LyA Radiative Transfer: Modeling Spectrum and Surface Brightness Profile of LyA-Emitting Galaxies at z=3-6

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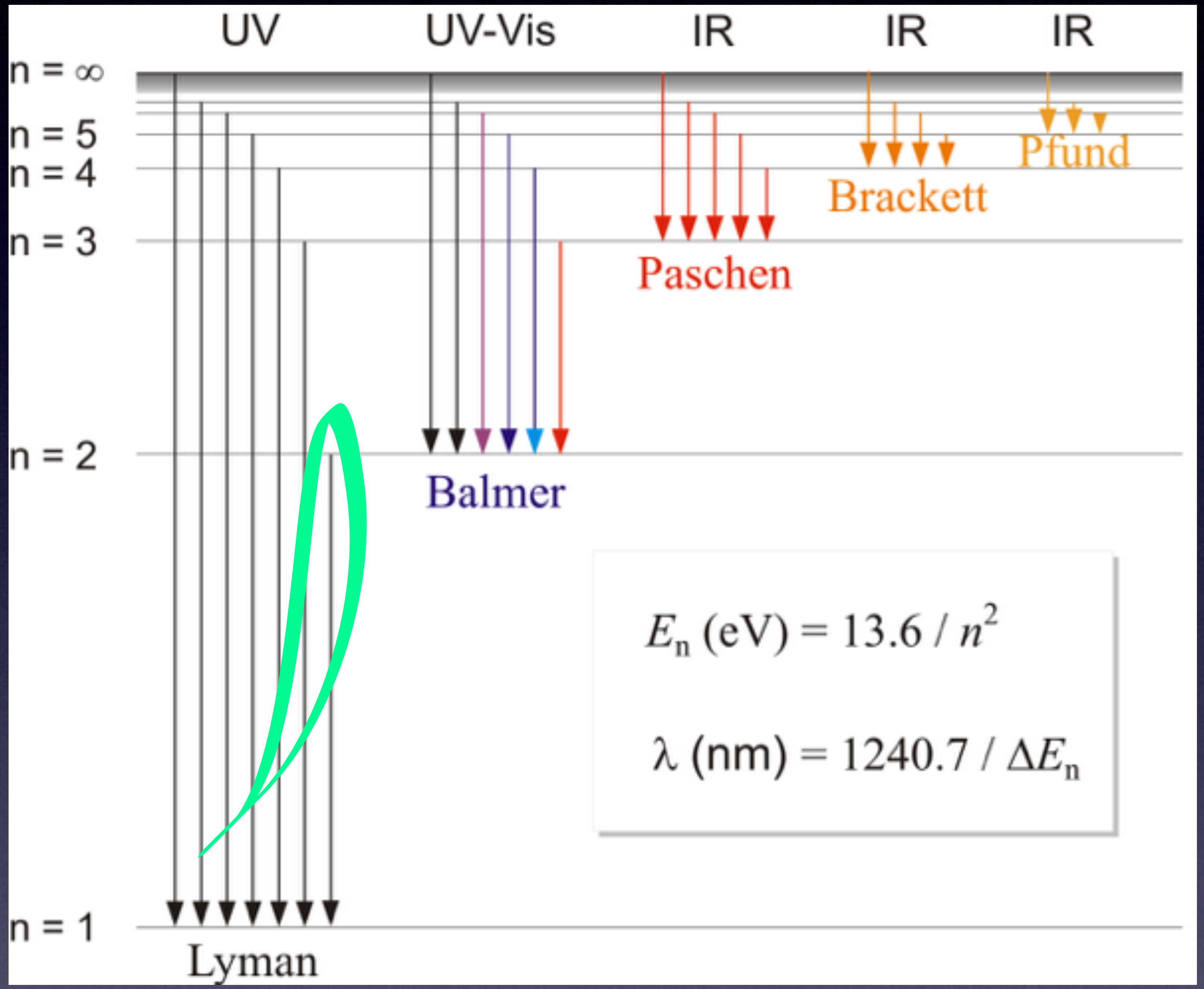
Shanghai 2019
3-7 November 2019 @ Jiao Tong University

Song et al., submitted to ApJ

LyA

- HI 2p-1s transition - 1216Å
- LyA emission through
  - Collisional excitation
  - Recombination

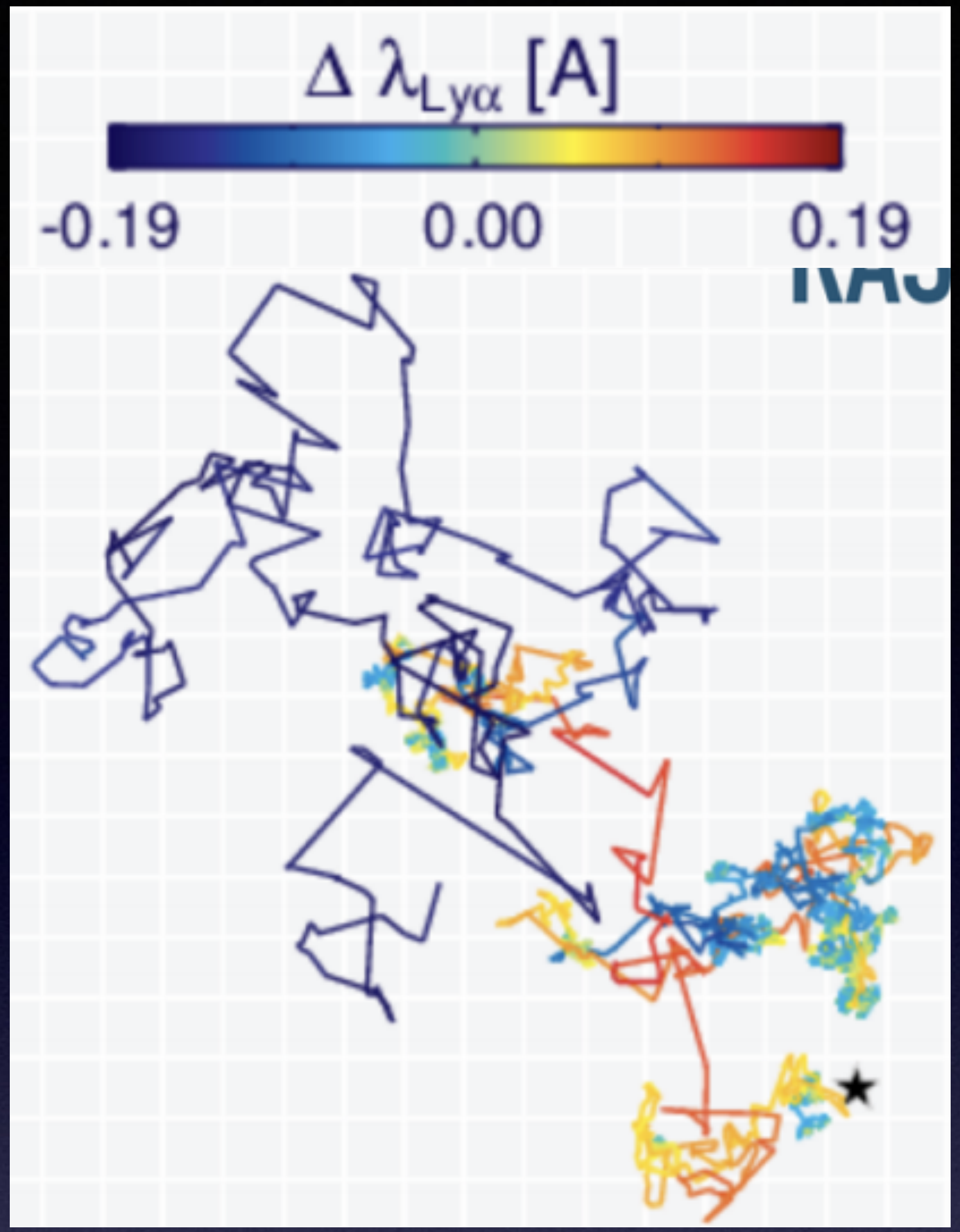


Eni Generalic

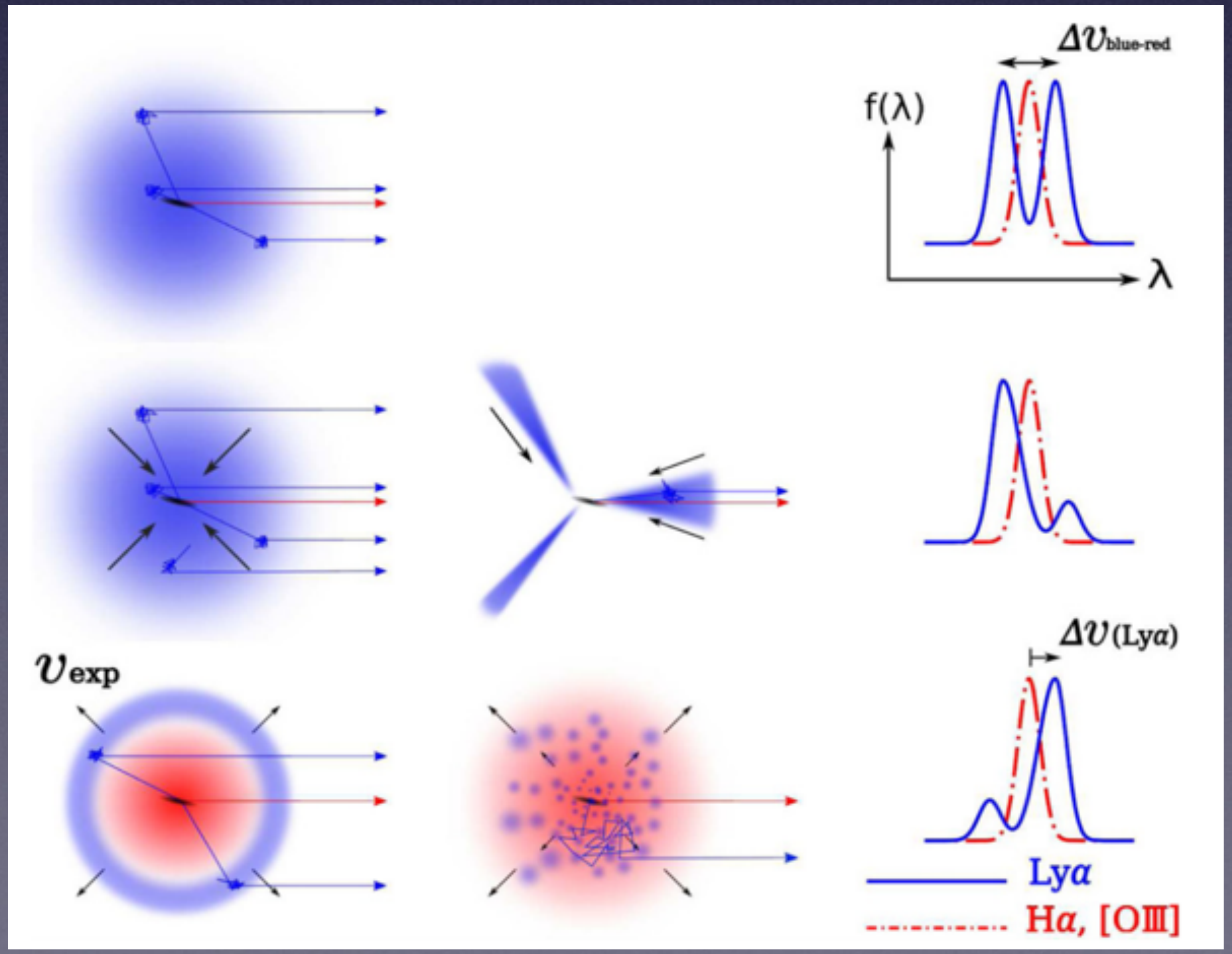
- HII regions - Strong emission from star-forming galaxies
  - Probe of early universe (e.g., SILVERUSH, MUSE, HETDEX, …)

LyA

- ✦ Resonance line
  - Huge number of scatterings
  - Sensitively affected by spatial and kinematic distributions of medium

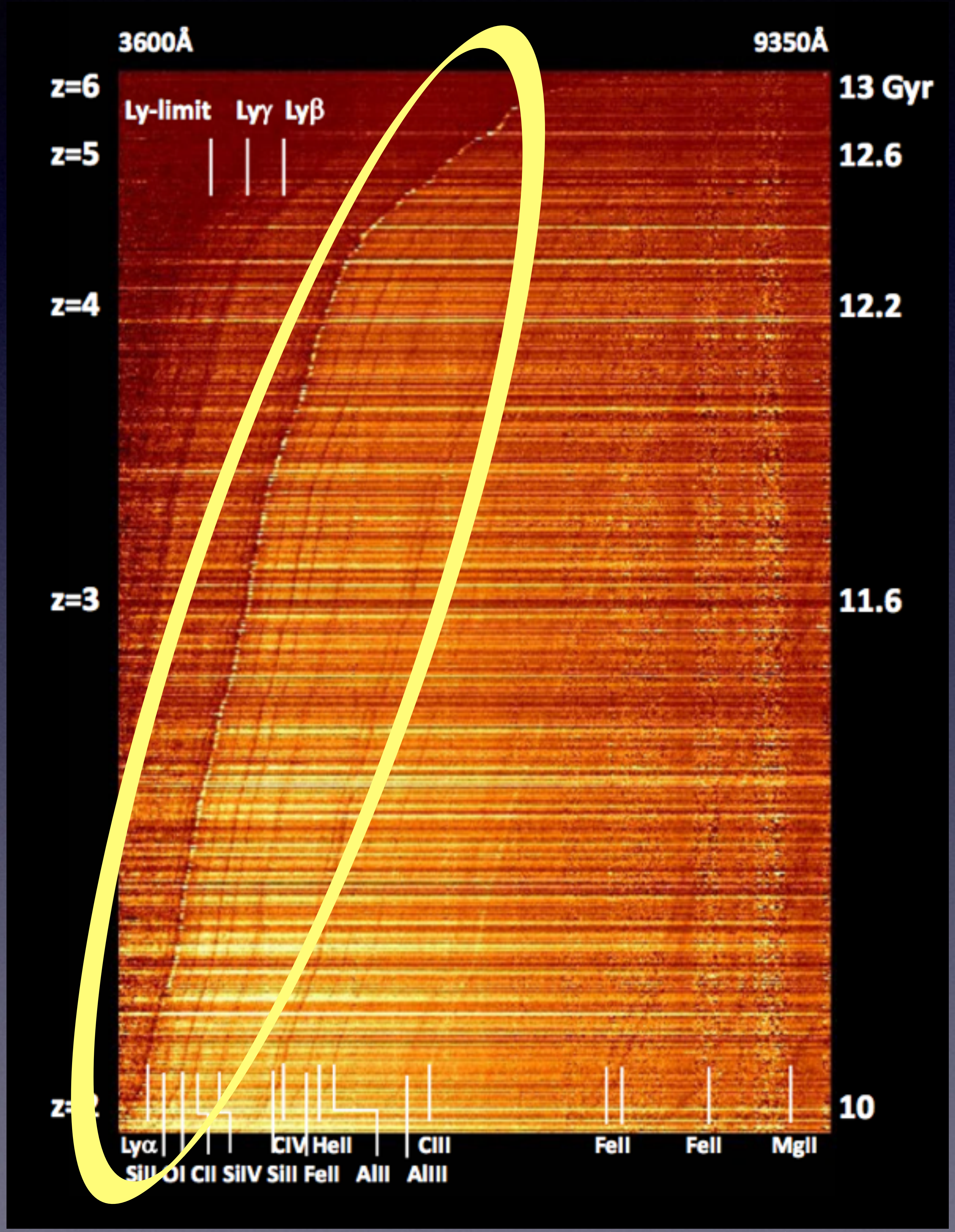


RASCAS
(Michel-Dansac et al.)

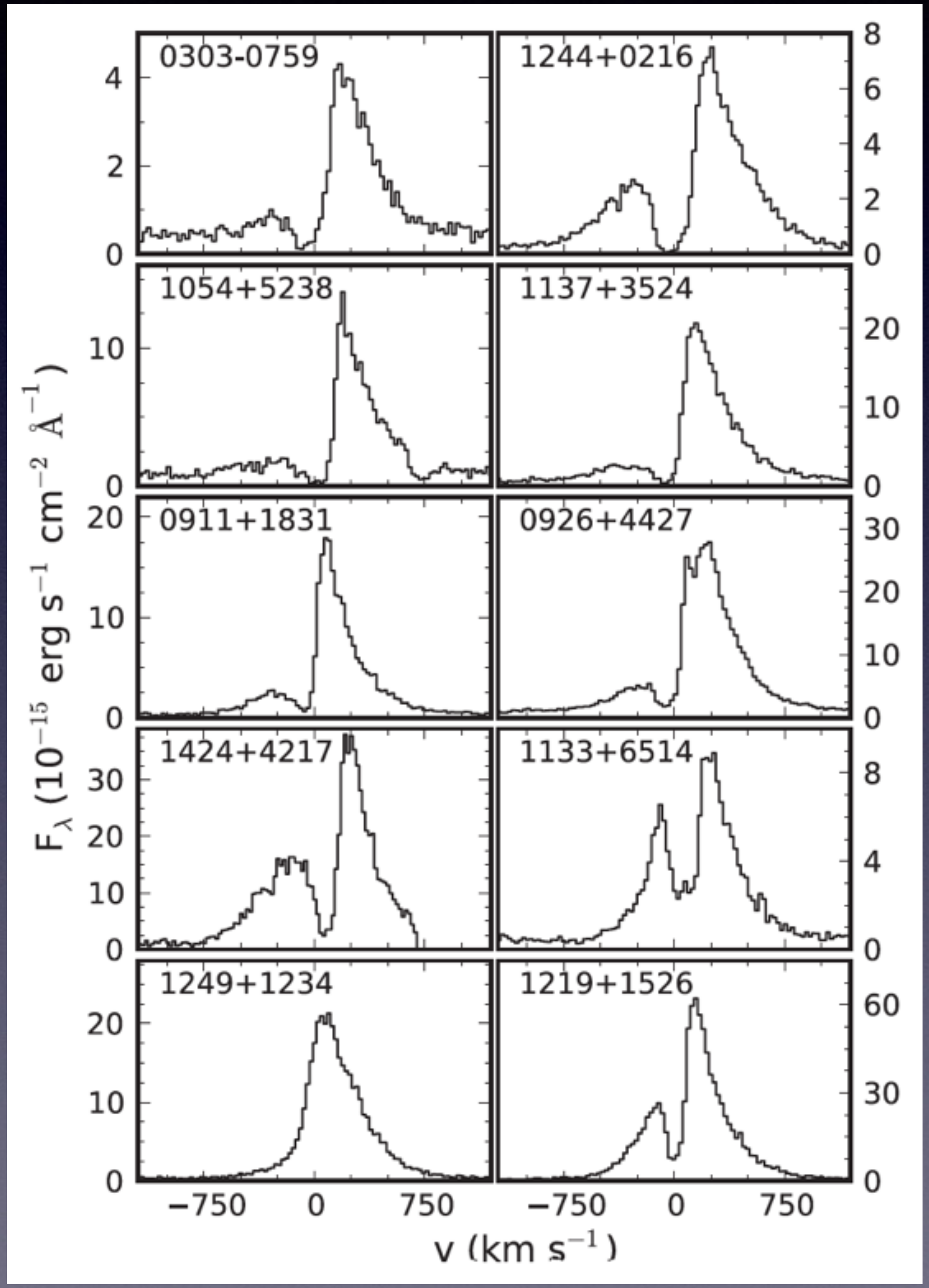


Yang et al. (2014)

LyA Spectrum



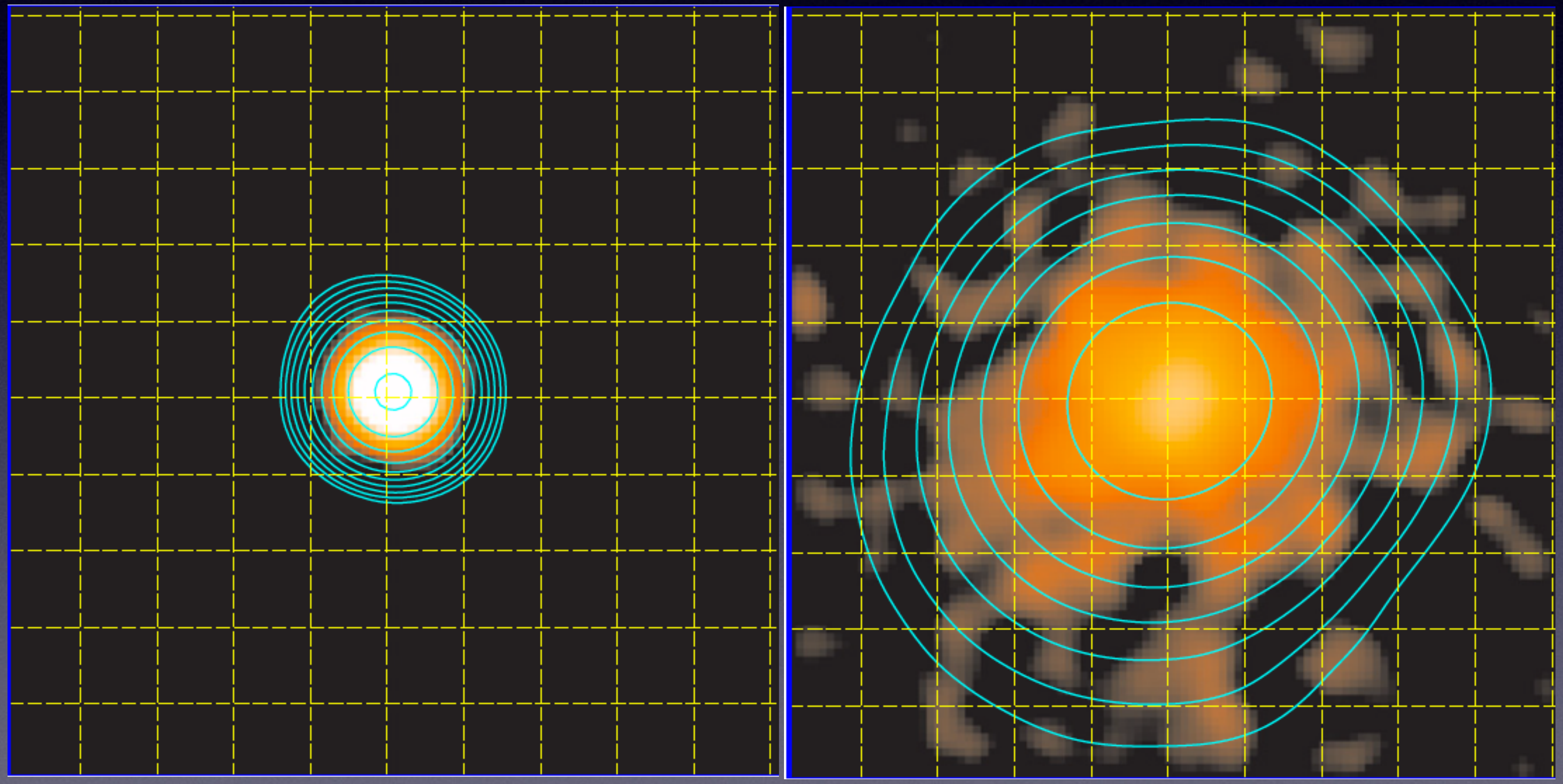
Le Fevre et al. (2015)



Henry et al. (2015)

LyA Halo

92 UV continuum-selected LBGs at <z>=2.65



FUV continuum (*averaged*) LyA (*stacked*)

Steidel et al. (2011)

LyA Radiative Transfer

Dijkstra (2017, a review on LyA RT)

$$\frac{dI_\nu(s,\mathbf{n})}{ds} = -[\underbrace{\alpha_\nu^{\rm HI}(s)}_{\text{I: absorption}} + \underbrace{\alpha_\nu^{\rm dest}(s)}_{\text{IV: `destruction'}}]I_\nu(s,\mathbf{n}) + \underbrace{j_\nu(s)}_{\text{II: emission}} + \underbrace{\int d\nu' \int d^3\hat{\mathbf{n}}'\, \alpha_{\nu'}(s) I_{\nu'}(s,\hat{\mathbf{n}}') R(\nu,\nu',\mathbf{n},\hat{\mathbf{n}}')}_{\text{III: scattering}}. \quad (58)$$

This is analytically solvable only for simple cases.
(e.g., uniform, static gas cloud surrounding a central LyA source)

So, *Monte-Carlo simulation !*
(a succession of random scattering events)

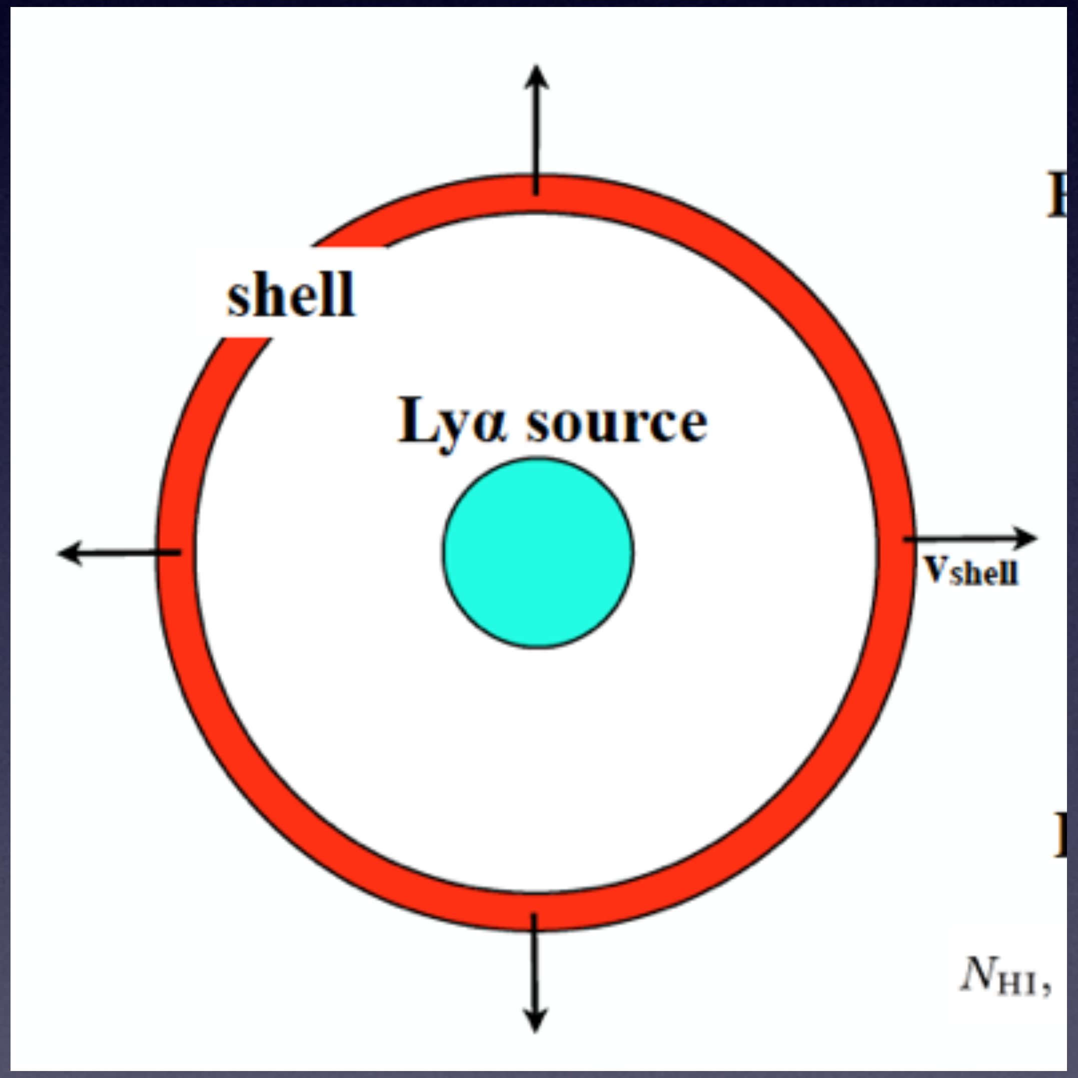
Monte-Carlo RT

$$\frac{dI_\nu(s,\mathbf{n})}{ds} = -[\underbrace{\alpha_\nu^{\rm HI}(s)} + \underbrace{\alpha_\nu^{\rm dest}(s)}]I_\nu(s,\mathbf{n}) + \underbrace{j_\nu(s)} + \underbrace{\int d\nu' \int d^3\hat{\mathbf{n}}'\, \alpha_{\nu'}(s) I_{\nu'}(s,\hat{\mathbf{n}}') R(\nu,\nu',\mathbf{n},\hat{\mathbf{n}}')}. \quad (58)$$

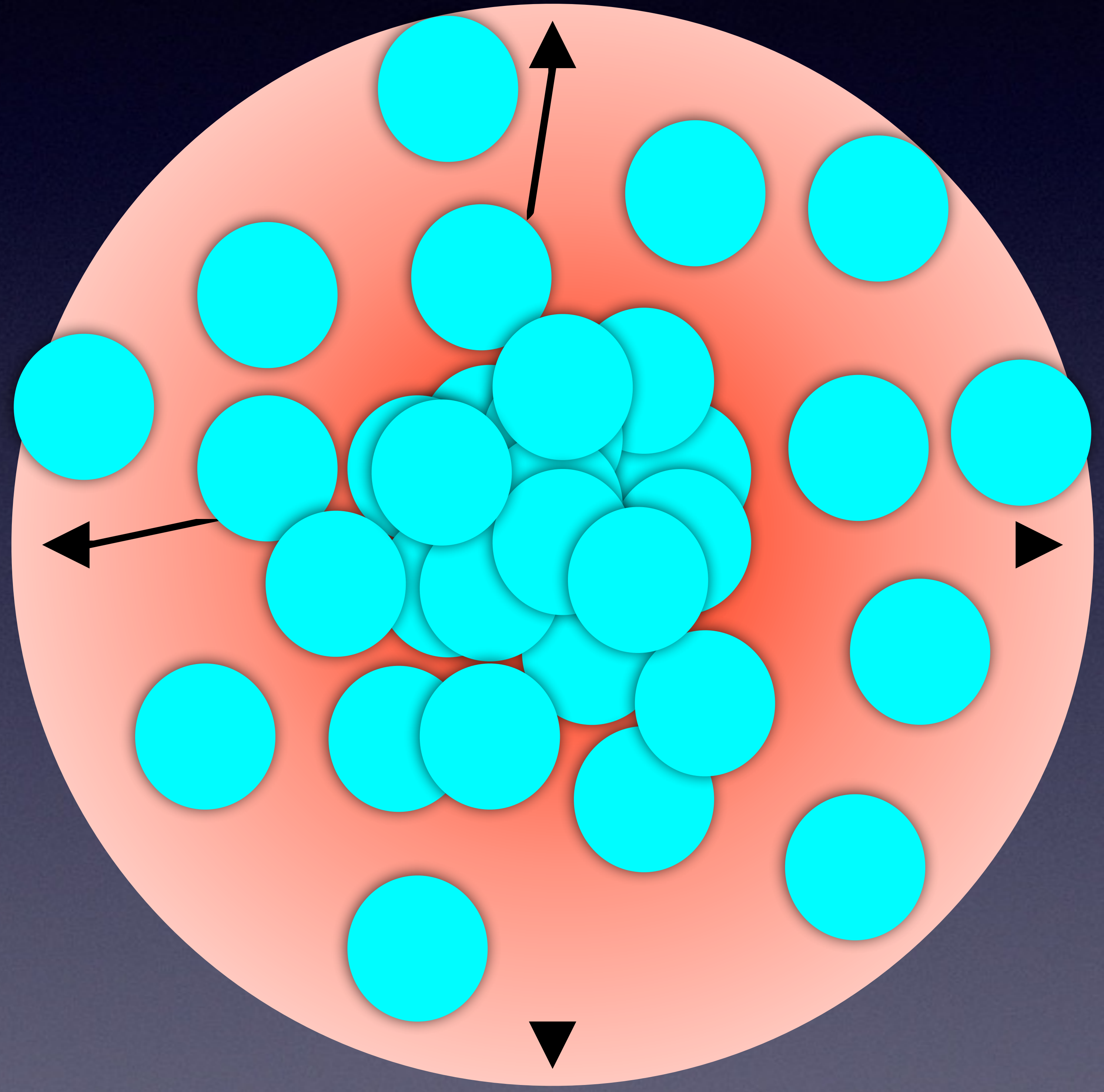
1. Generate a photon (randomly draw **r**, **k**, and ν).
2. Let the photon travel a distance *d* that corresponds to a randomly chosen τ ($\tau = \int_0^d n(\mathbf{x})\sigma\, d|\mathbf{x}|$).
3. After travelling *d*, decide whether to scatter (by hydrogen or dust) or destruct (by dust) the photon.
   - 3.1. Destruct - Go to 1.
   - 3.2. Scatter - Draw new **k** and ν, go to 2, and repeat until the photon is escaping or destructed.

Galaxy Model

Dijkstra (2017)



Our model

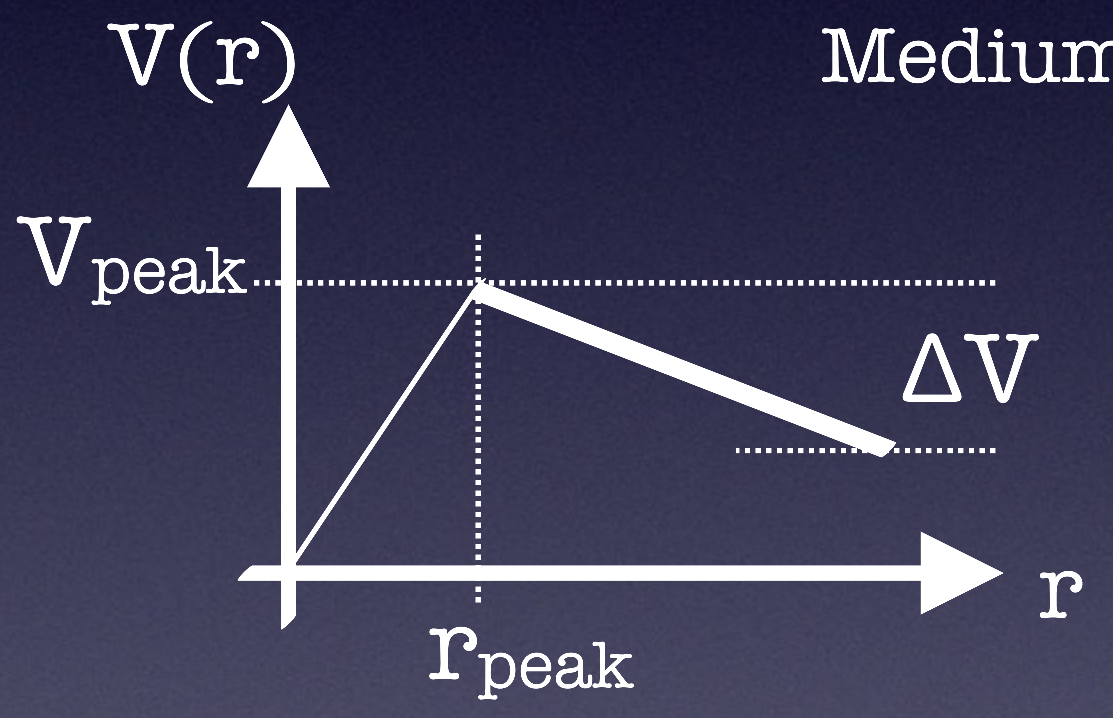


Expanding *shell* with constant velocity;
Uniform medium distribution;
Central point source

Expanding *halo* with velocity profile;
Density distributions for sources and medium

Our LyA MCRT modeling

Medium temperature =10^4K
Intrinsic LyA spectrum =Voigt profile
Source distribution =exp(-r/rs_{cont})



Momentum-driven wind
in gravitational potential well

Table 1. Parameter Grid of Simulation

	Parameter	Values
Medium density distribution scale radius	rs_{HI}[a]	$[0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9]$
Velocity profile parameters	r_{peak}[b]	$[0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6]$
Velocity profile parameters	V_{peak}[c]	$[100, 200, 300, 400, 500]$
Velocity profile parameters	ΔV[d]	$[-500, -450, -400, \ldots, -100, -50, 0]$
Optical depth	$\log \tau_0$[e]	$[5.7, 6.0, 6.3, 6.6, 6.9, 7.2]$
Dust-to-gas ratio	DGR[g]	$[0.0, 0.2, 0.4, \ldots, 1.6, 1.8, 2.0]$
Redshift	z[g]	$z_0 + [0.01, 0.02, 0.03, \ldots, 0.08, 0.09, 0.10]$

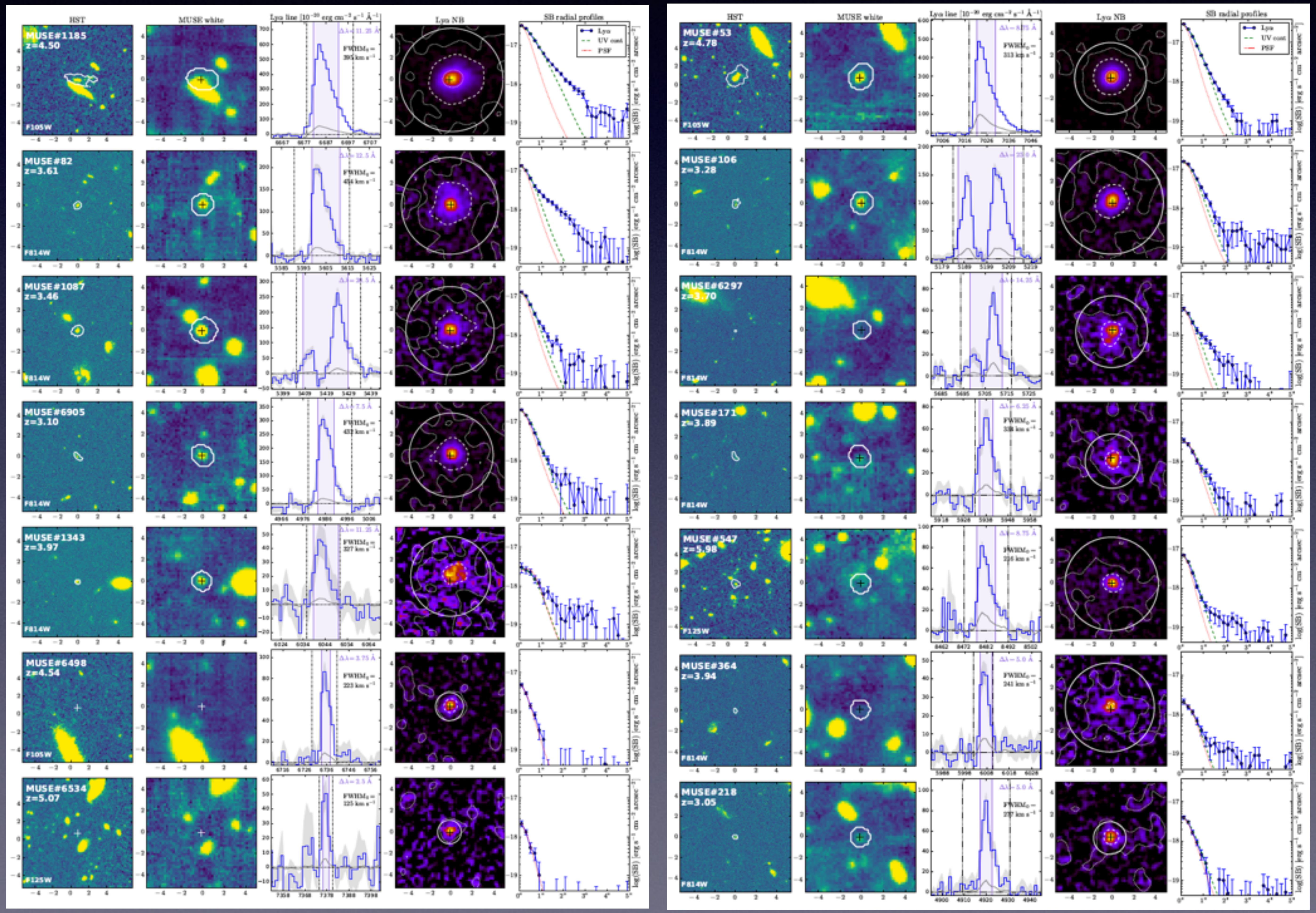
LaRT
(Seon & Kim to be submitted)

13,230 simulations
(10^6 photons/simulation)

LyA Seen by MUSE

Examples out of 145 star-forming galaxies at 3<z<6

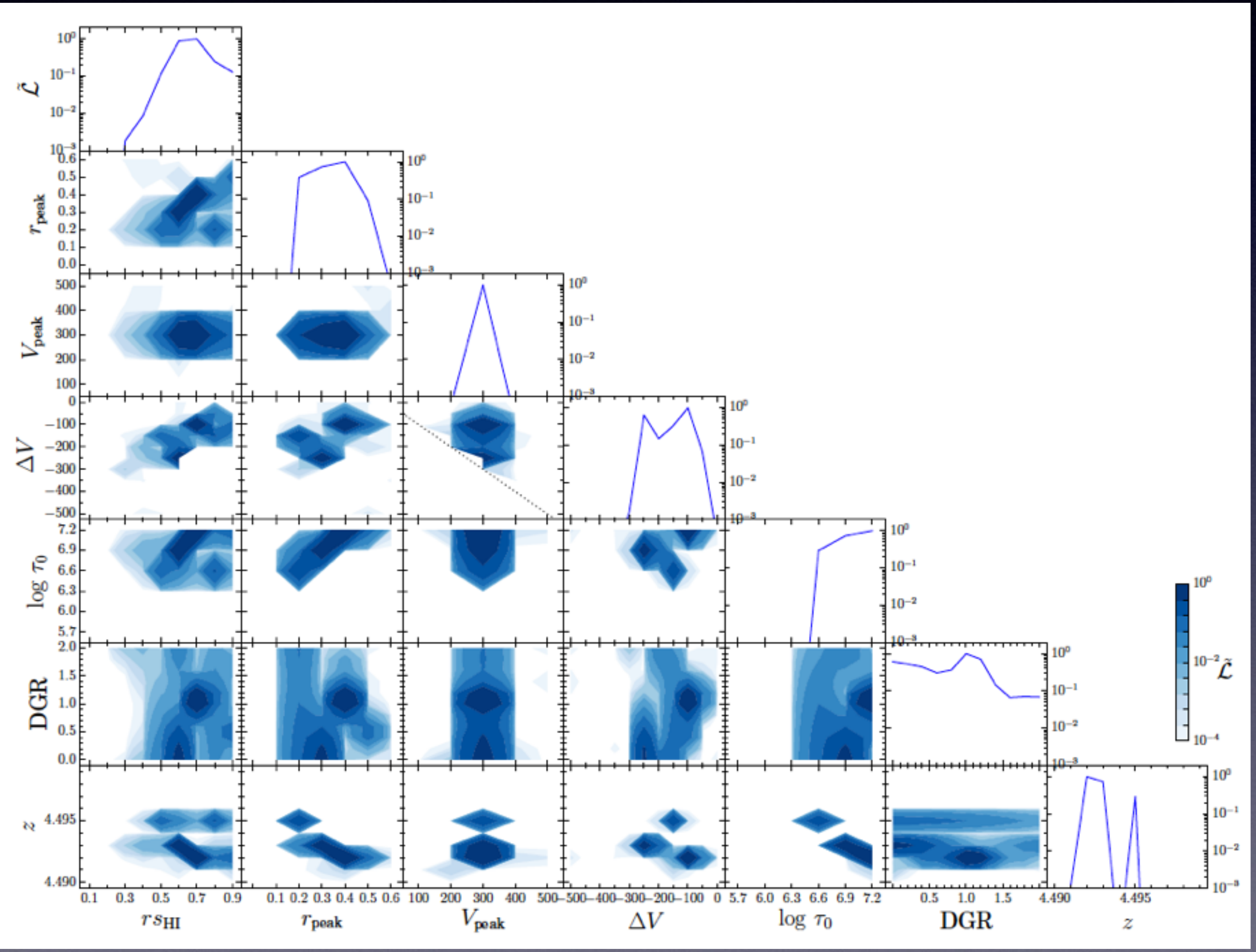
Reproduce these!
(but only shapes)

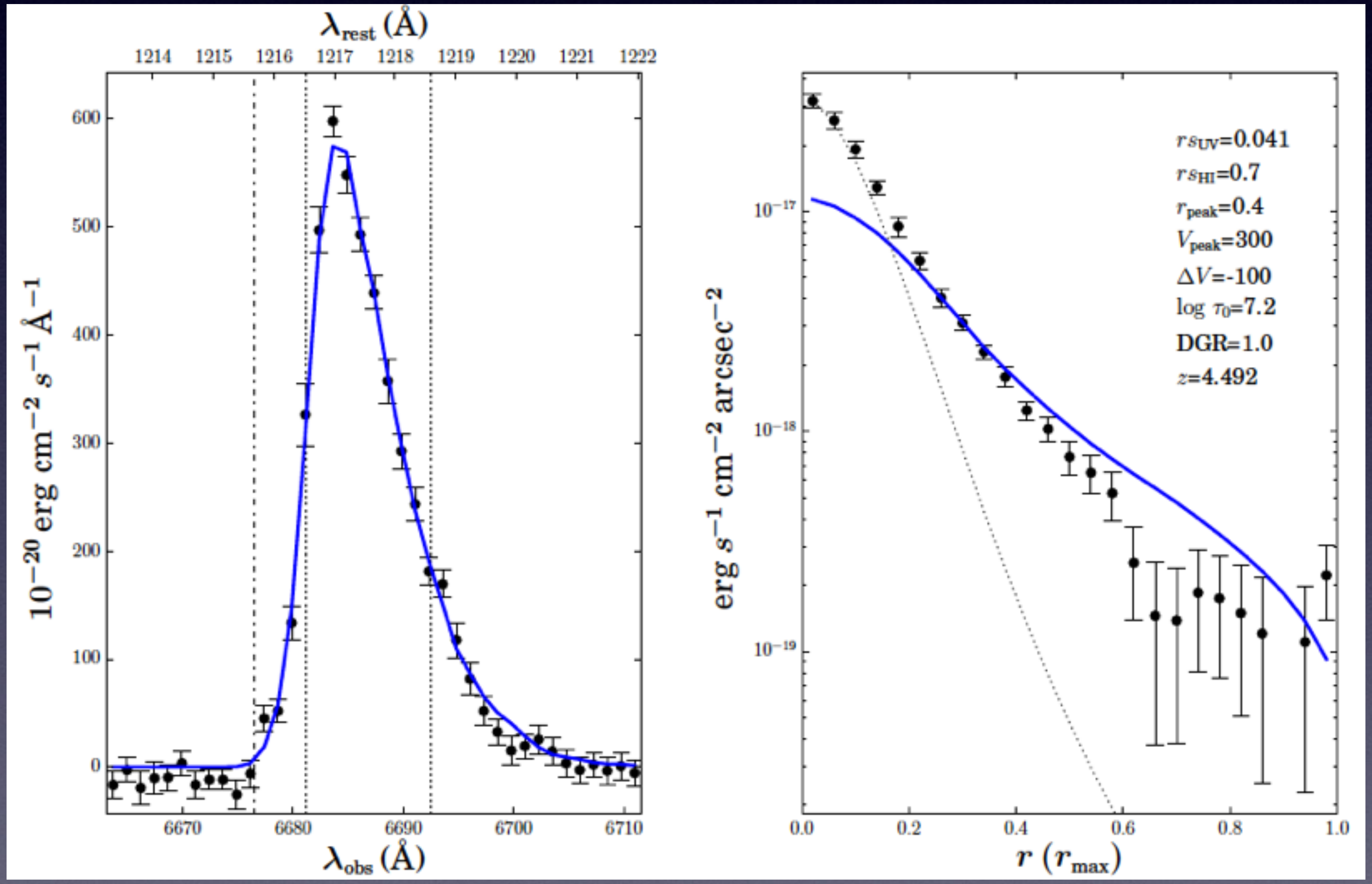


Leclercq et al. (2017)

Fits to Observations

Fit to spectrum only

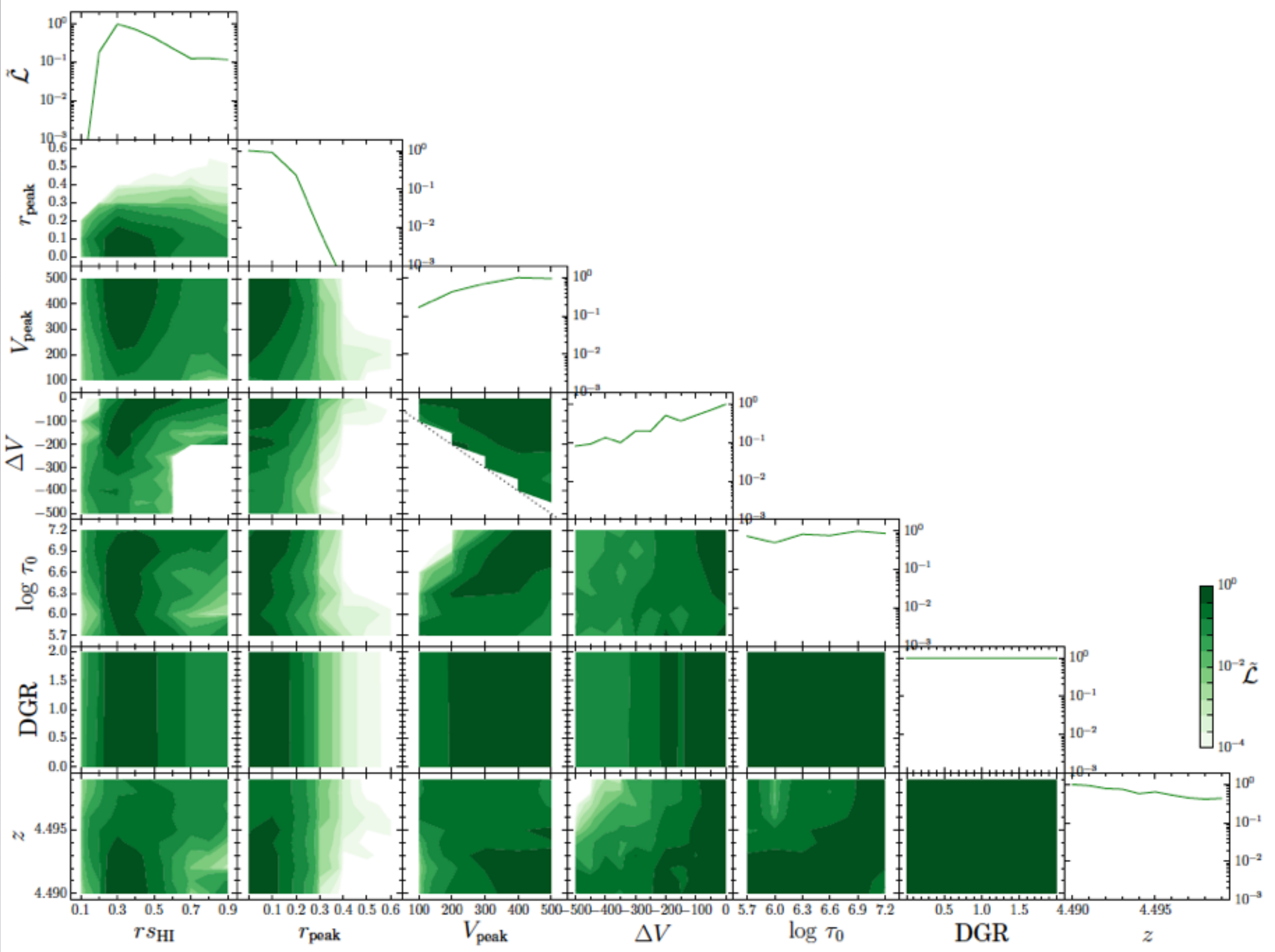


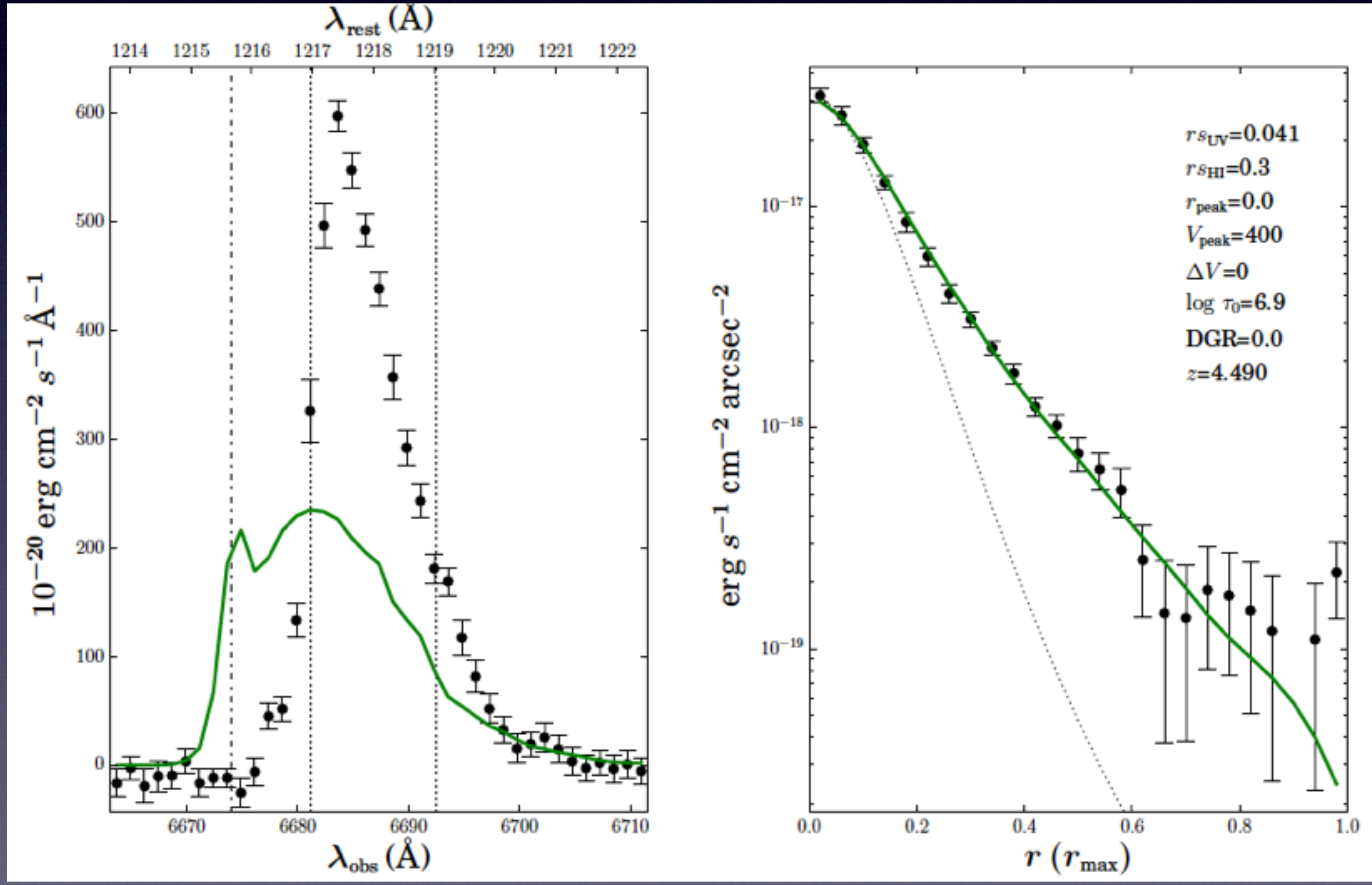


e.g., MUSE #1185

Fits to Observations

Fit to SBP only

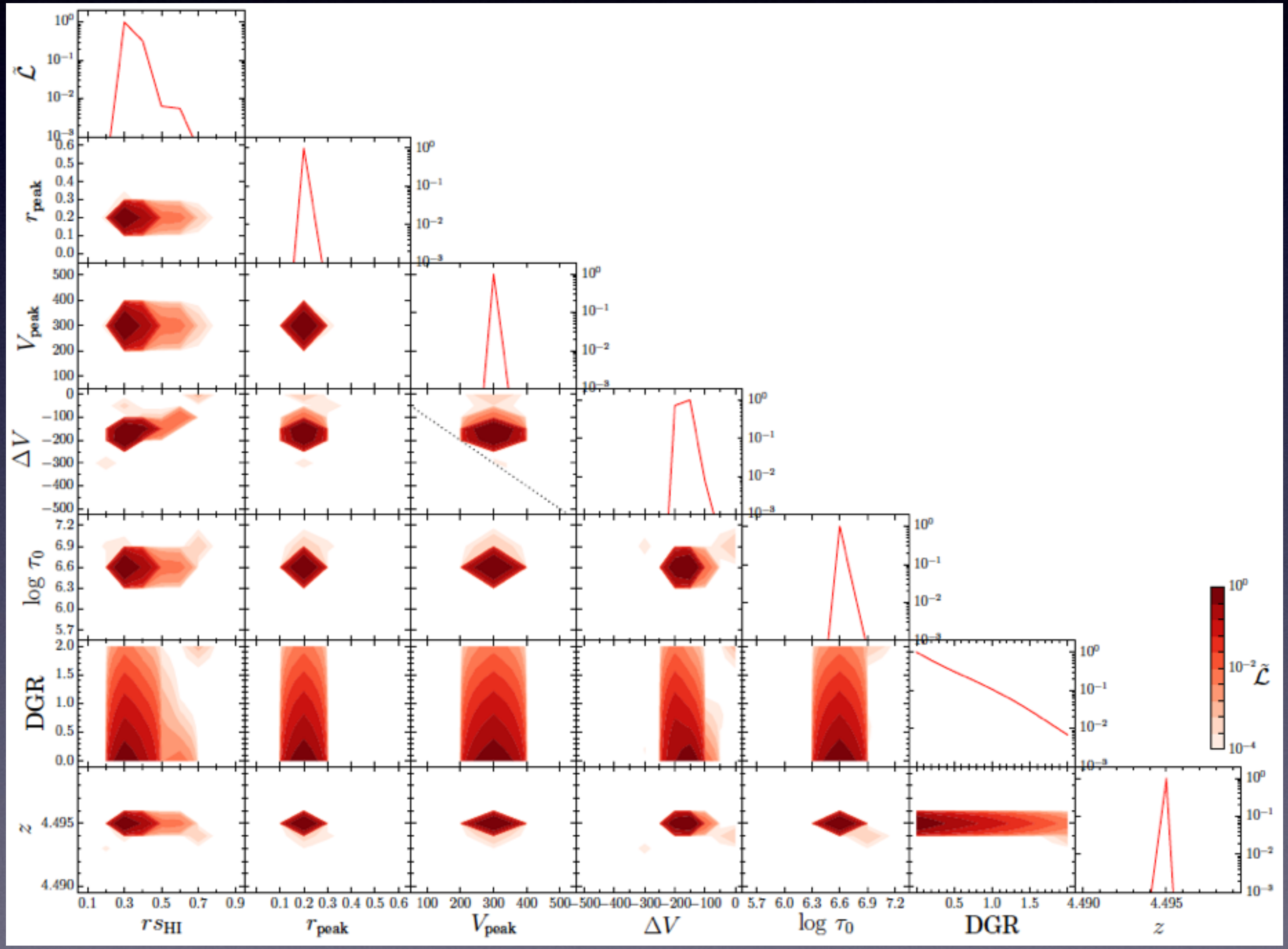


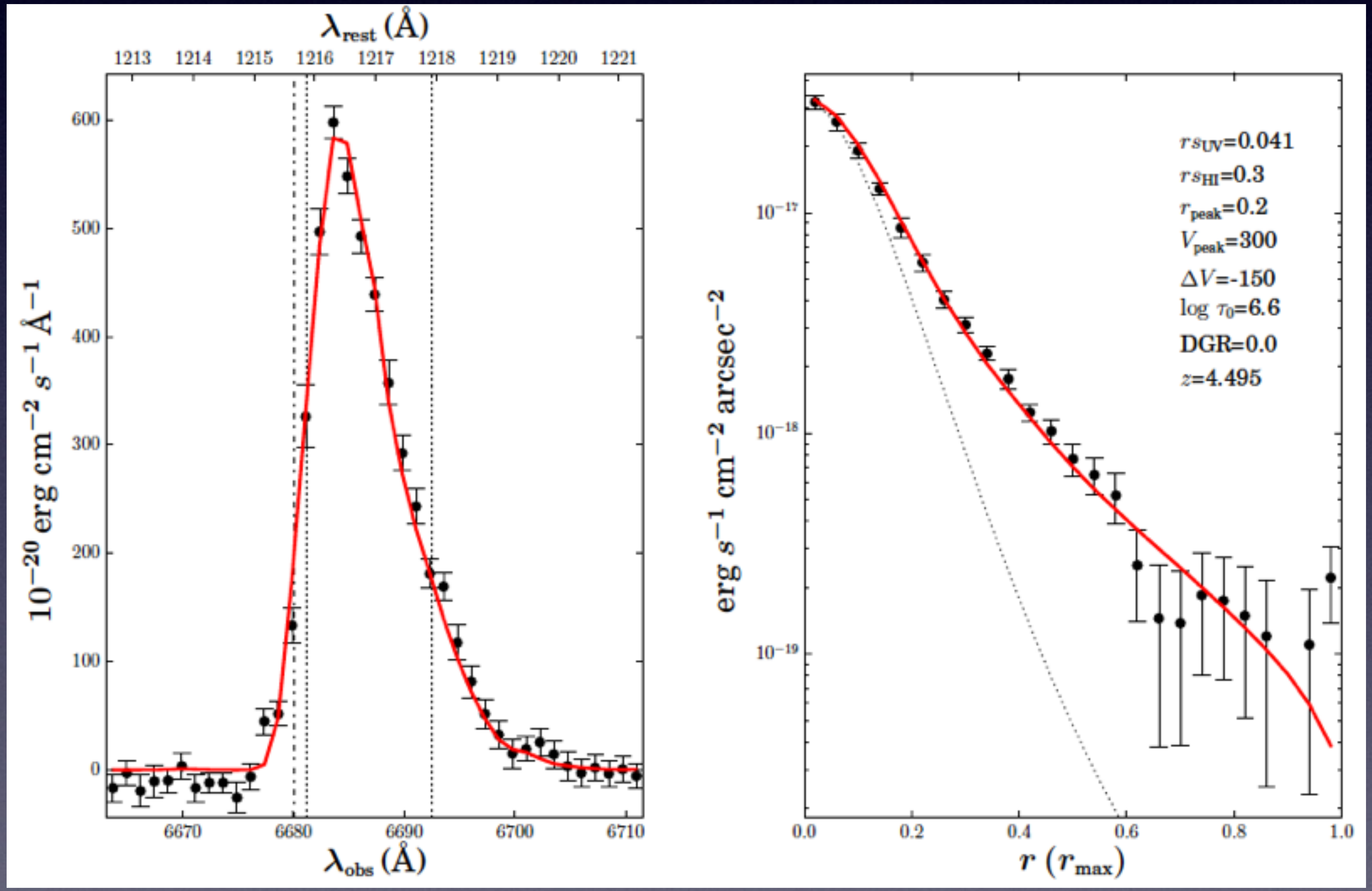


e.g., MUSE #1185

Fits to Observations

Fit to both





e.g., MUSE #1185

Fits to Observations

LyA source scale radius

MUSE #	$rs_{\rm cont}$ [a]
1185	0.041
82	0.017
6905	0.029
1343	0.016
53	0.030
171	0.025
547	0.011
364	0.014

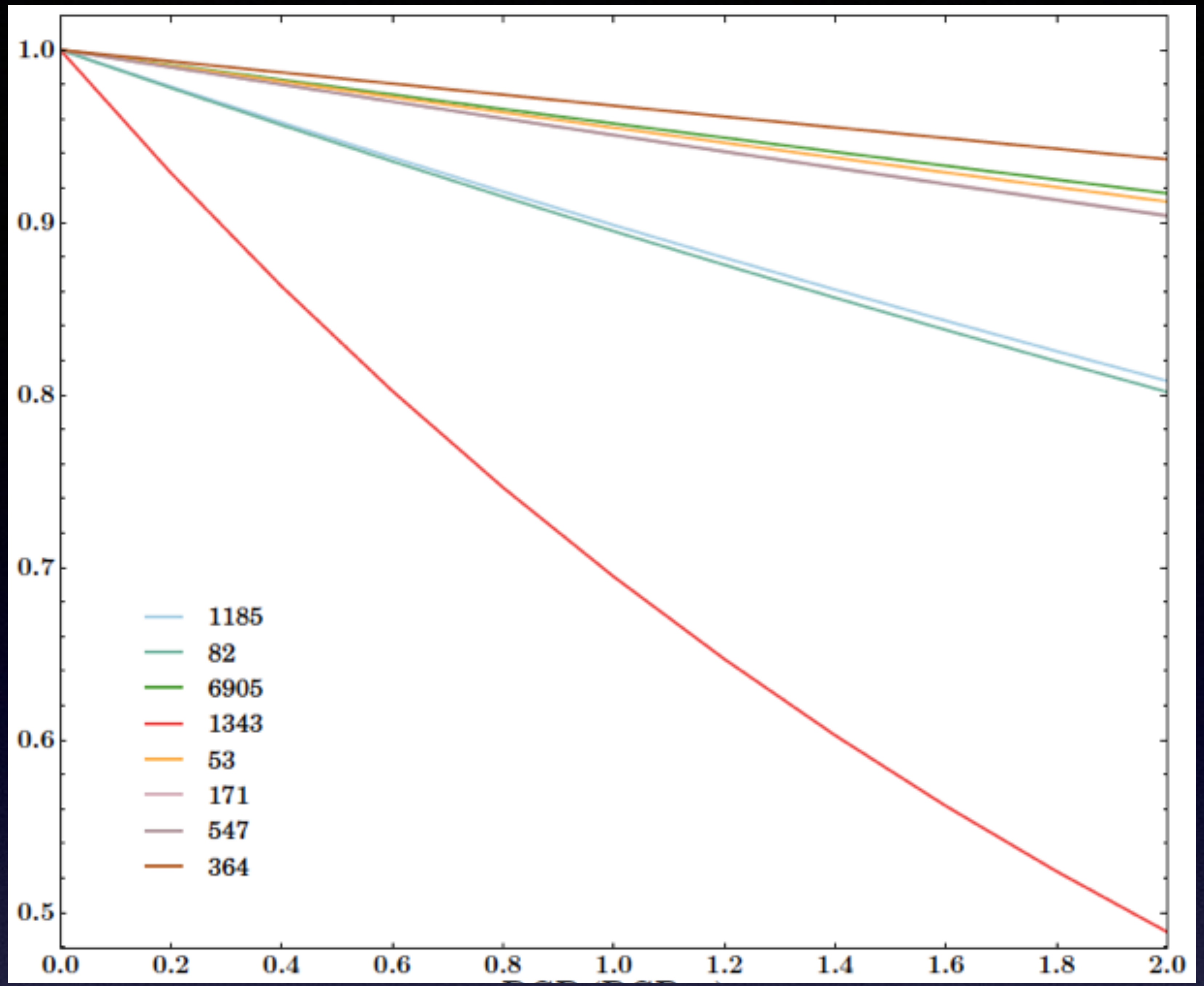
Table 3. Best-fit Parameter Values

MUSE #	$\mathcal{L}$ [a]	$rs_{\rm HI}$	$r_{\rm peak}$	$V_{\rm peak}$	ΔV	$\log \tau_0$	DGR	z	$\chi^2_{\nu,\rm sp}$ [b]	$\chi^2_{\nu,\rm SBP}$ [c]
1185	tot	$0.3^{+0.1}_{-0.1}$	$0.2^{+0.0}_{-0.0}$	300^{+43}_{-43}	$-150^{+15[illegible]}_{-3[illegible]}$	$6.6^{+0.1}_{-0.1}$	$0.0^{+0.4}$	$4.495^{+0.000}_{-0.000}$	1.88	1.14
82	tot	$0.5^{+0.4}_{-0.1}$	$0.1^{+0.0}_{-0.0}$	300^{+43}_{-43}	$-250^{+[illegible]7}_{-[illegible]30}$	$6.6^{+0.1}_{-0.1}$	$2.0_{-1.3}$	$3.604^{+0.000}_{-0.000}$	0.94	1.16
6905	tot	$0.1^{+0.0}$	$0.0^{+0.1}$	300^{+52}_{-53}	-300^{+44}_{-83}	$6.3^{+0.3}_{-0.6}$	$0.0^{+1.3}$	$3.098^{+0.001}_{-0.001}$	0.82	0.49
1343	tot	$0.8^{+0.1}_{-0.3}$	$0.4^{+0.2}_{-0.2}$	$200^{+16[illegible]}_{-10[illegible]}$	$-20[illegible]^{+125}_{-167}$	$6.9^{+0.3}_{-0.4}$	$2.0_{-1.4}$	$3.964^{+0.002}_{-0.004}$	0.96	1.36
53	tot	$0.4^{+0.1}_{-0.1}$	$0.1^{+0.0}_{-0.1}$	$300^{+4[illegible]}_{-[illegible]}$	$-[illegible]0^{+22}_{-23}$	$6.3^{+0.1}_{-0.1}$	$2.0_{-1.0}$	$4.776^{+0.000}_{-0.000}$	1.65	1.50
171	tot	$0.8^{+0.1}_{-0.4}$	$0.0^{+0.1}$	$200^{+[illegible]8}_{-[illegible]1}$	$[illegible]0_{-175}$	$6.3^{+0.2}_{-0.2}$	$2.0_{-1.4}$	$3.882^{+0.003}_{-0.001}$	1.20	0.81
547	tot	$0.7^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$300^{+[illegible]00}_{-[illegible]8}$	-200^{+88}_{-188}	$6.3^{+1.0}_{-0.1}$	$2.0_{-1.4}$	$5.974^{+0.001}_{-0.001}$	1.25	1.07
364	tot	$0.9_{-0.4}$	$0.3^{+0.4}_{-0.1}$	200^{+77}_{-70}	-200^{+67}_{-300}	$6.0^{+0.3}_{-0.3}$	$2.0_{-1.4}$	$3.939^{+0.004}_{-0.001}$	0.68	0.36

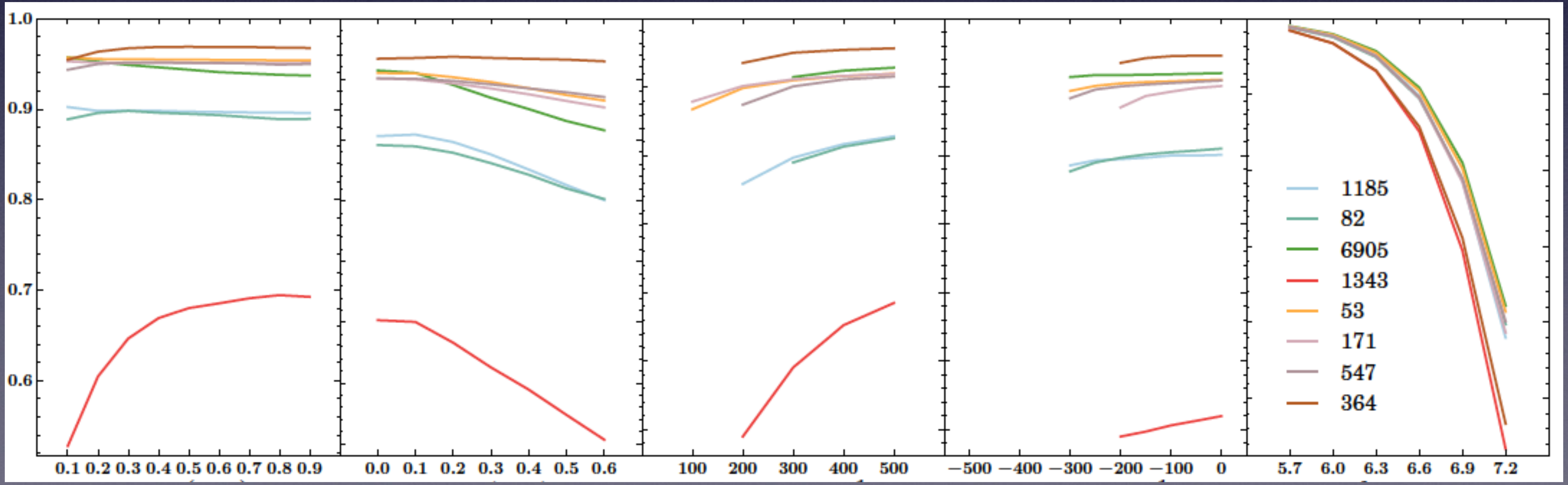
HI medium scale radius

Velocity change toward edge

LyA Escape Fraction

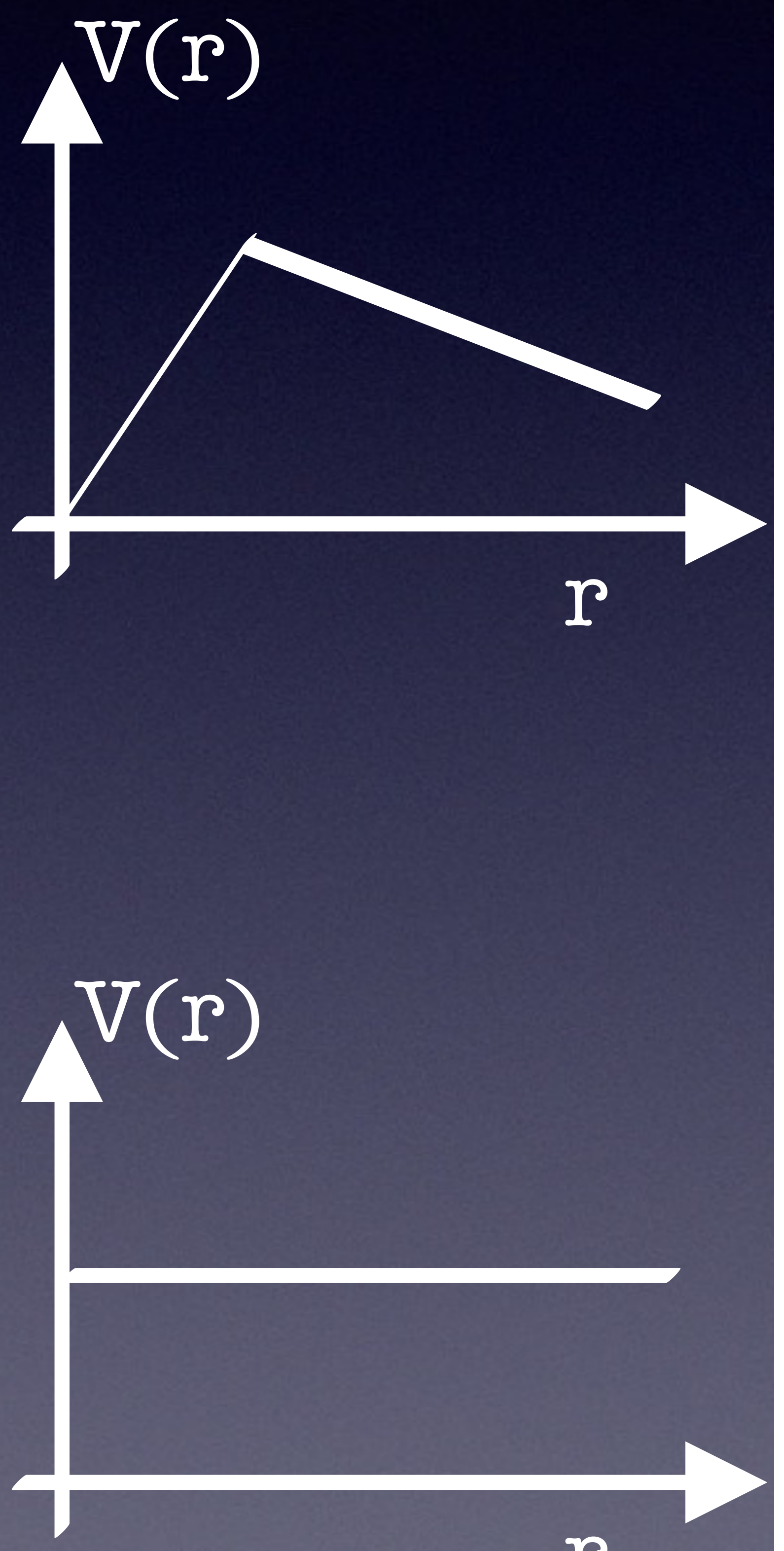


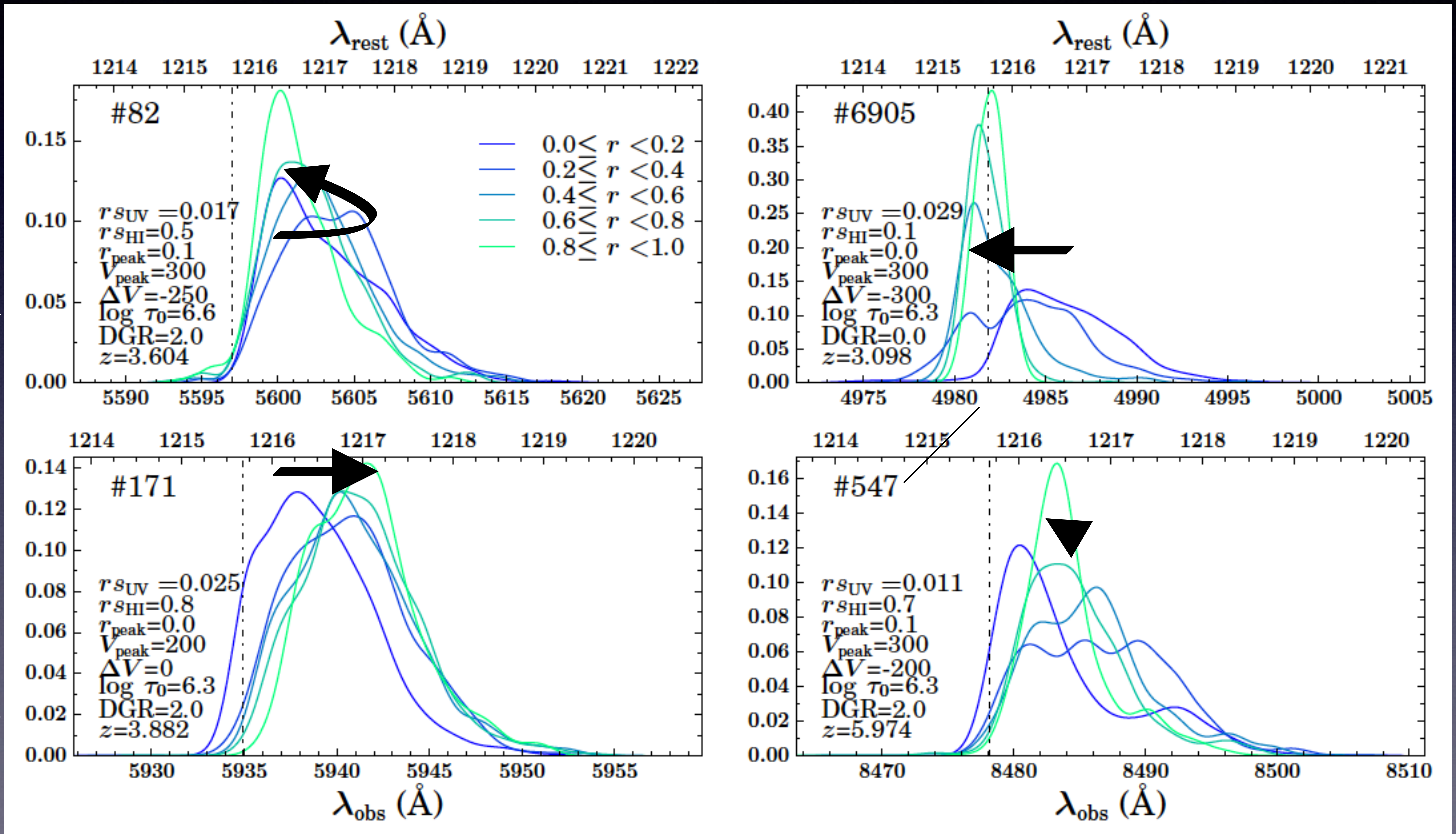
DGR

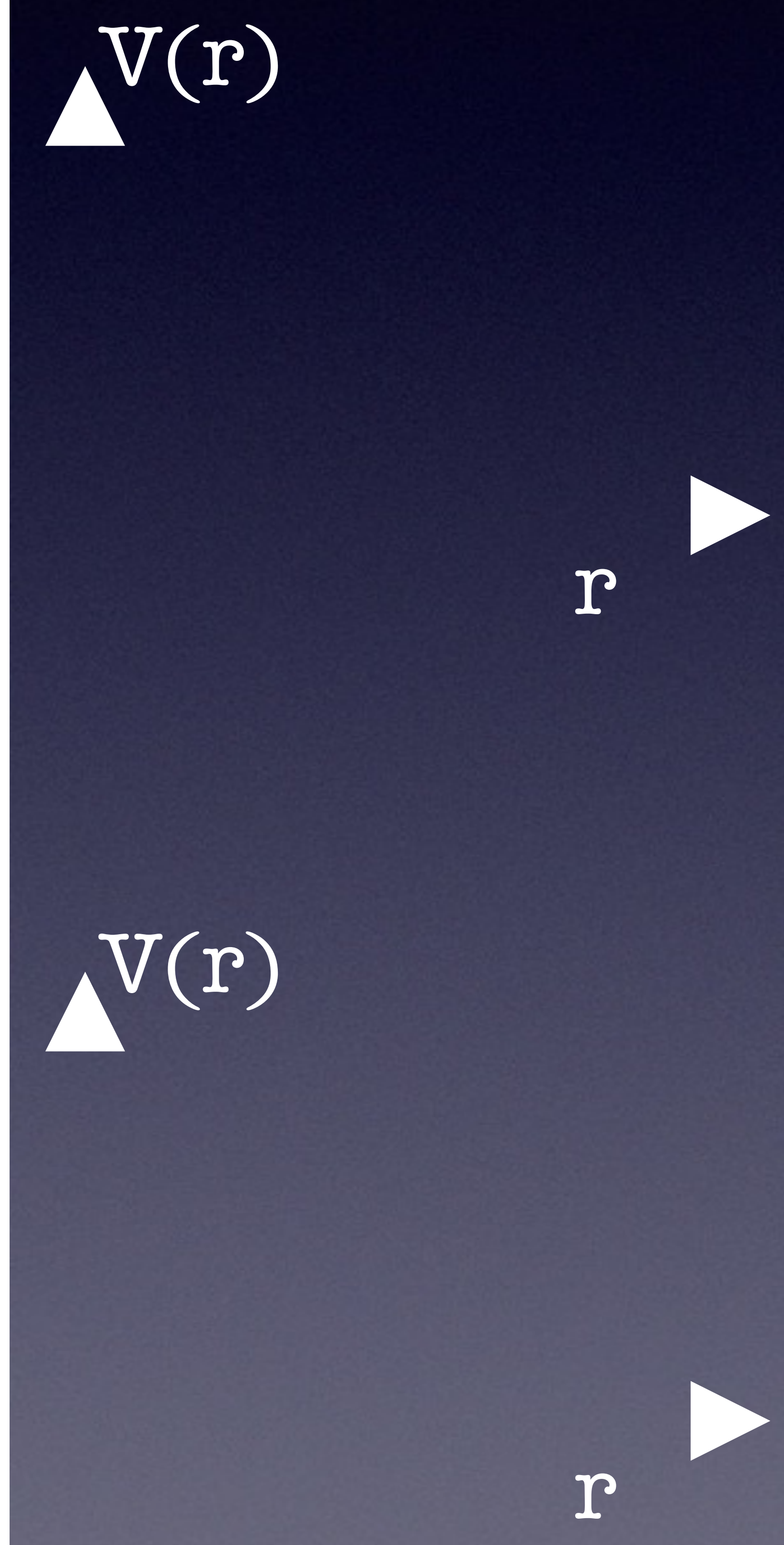


rs_{HI} r_{peak} V_{peak} ΔV $\log \tau_0$

Spatially-resolved Spectra







Summary

- This study is the *first* attempt to model the observed LyA spectrum and surface brightness profile *simultaneously* with *an expanding halo model*.
- Best-fit results indicate that HI medium has a much more extended distribution than SF regions and accelerating-and-then-decelerating motion toward the edge.
- We could understand better the kinematics of ISM/CGM with spatially-resolved spectra.
- We will extend this study to understand various LyA properties in early universe.