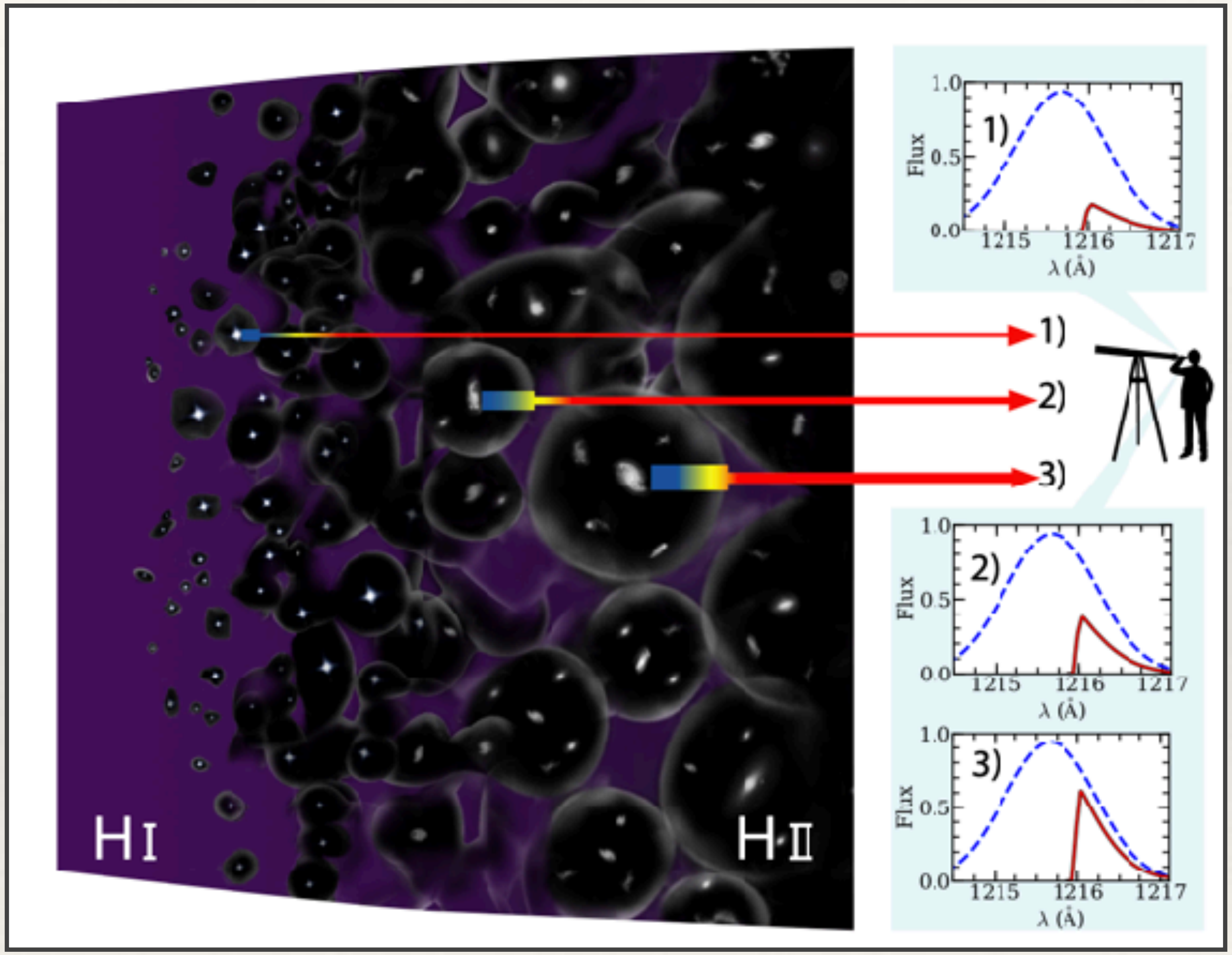
Two third of photons below 912 Å converted to Lyα photons.

LAE as a Probe of Reionization History

Lyα cross section



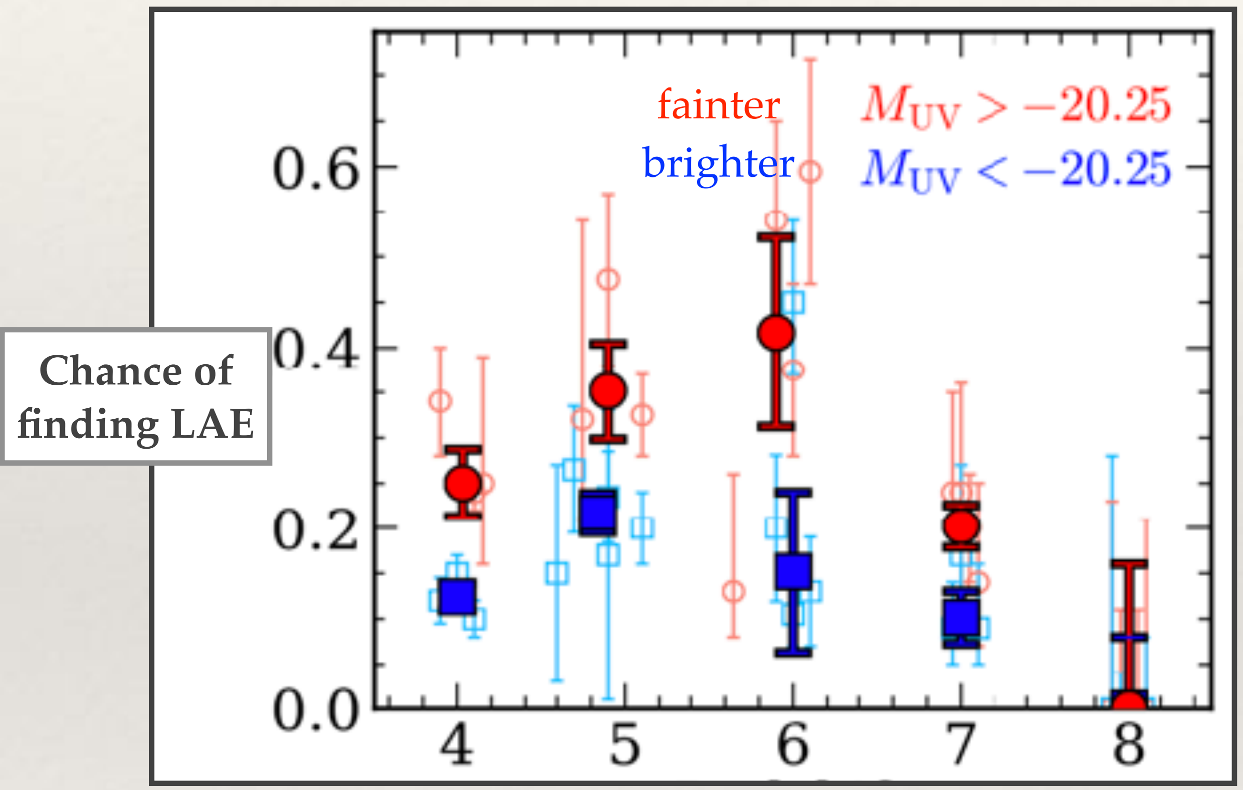
Offset from Lyα in km/s



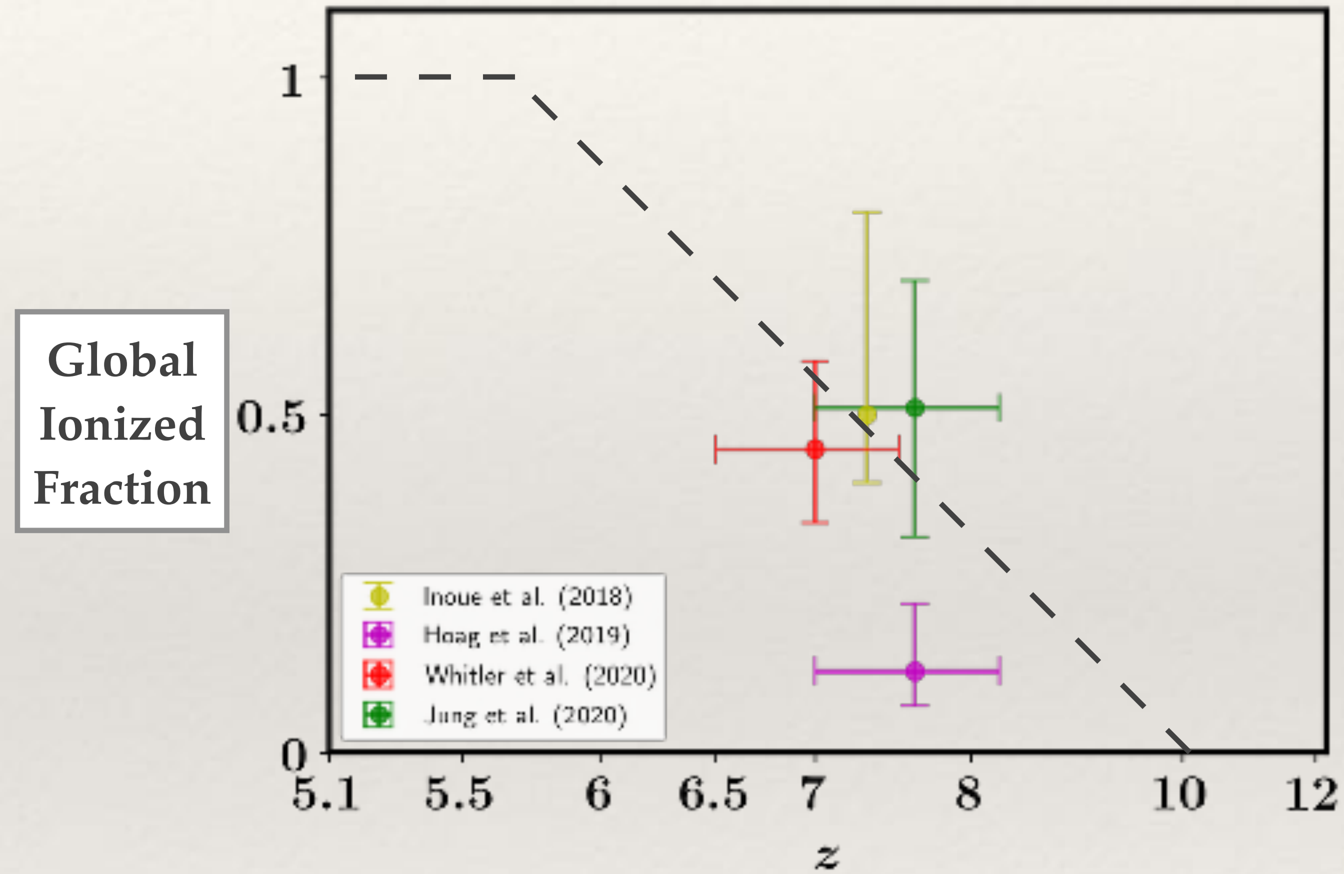
(Ouchi+ 2020)

HI in the IGM can easily suppress Lyα emission.

Lyα Line as a Probe of Reionization History



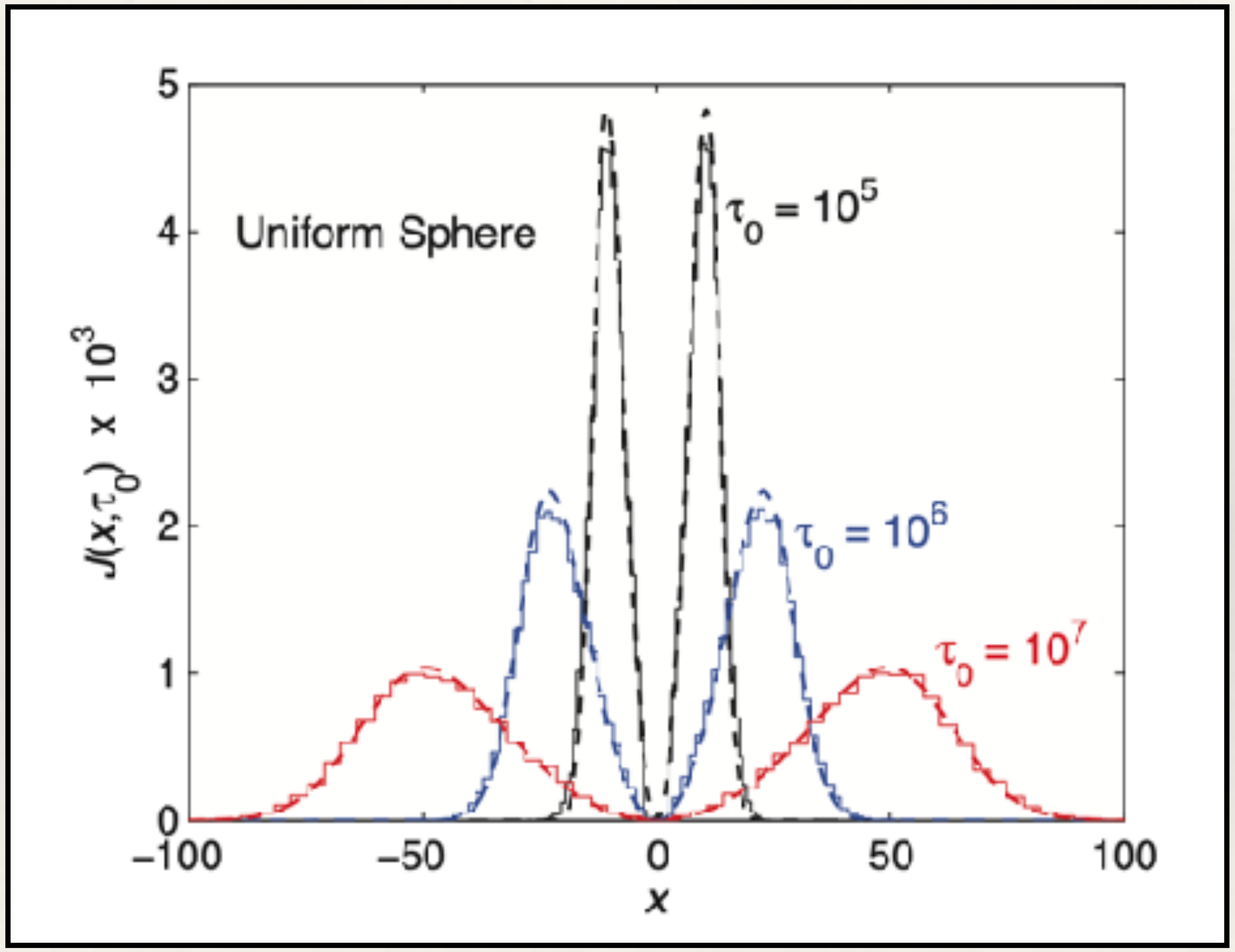
(Ouchi+ 2020)



Steep decline of Lyα emission toward high-*z*
Starting to constrain HI fraction at *z* > 7,
but the results have not converged yet.

Emission Profile After ISM

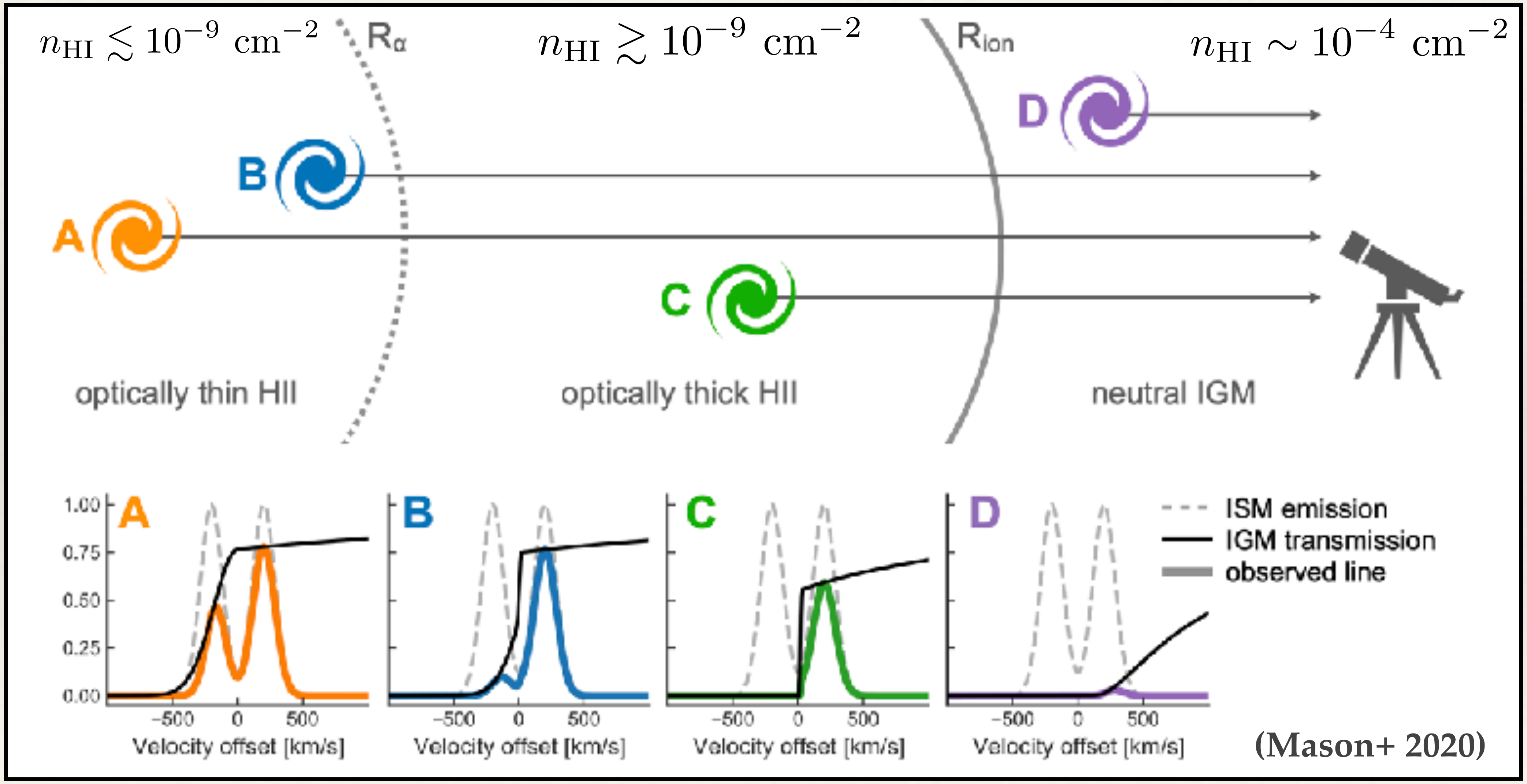
Homogeneous static sphere model



Dijkstra+ (2006)
Reproduced by Barnes+ (2014)

IGM Transmission during Reionization

Theoretical Picture

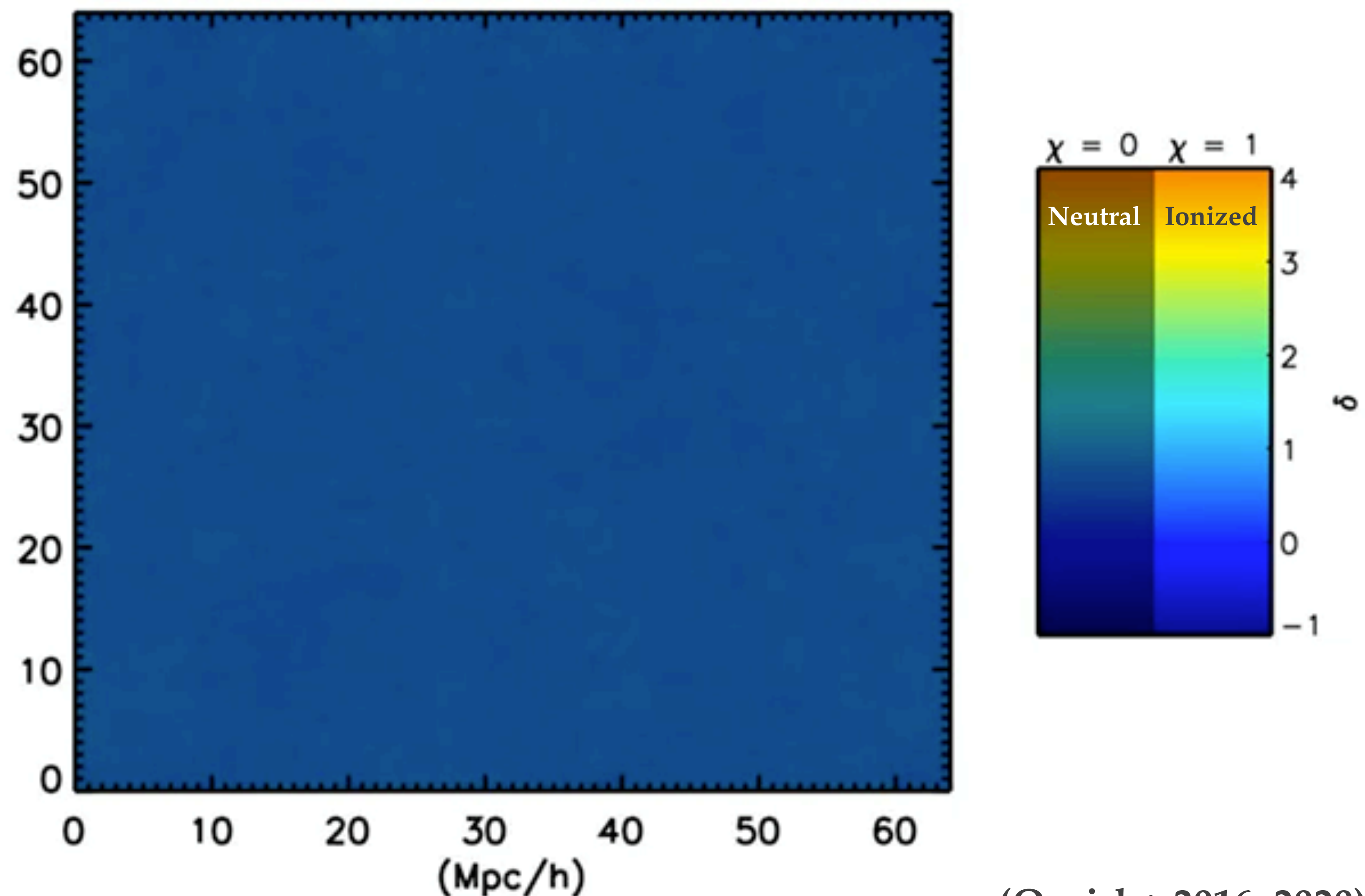


(Mason+ 2020)

Cosmic Dawn (CoDa) II Simulation

Motivation

Calculate IGM transmission using CoDa II data and compare to the theoretical picture.



(Ocvirk+ 2016, 2020)

Code

RAMSES w.

Fully coupled hydro+RT

Box size

64 h^{-1} cMpc

Resolution

4096^3

(cell size: 16 h^{-1} ckpc)

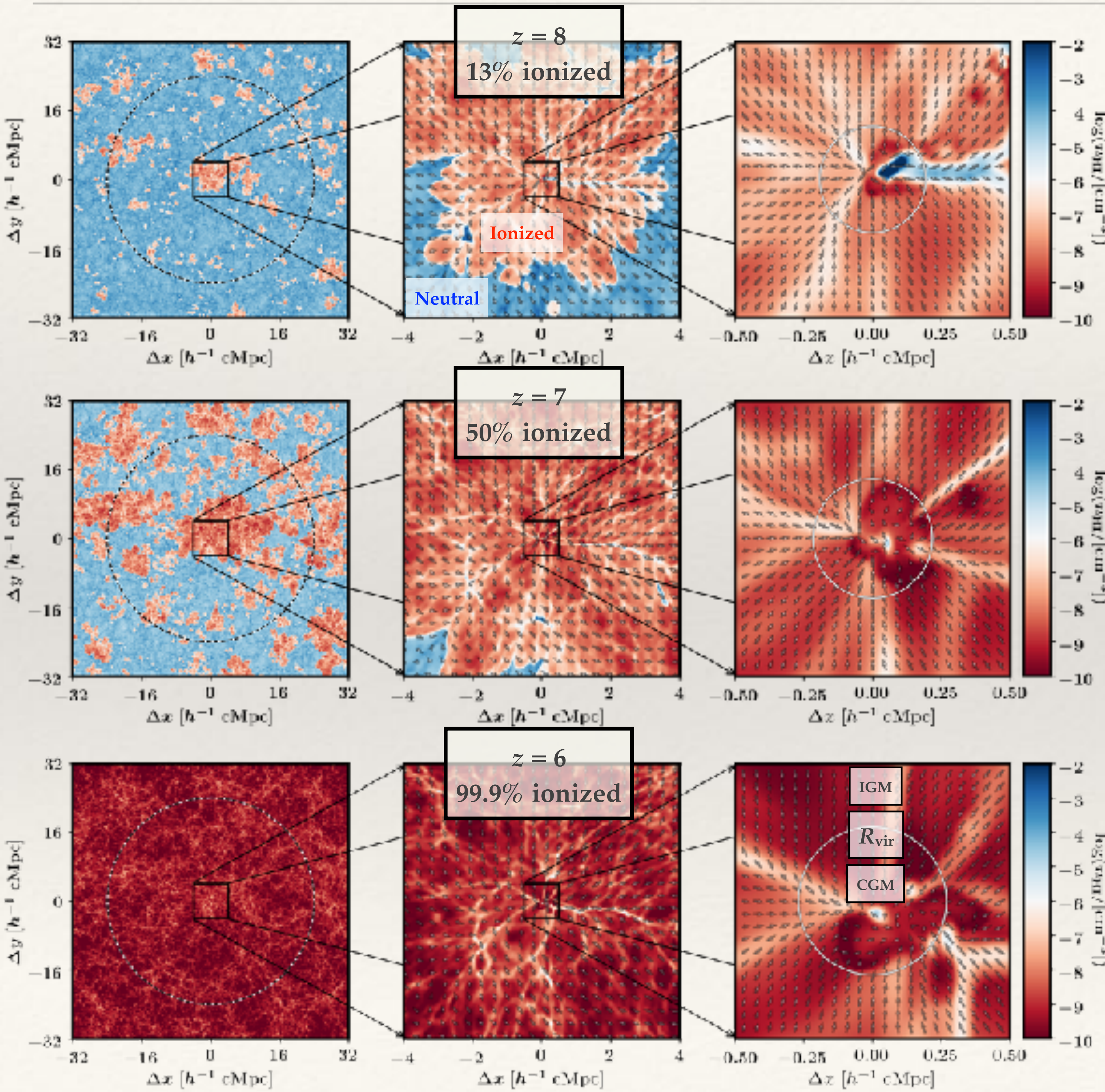
Physics

Star-formation

Ionizing radiation

SN feedback

Cosmic Dawn (CoDa) II Simulation

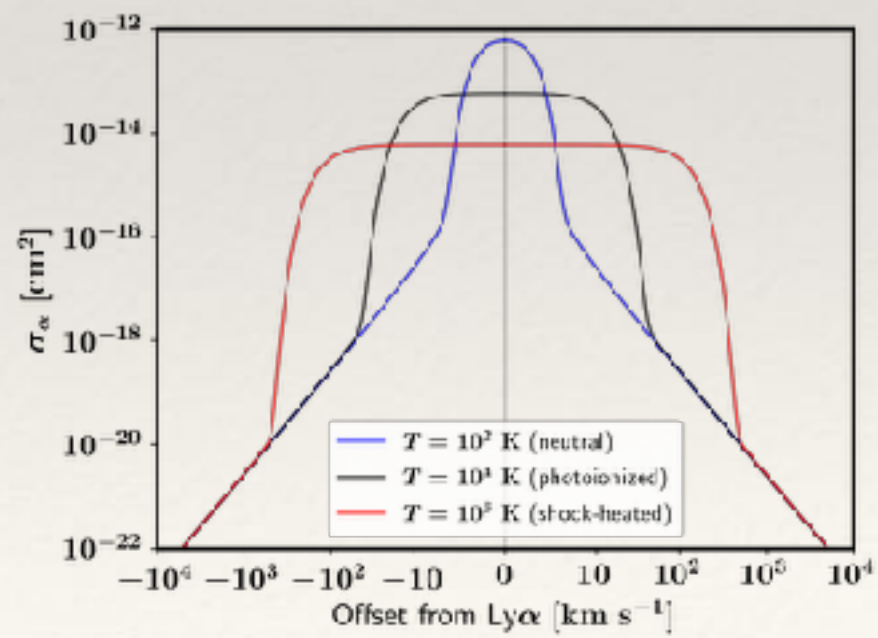


$$\tau(\nu_e) = \int_{r=r_{vir}}^{\infty} n_{\mathrm{HI}}\sigma_\alpha(\nu', T)dr$$

where

$$\nu' = \nu_e - \nu_e\frac{[r - r_{vir}]H}{c} + \nu_e\frac{v_{pe}}{c}$$

Lyα cross section

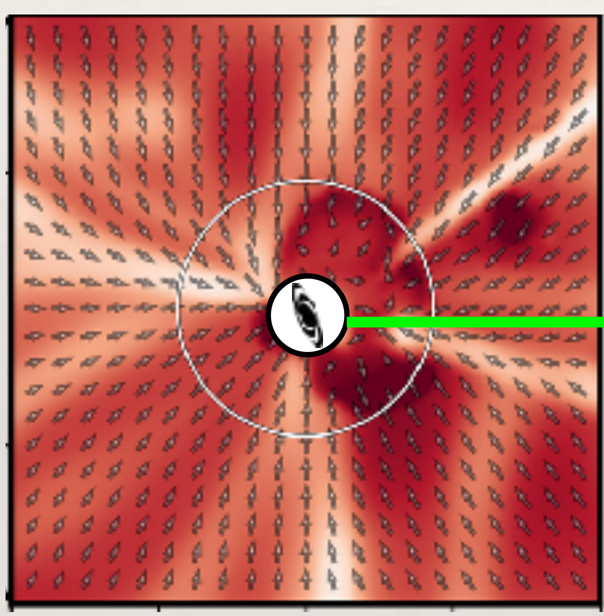


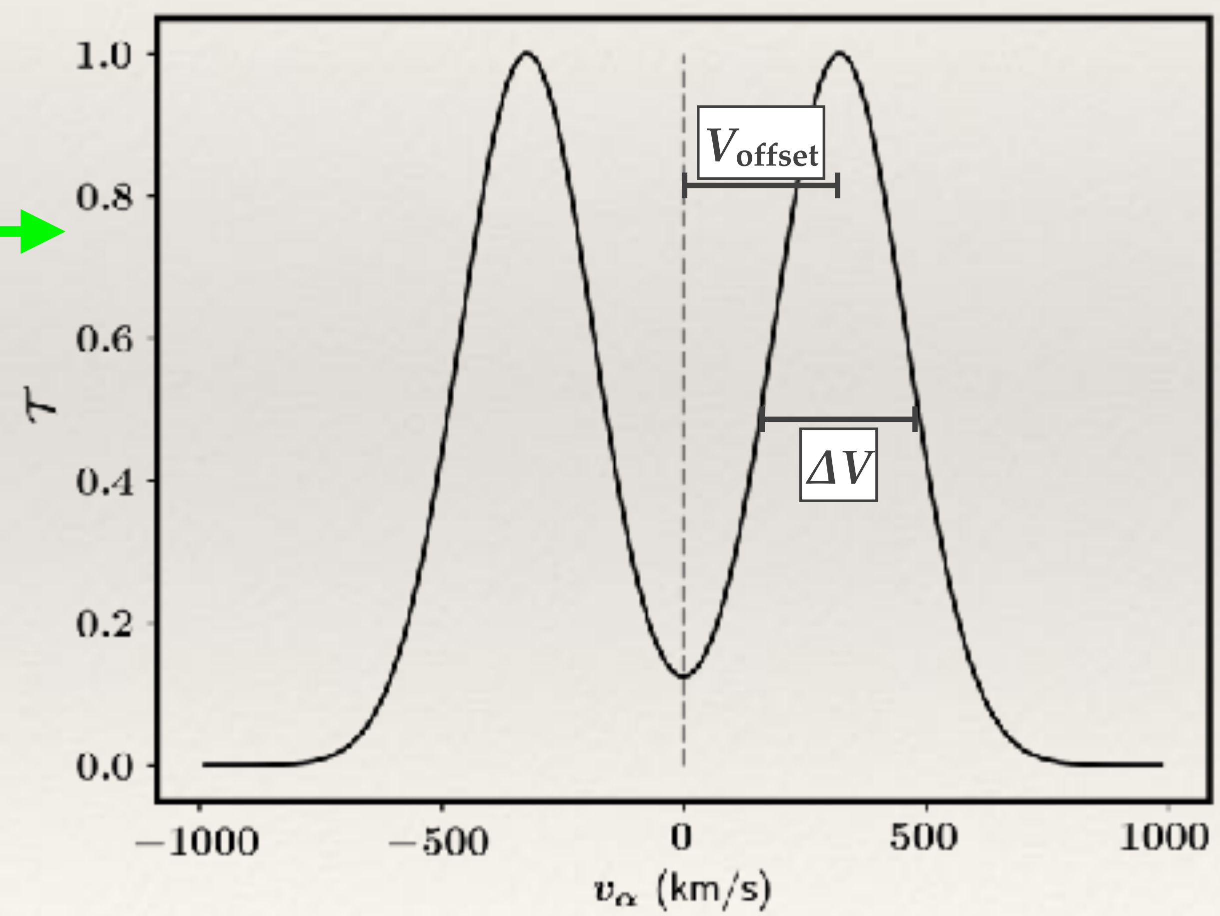
Flux-wighted IGM Transmissivity

$$(\text{Intrinsic emission}) = F_{\text{in}}(v_\alpha) \propto \exp\left(-\left[\frac{v_\alpha - V_{\text{offset}}}{\Delta V}\right]^2\right) + \exp\left(-\left[\frac{v_\alpha + V_{\text{offset}}}{\Delta V}\right]^2\right)$$

where $V_{\text{offset}} = V_c = \sqrt{\frac{GM_h}{R_{200}}}$

$$\Delta V = 2.355 \times V_c$$



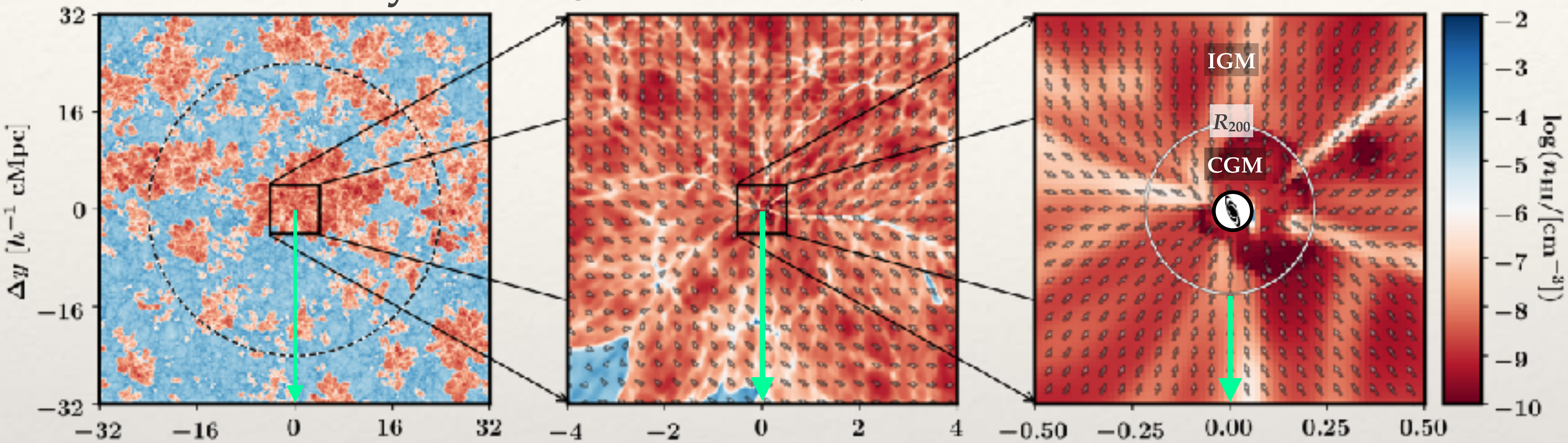


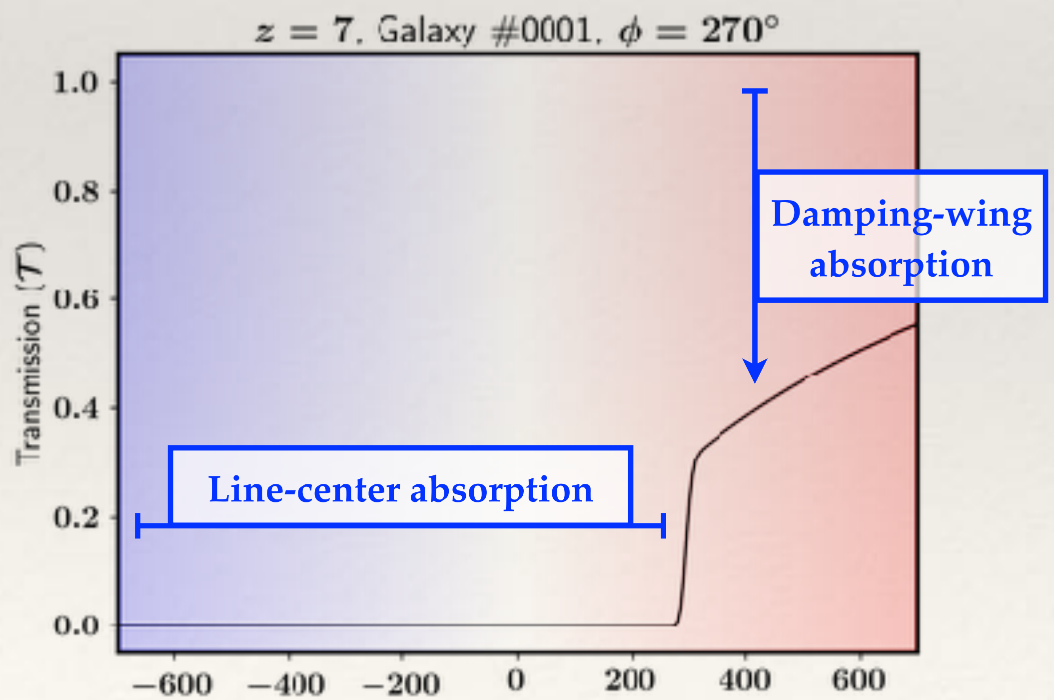
Motivated by recent observations (Yang+ 2016 & Verhamme+ 2018)

Offset from Lyα in the velocity unit

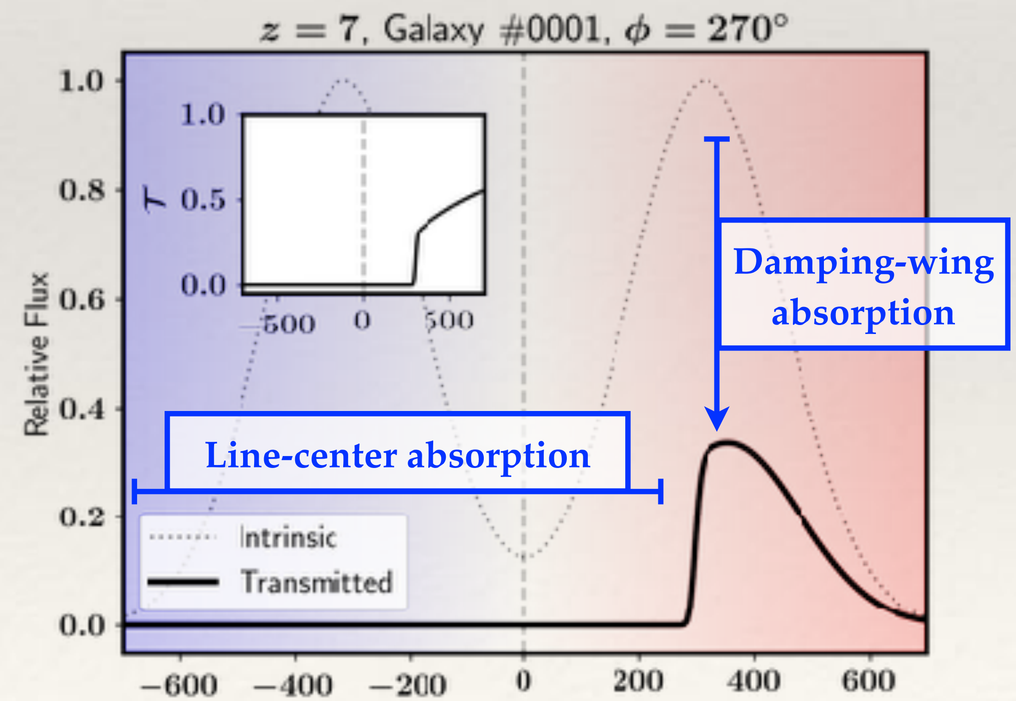
Transmission for a Typical Sightline

Galaxy with $M_{\rm UV}$ = -23.1 & $M_h = 1.1\times10^{12}\ M_\odot$ at $z = 7$





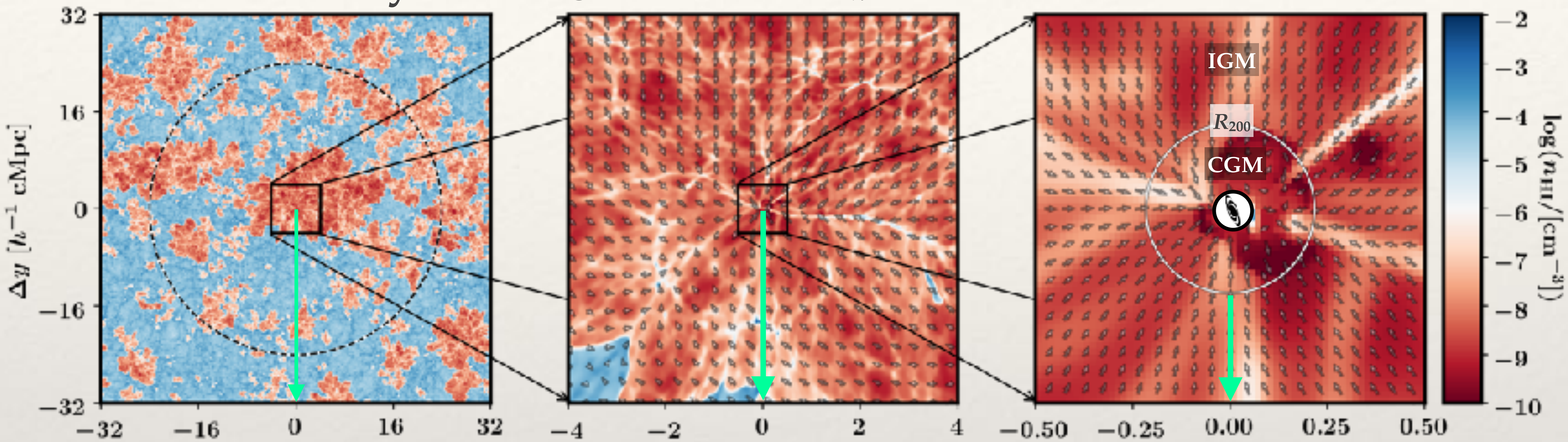
Offset from Lyα in the velocity unit

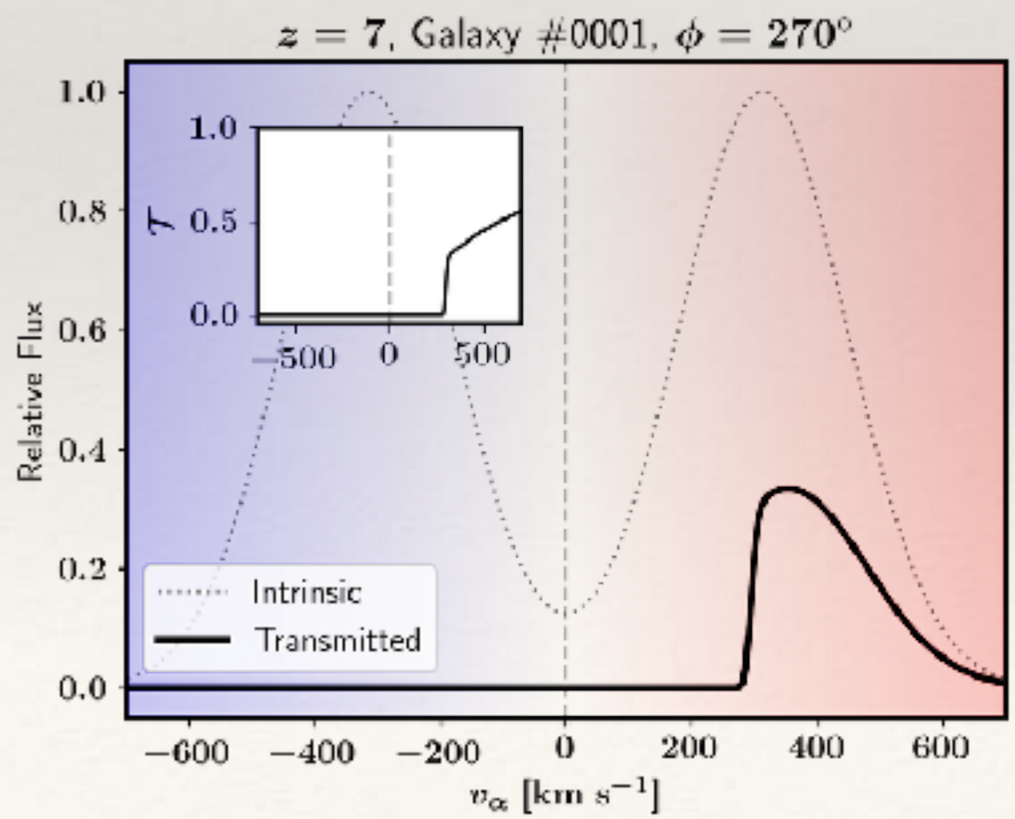


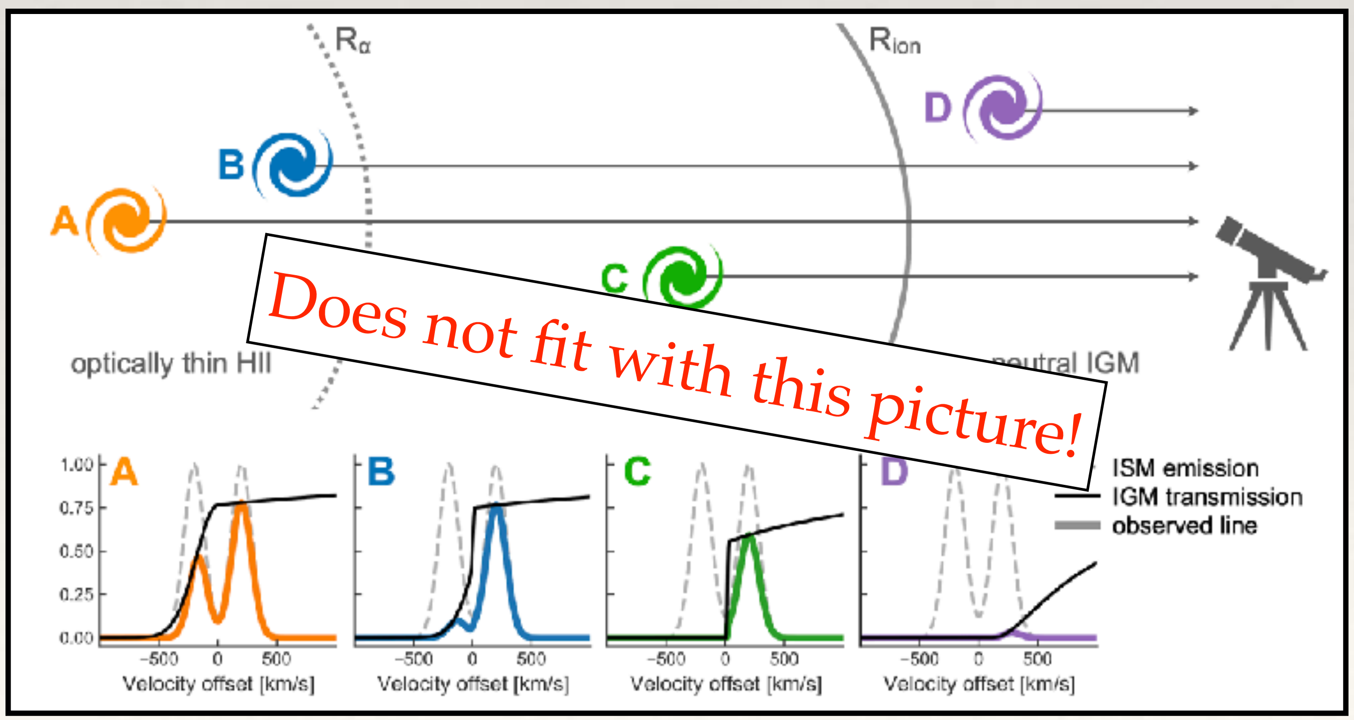
Offset from Lyα in the velocity unit

Transmission for a Typical Sightline

Galaxy with $M_{\mathrm{UV}} = -23.1$ & $M_h = 1.1\times10^{12}\ M_\odot$ at $z = 7$

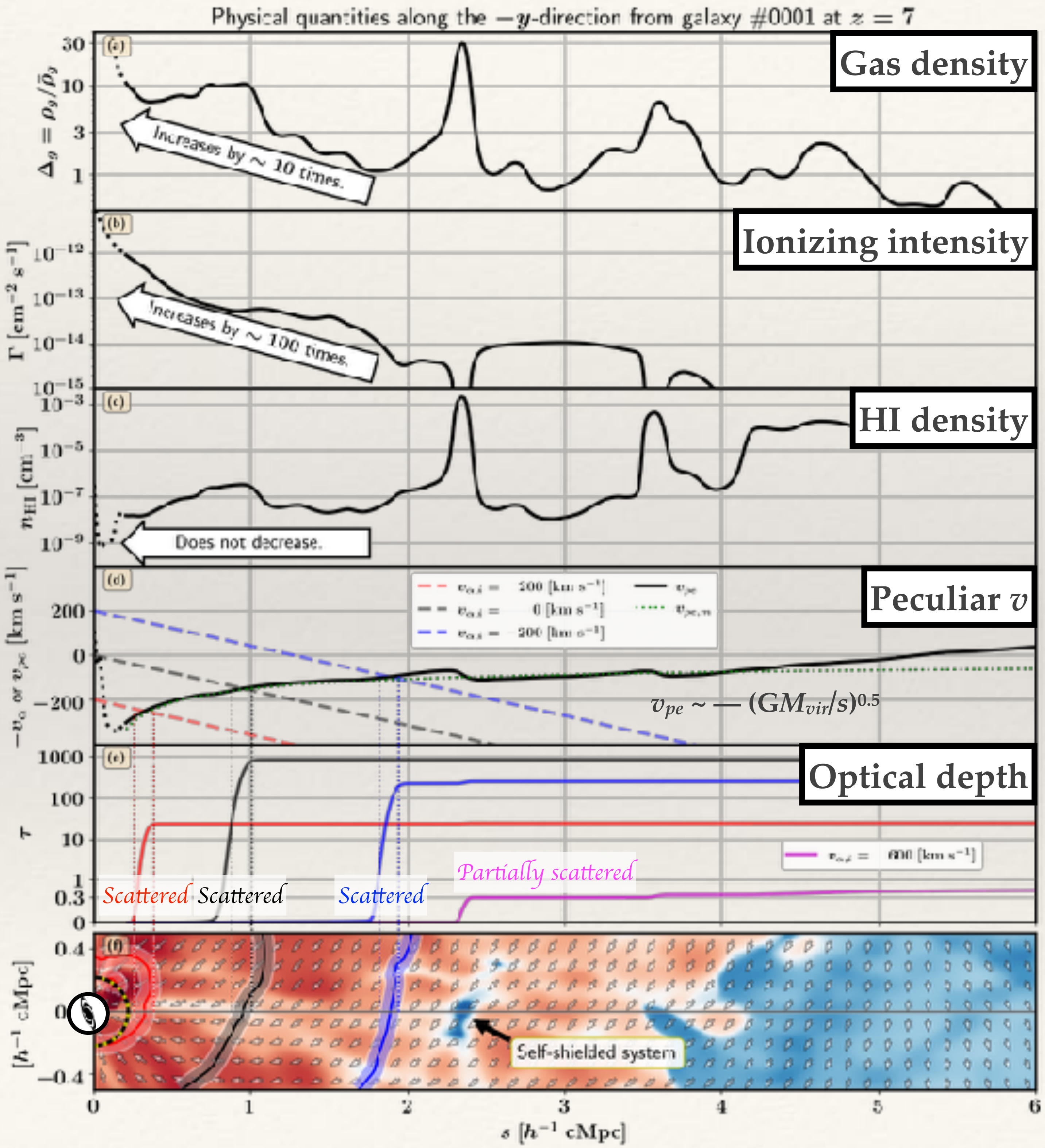


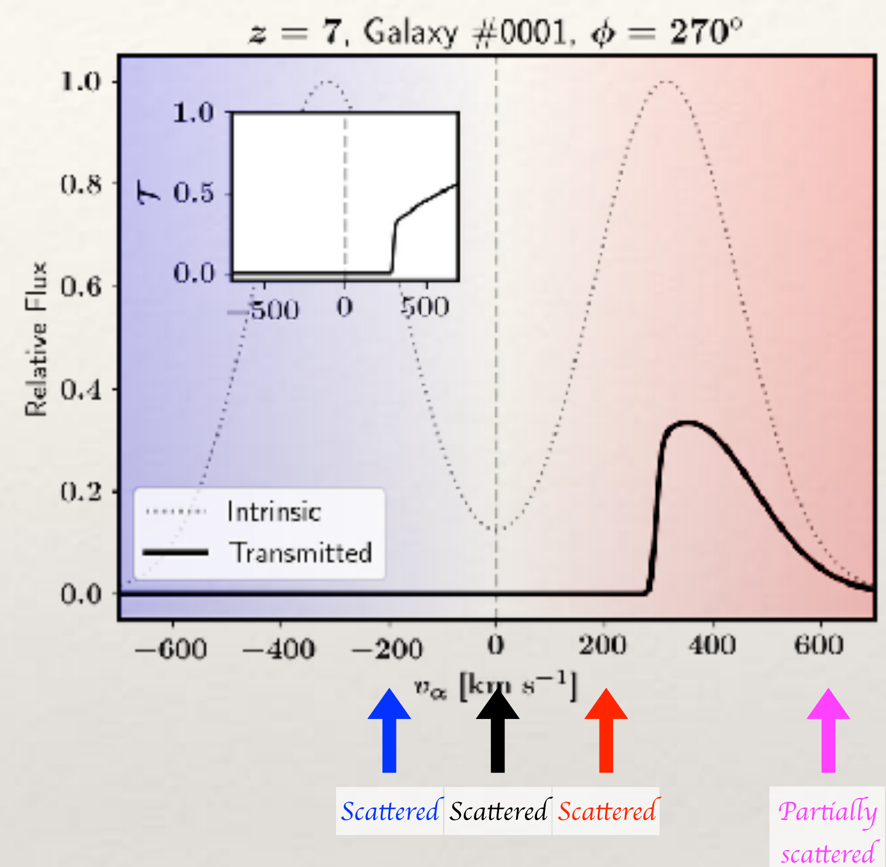


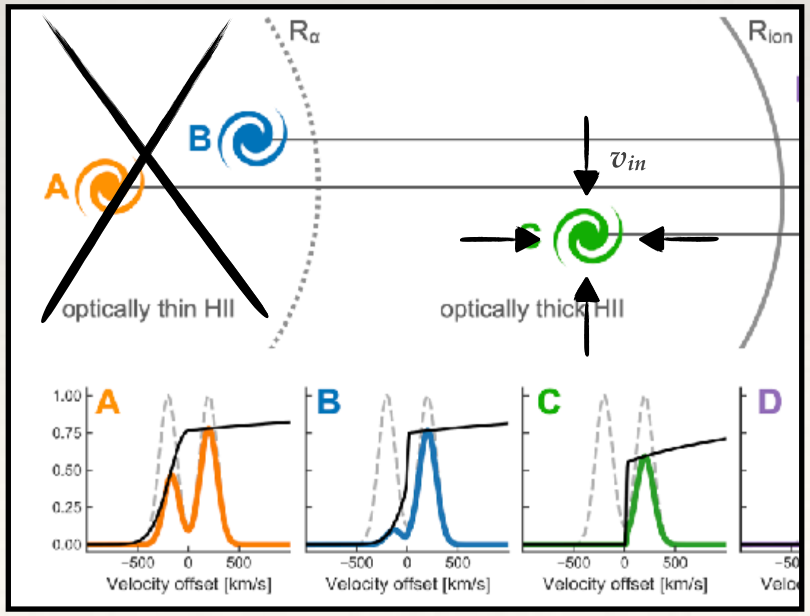


Does not fit with this picture!

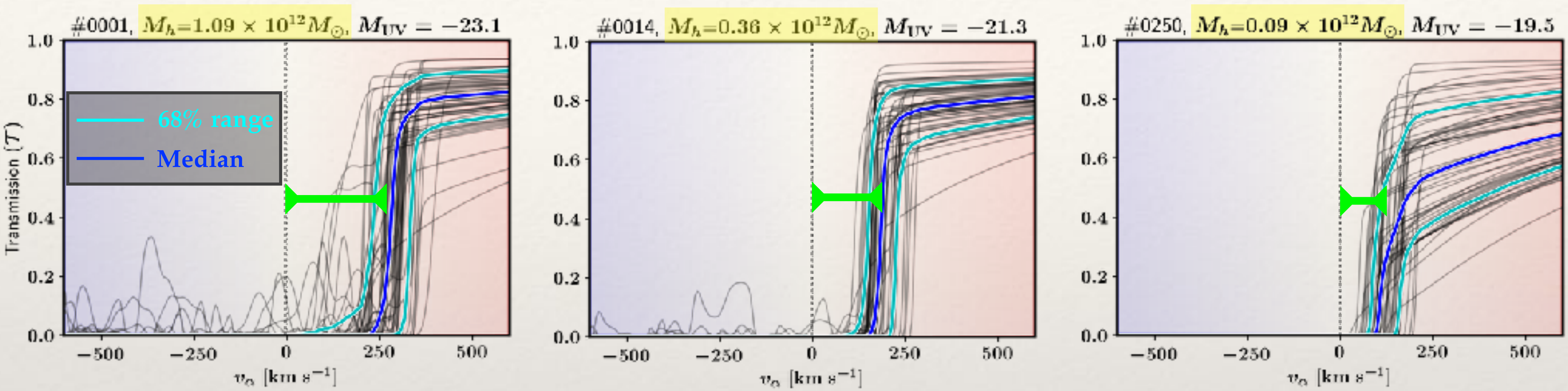
Resonance Absorption on the Red Side





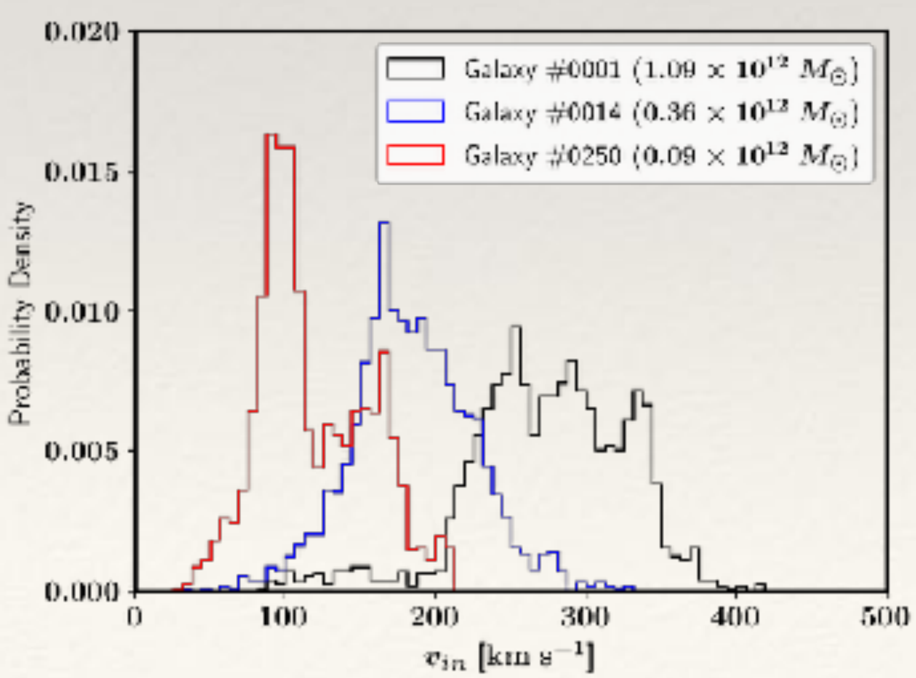


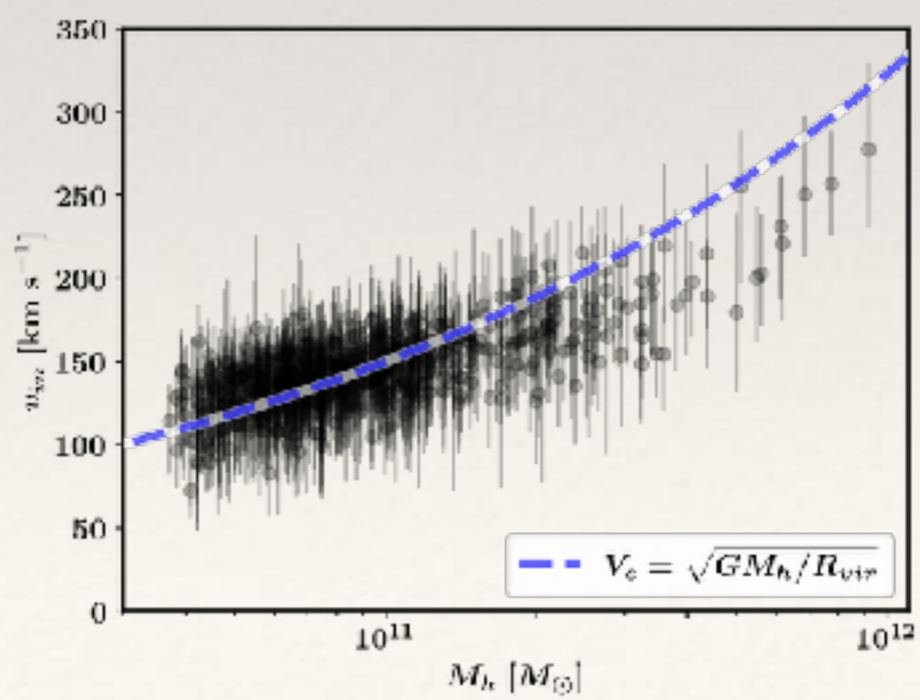
Halo-mass Dependence



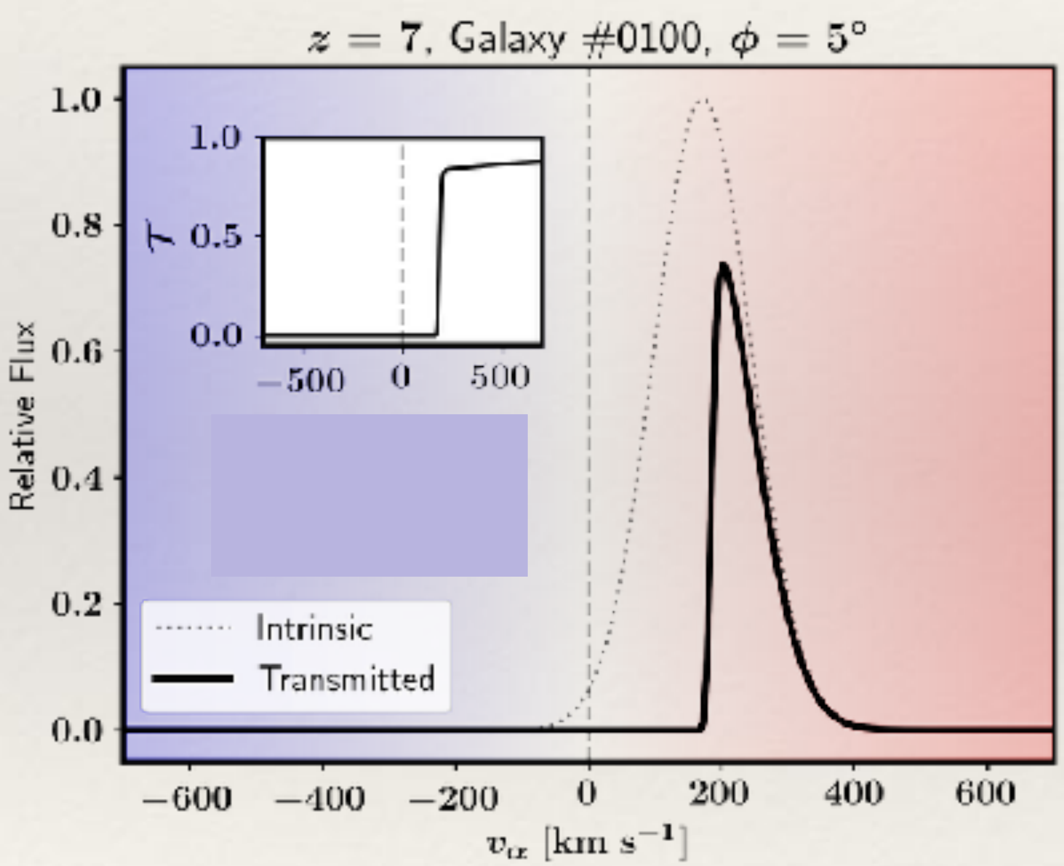
Infall velocity is larger for more massive galaxies.

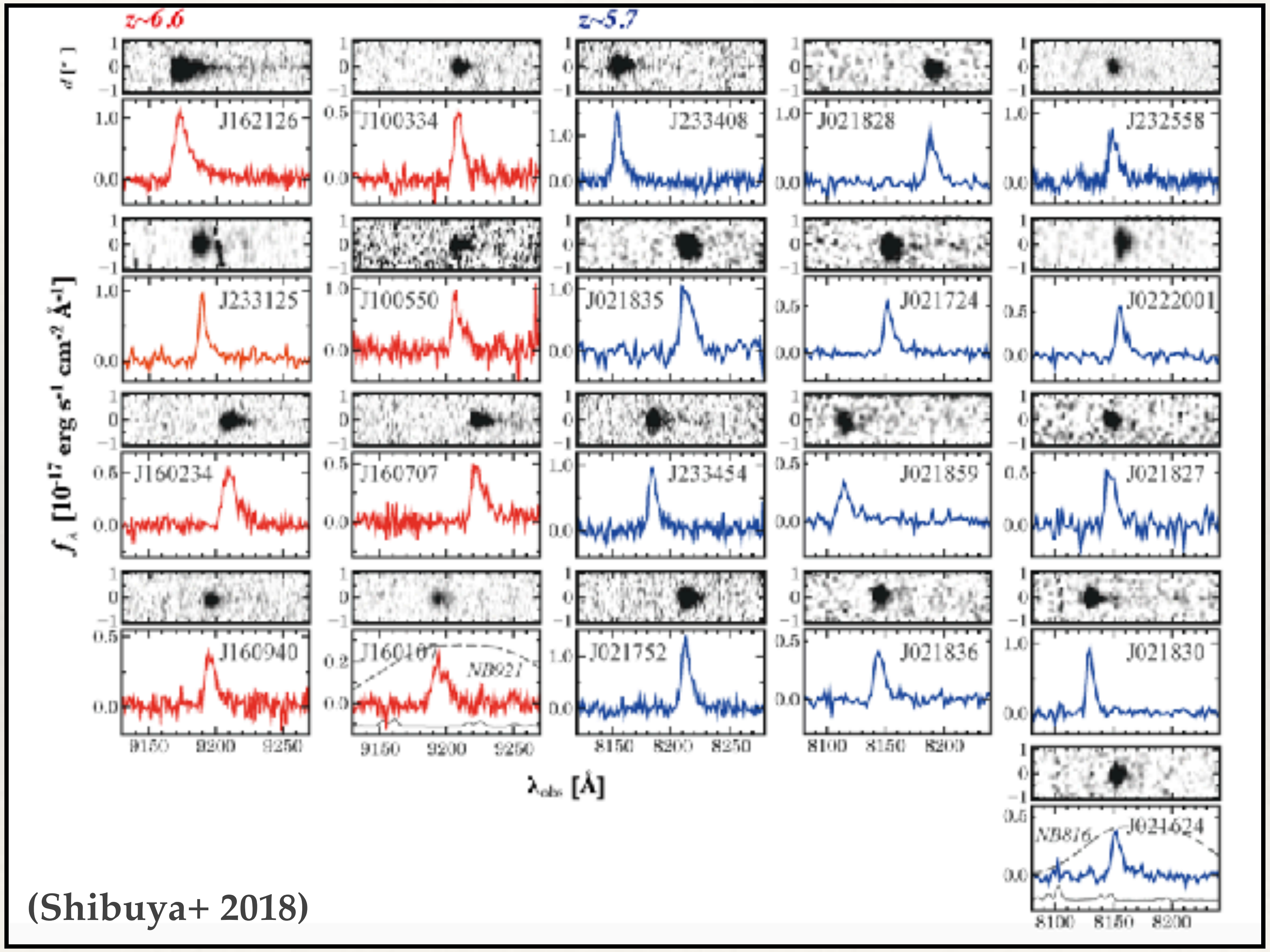
It is similar to the circular velocity as in the model of Mason+ 2018.





Implication for the Observed Line Shape

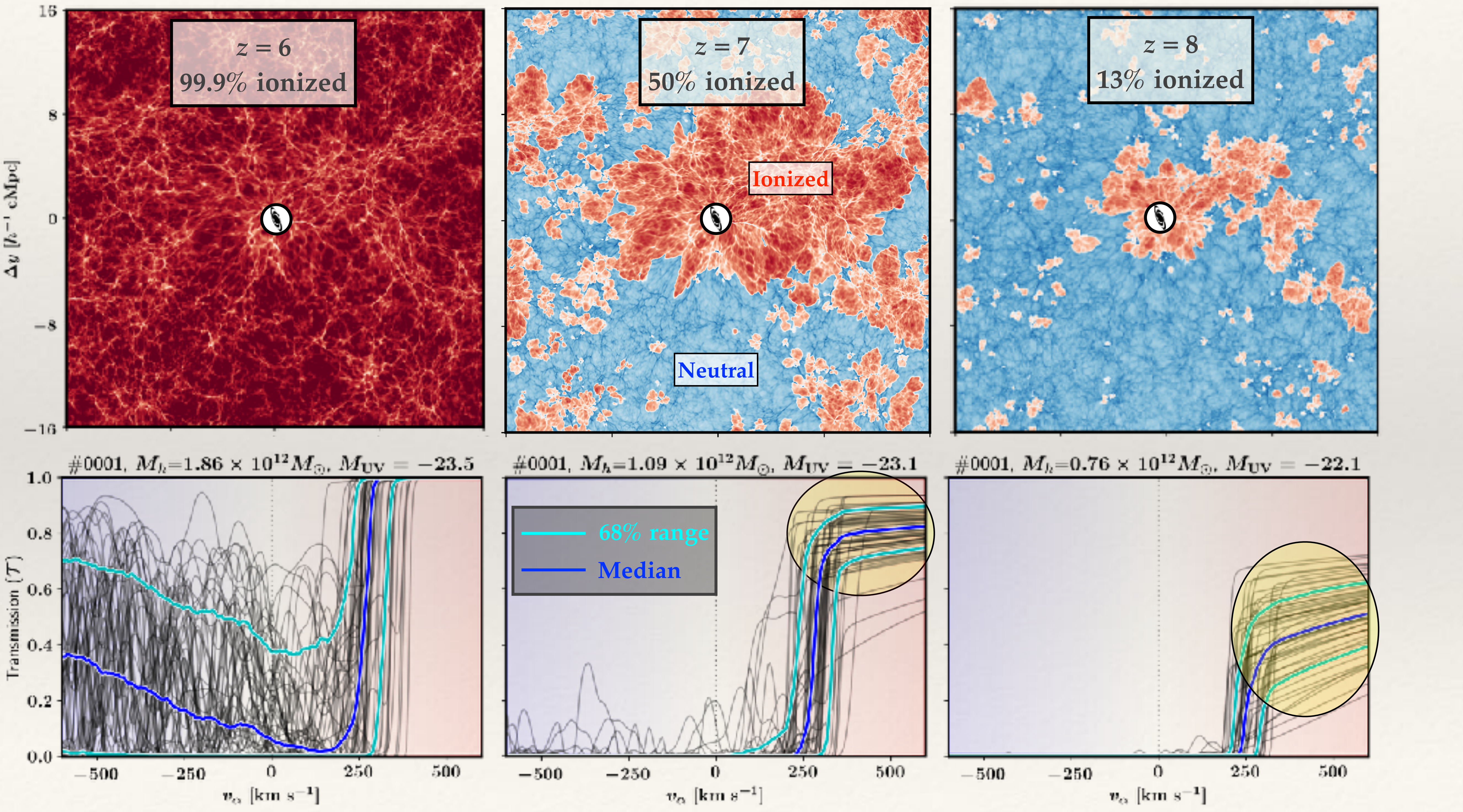




(Shibuya+ 2018)

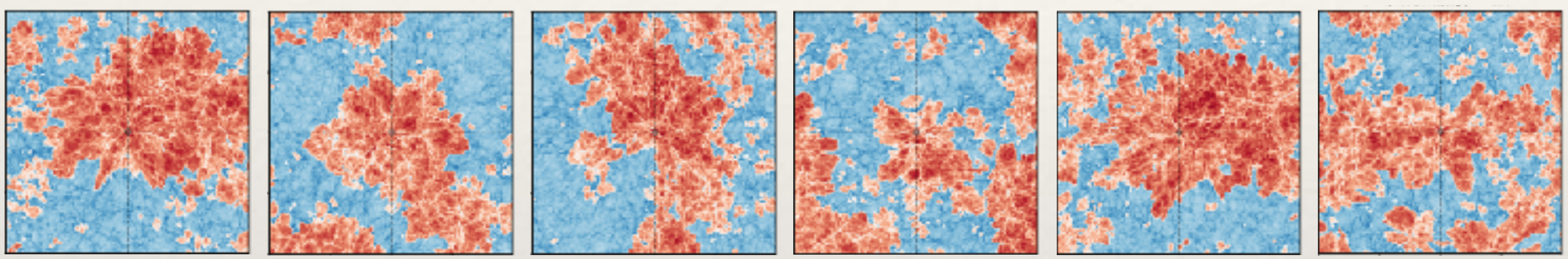
Asymmetric line profile due to the truncation of the red peak

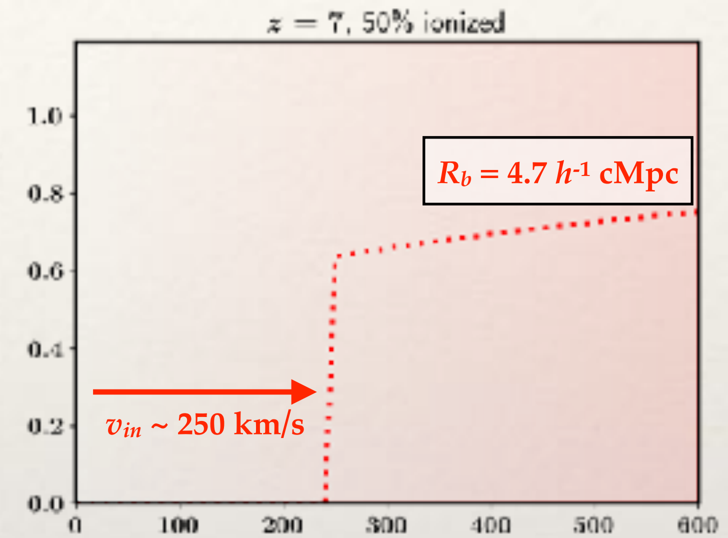
Redshift Evolution & Damping-wing Opacity



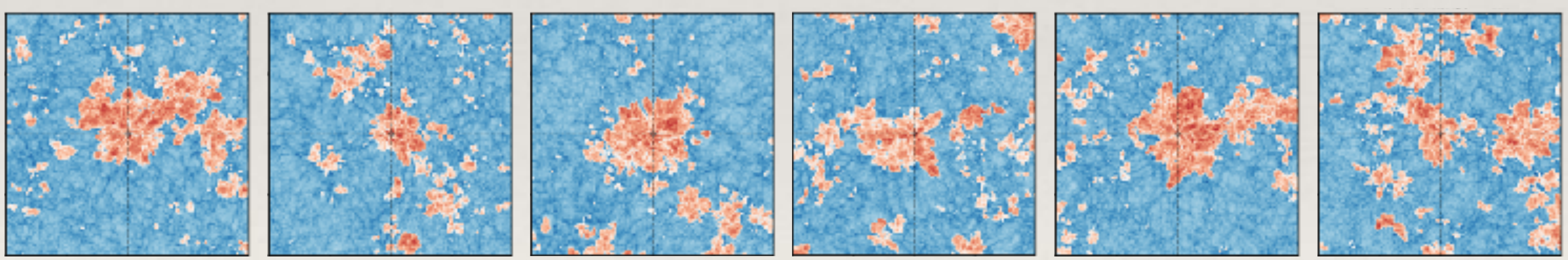
Redshift-dependence of HII-region size

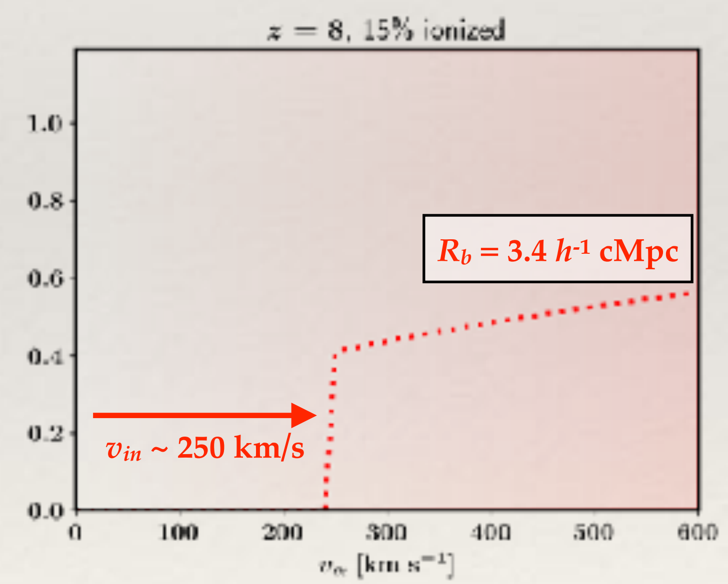
IGM around the six brightest galaxies at *z* = 7





IGM around the six brightest galaxies at *z* = 8

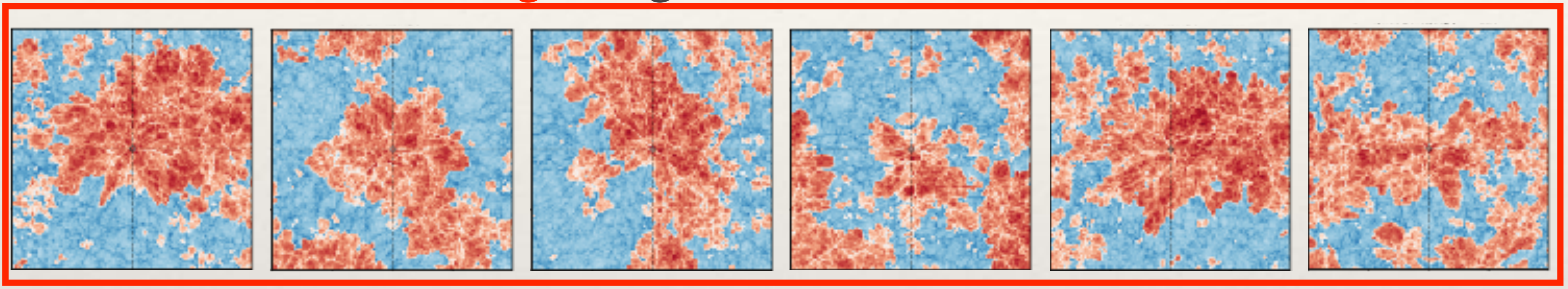




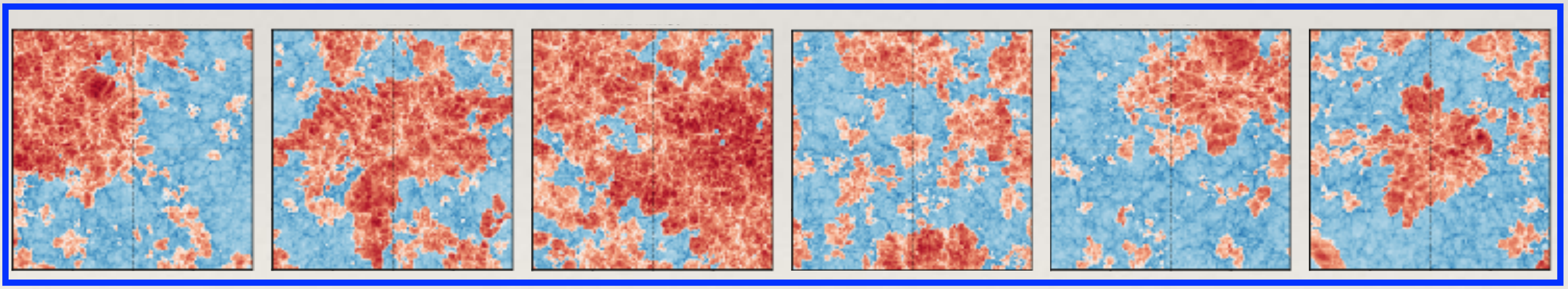
Higher *z* - smaller transmission

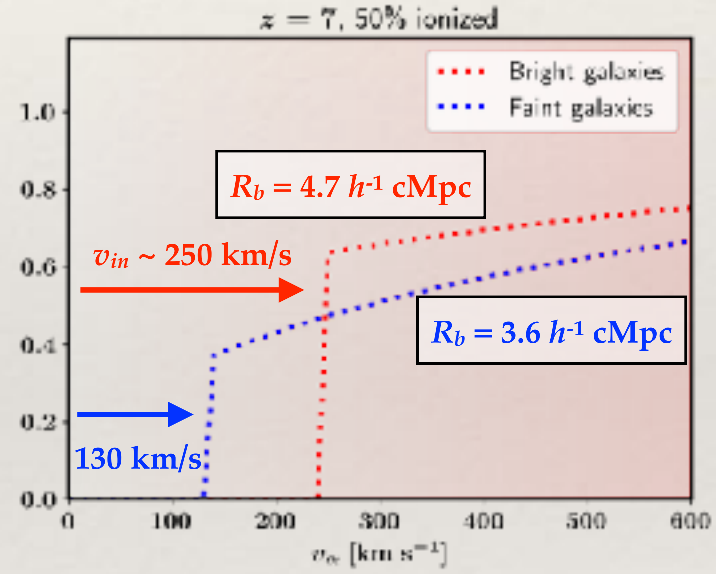
M_{UV}-dependence of HII-region size

IGM around **brighter** galaxies with M_{UV} < -22 at z = 7



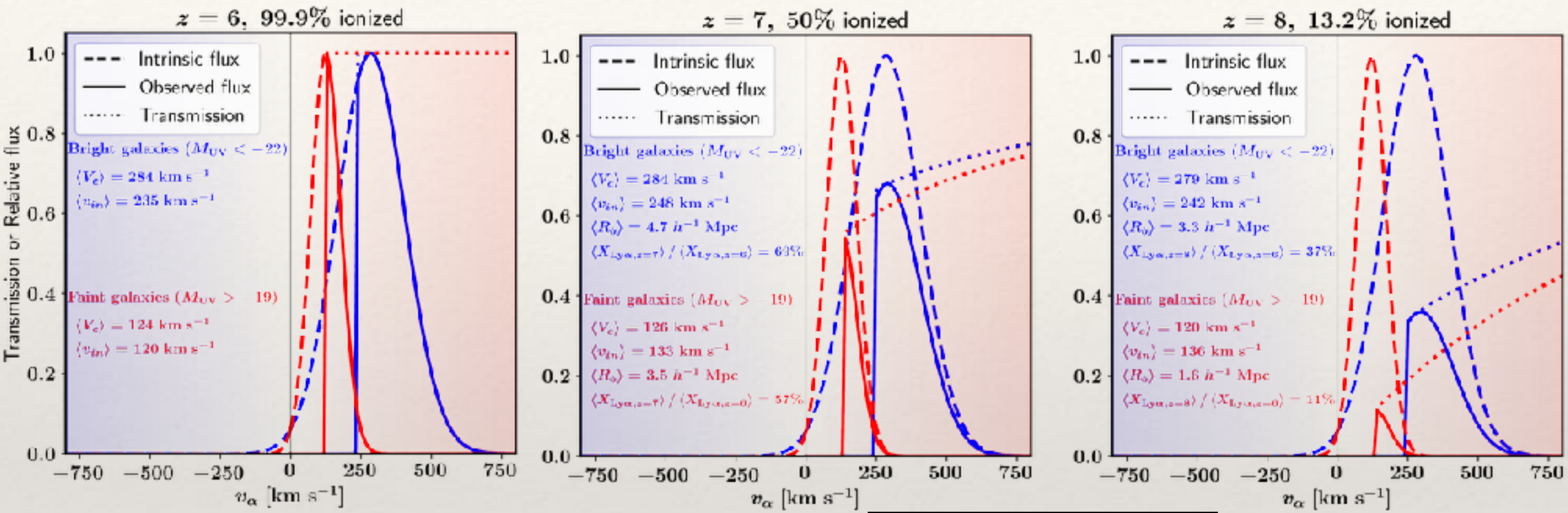
IGM around **fainter** galaxies with M_{UV} > -19 at z = 7





Weak MUV dependence & large scatter

z and M_{UV} dependence



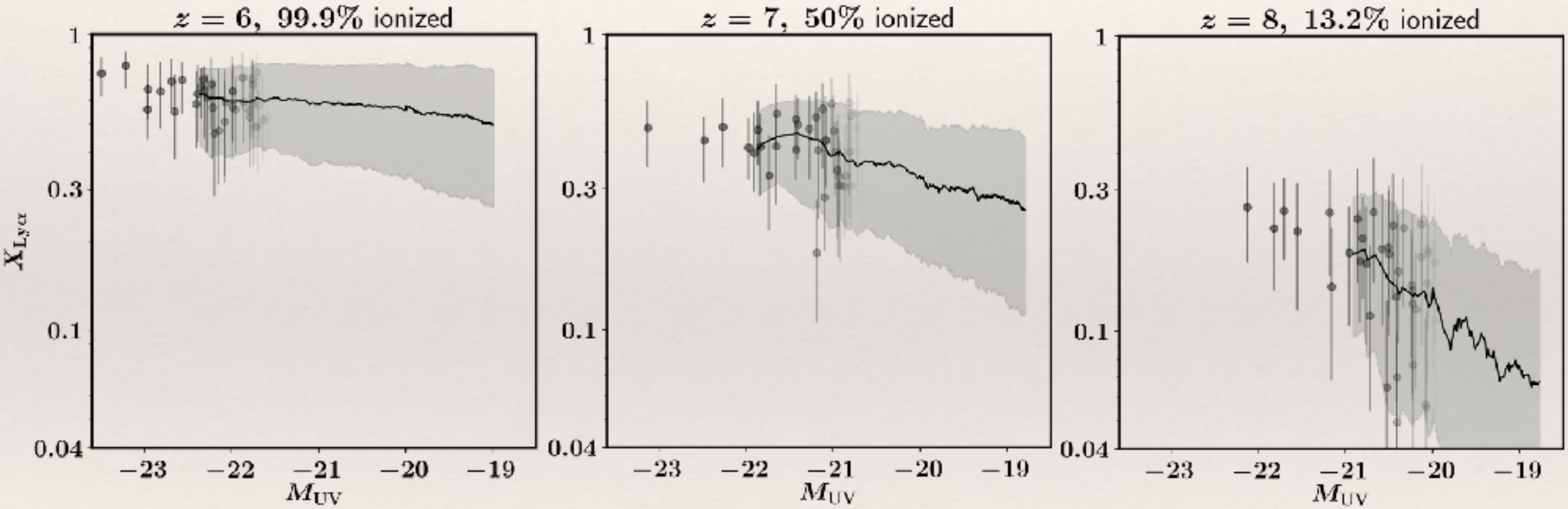
Flux-weighted transmission

$$X_{\mathrm{Ly}\alpha} \equiv \frac{\int dv_\alpha \mathcal{T}(v_\alpha) F_{\mathrm{in}}(v_\alpha)}{\int dv_\alpha F_{\mathrm{in}}(v_\alpha)}$$

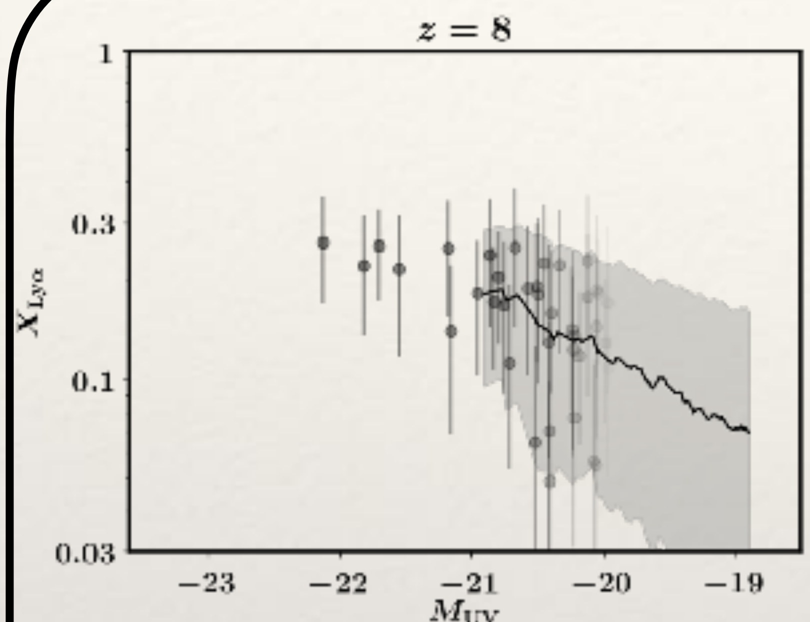
$X_{\mathrm{Ly}\alpha}$ = 0.44	0.63	0.26	0.44	0.056	0.24
$X_{\mathrm{Ly}\alpha,z}$ / $X_{\mathrm{Ly}\alpha,z=6}$ =		58%	70%	12%	37%

Fainter galaxies are more susceptible to damping-wing opacity because (1) they reside in smaller HII bubbles and (2) transmit bluer photons.

Full statistics of $X_{Ly\alpha}$



Implication of the Variation in $X_{Ly\alpha}$

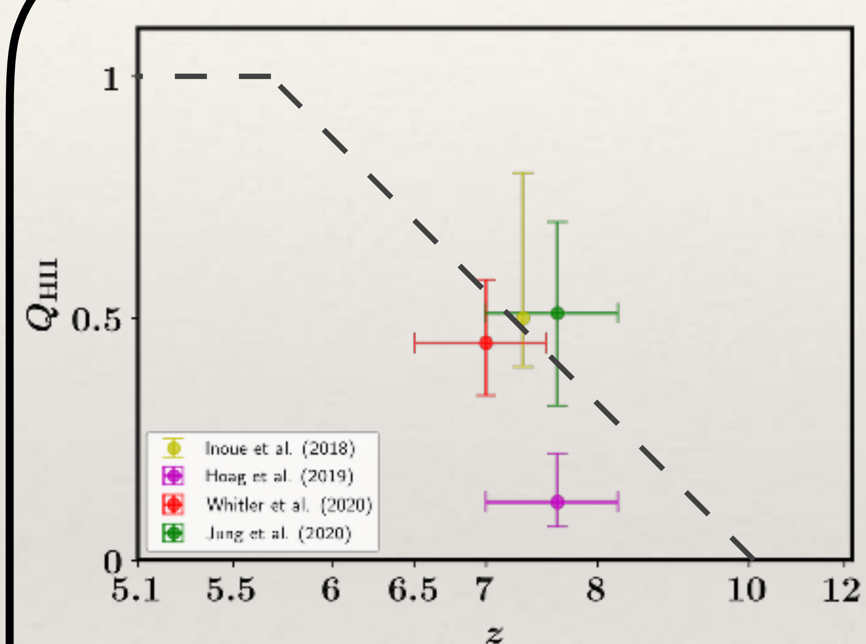


A single measurement has a huge uncertainty in IGM transmission.

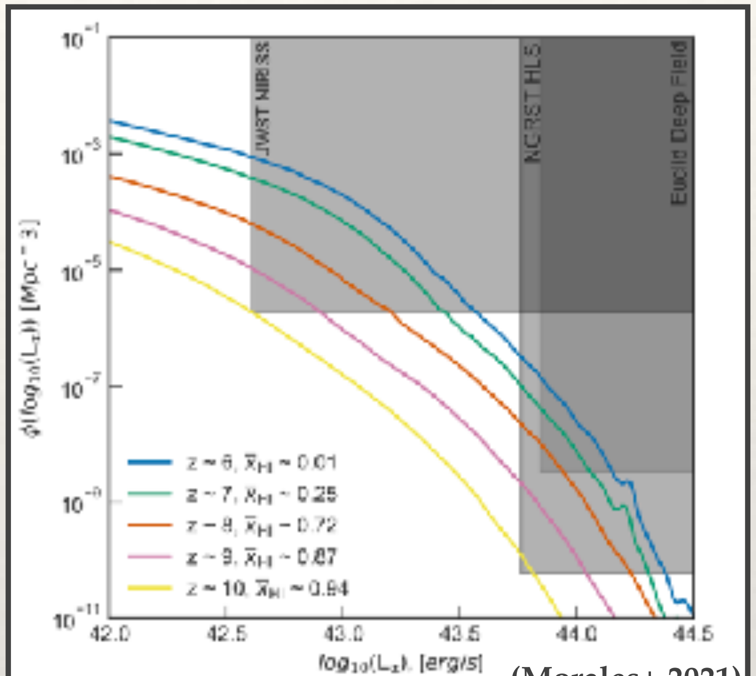
TABLE 4
MEDIAN-TO-68% RANGE RATIO OF $X_{Ly\alpha}$

M_{UV}	-22	-21	-20	-19
$z = 6$	47%	72%	82%	100%
$z = 7$	55%	94%	104%	127%
$z = 8$	N/A	101%	148%	197%

The ratio > 100% means more than 100 galaxies are needed to constrain the transmission to 10% level.



Recent LAE surveys at $z > 7$ are based on < 100 galaxies.
Perhaps, this is why the results did not converge yet?

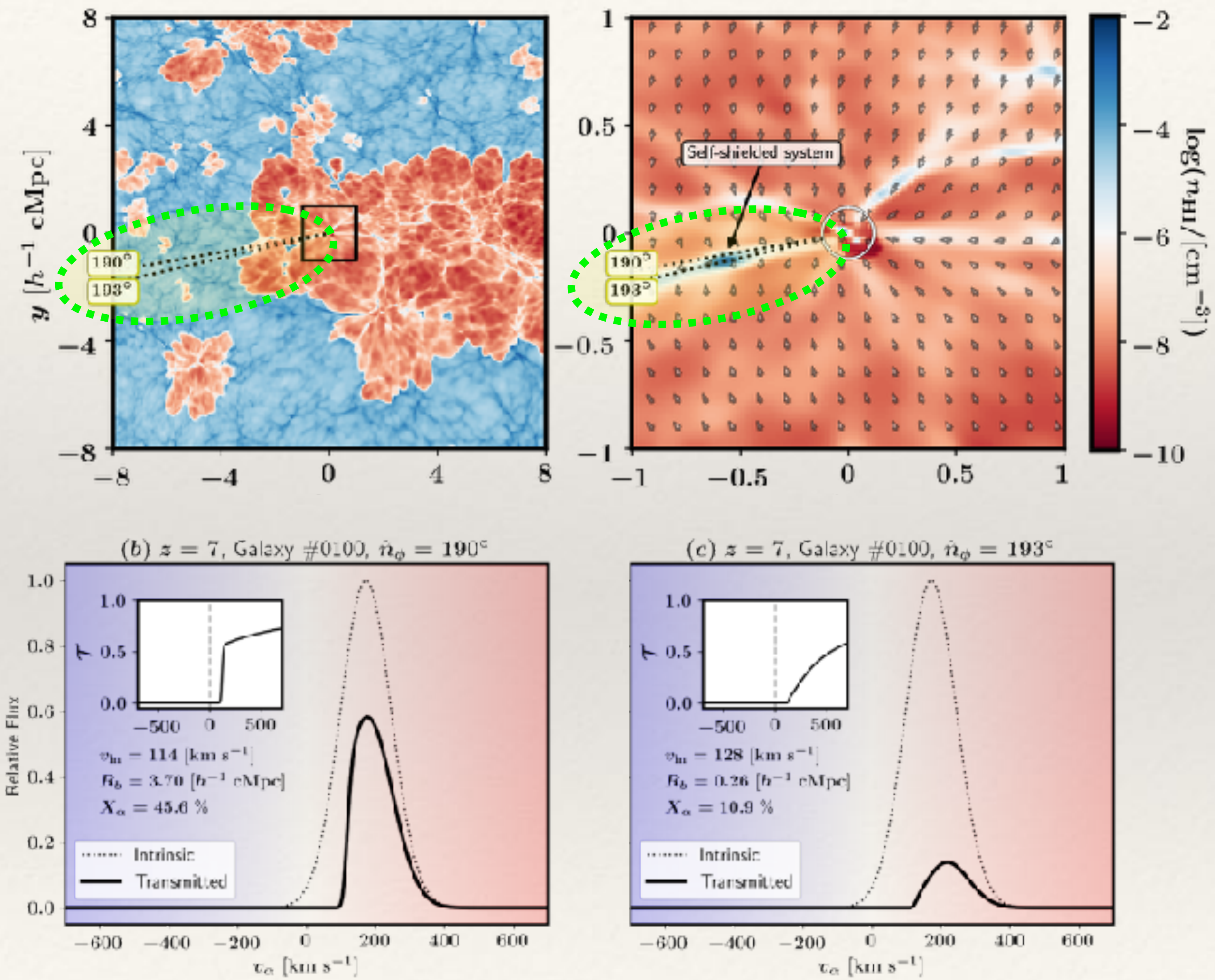


(Morales+ 2021)

JWST, NGRST, and Euclid will improve the statistics by enlarging the LAE sample.

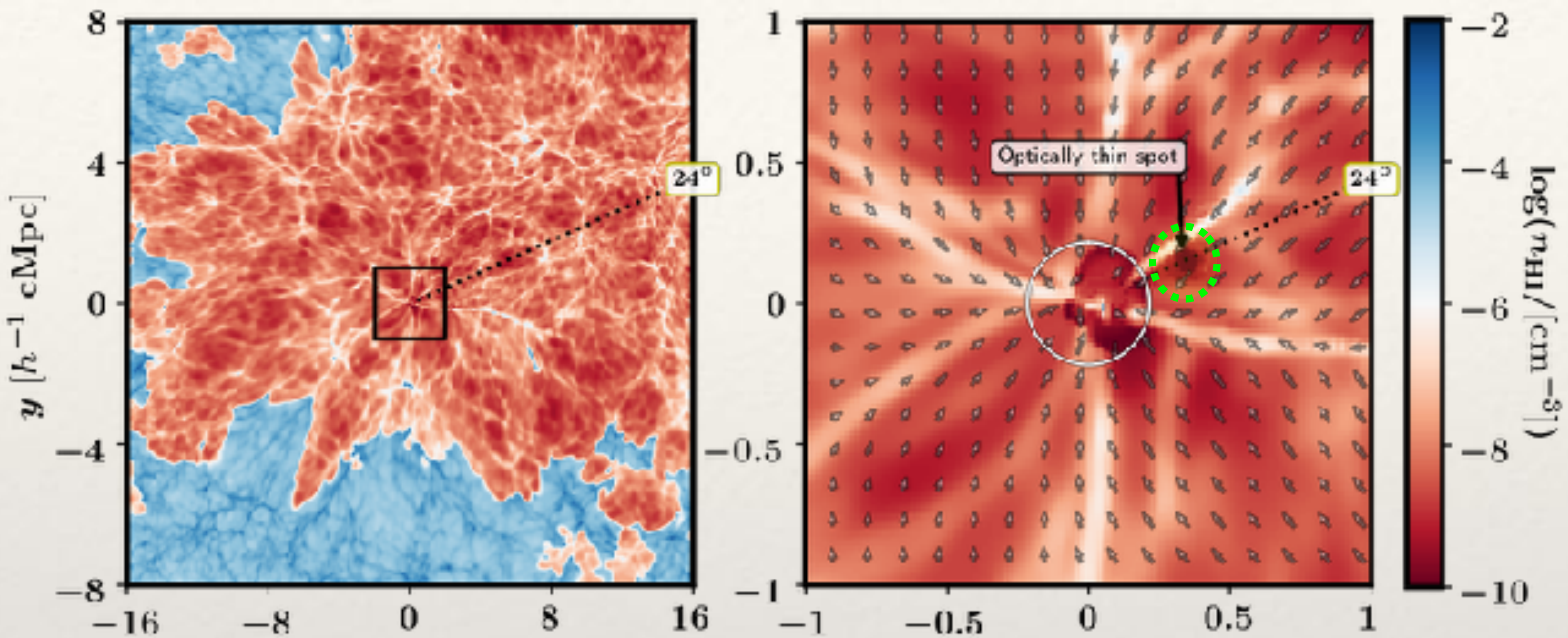
Bright galaxies have relatively small uncertainty. Perhaps, NGRST and Euclid will be more efficient in constraining reionization history.

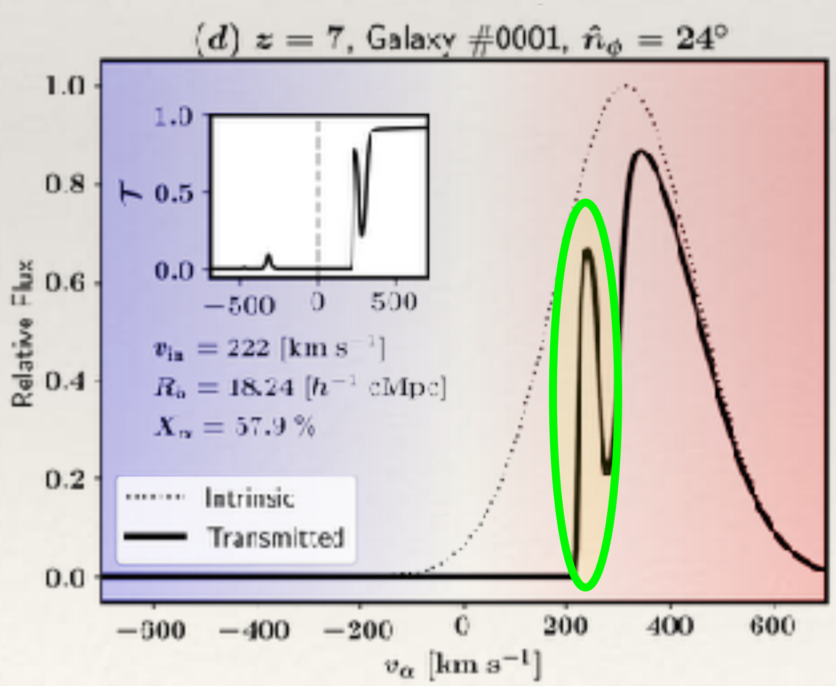
Interesting Case: Self-shielded Systems

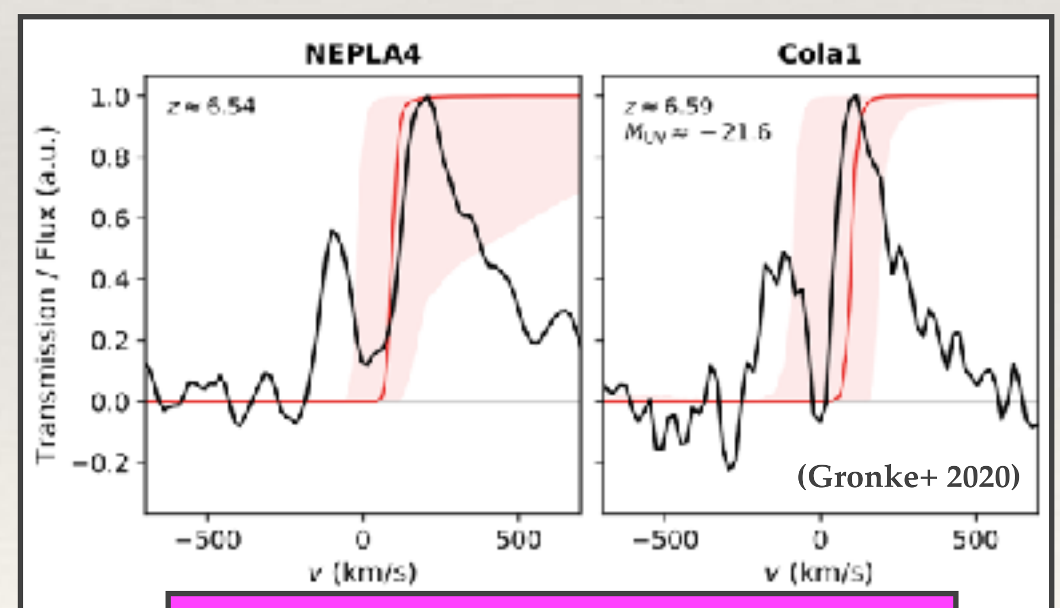


Some sightlines can be blocked by self-shielded neutral clumps.

Interesting Case: Pseudo blue peak







Impossible to explain blue peak at $z \sim 6.5$

Nearby supernova explosion results in a pseudo-blue-peak feature.
Possible scenario for $z > 6$ double-peaked LAEs?

Summary

Calculated IGM transmission of Lyα using CoDaII.

Findings

- Gravitational infall motion in IGM truncates a significant fraction (~0.5) of the red-side emission.
- Brighter galaxies are subject to less opacity because (1) they reside in larger HII bubbles and (2) transmit redder photons due to stronger infall motion.
- Self-shielded systems block certain sightlines.
- Pseudo-blue-peak feature generated by supernova explosions
- Large sightline variation in transmissivity requiring large (>>100) sample size. The variation is larger for fainter galaxies at higher redshifts.