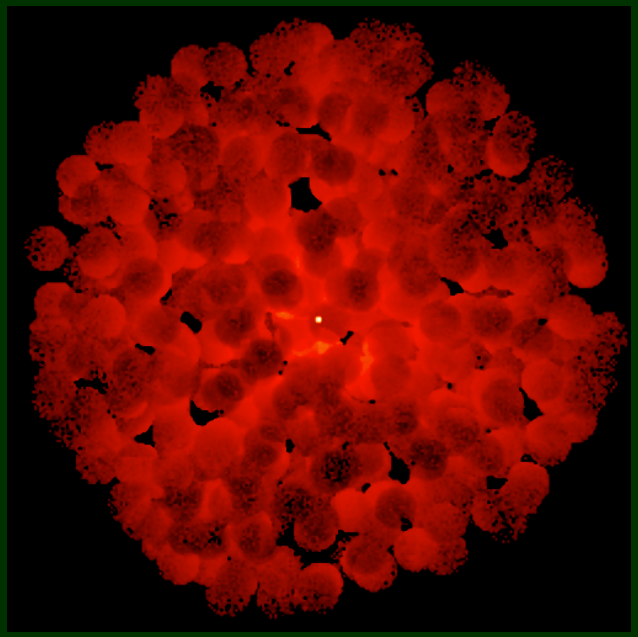
Lighting up the light-shedding of illuminated enlightenment of bright light

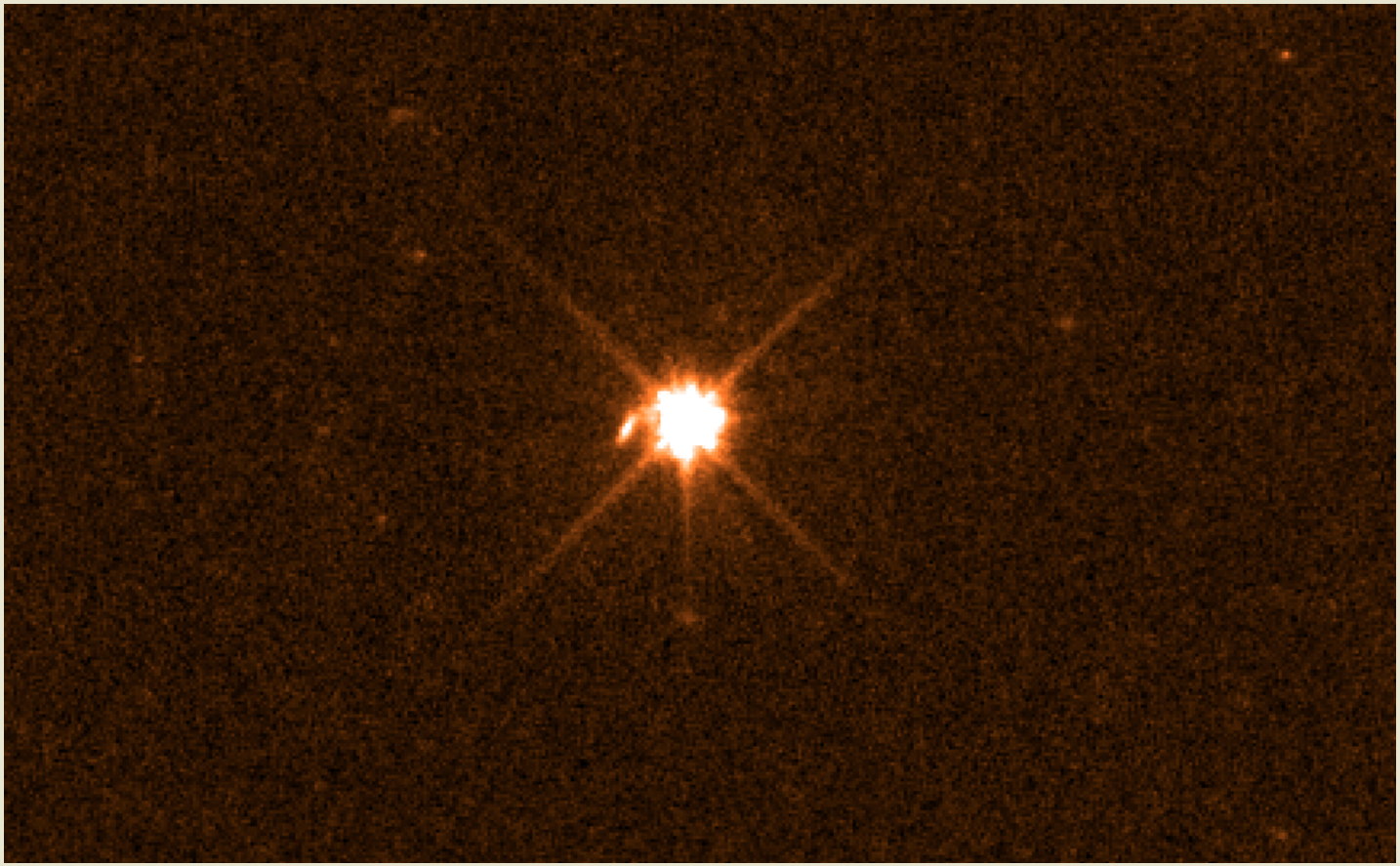
– or –

Modeling Lya spectra



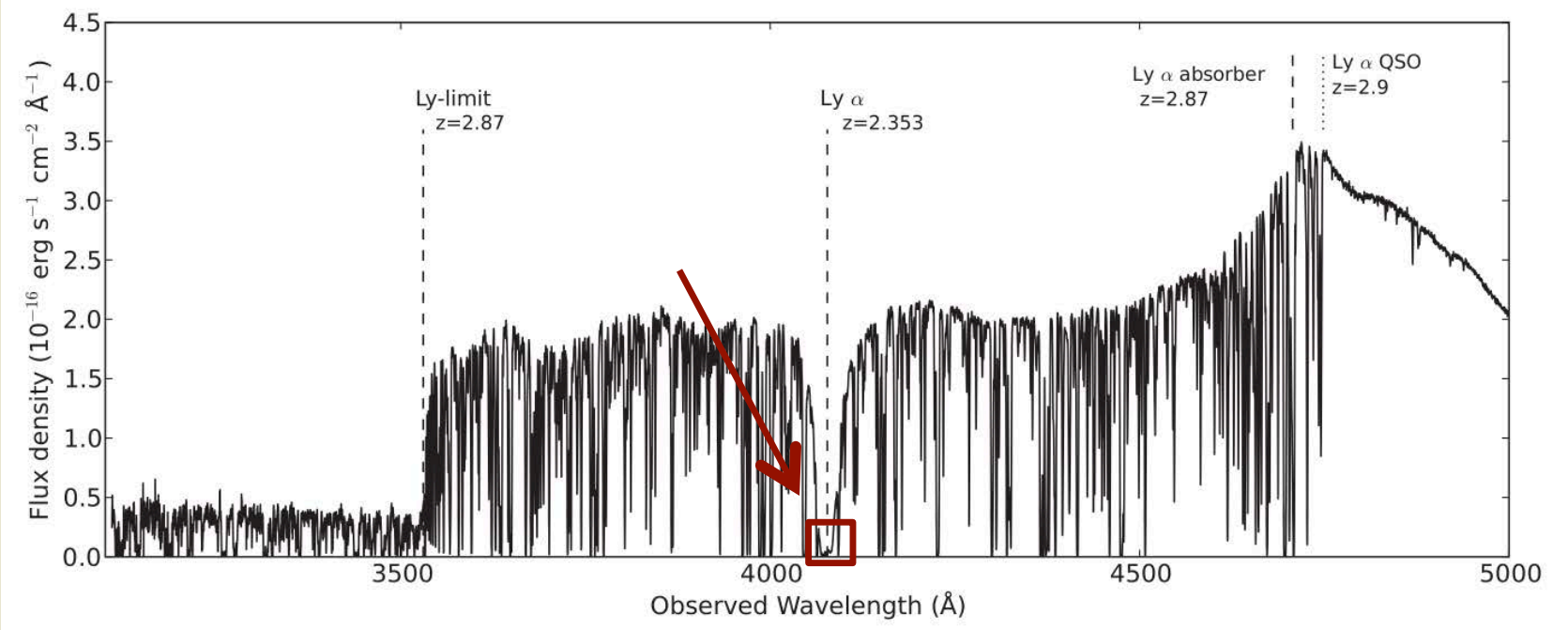
Peter Laursen,
with Jens-Kristian Krogager
& Johan Fynbo

QSO2222-0946



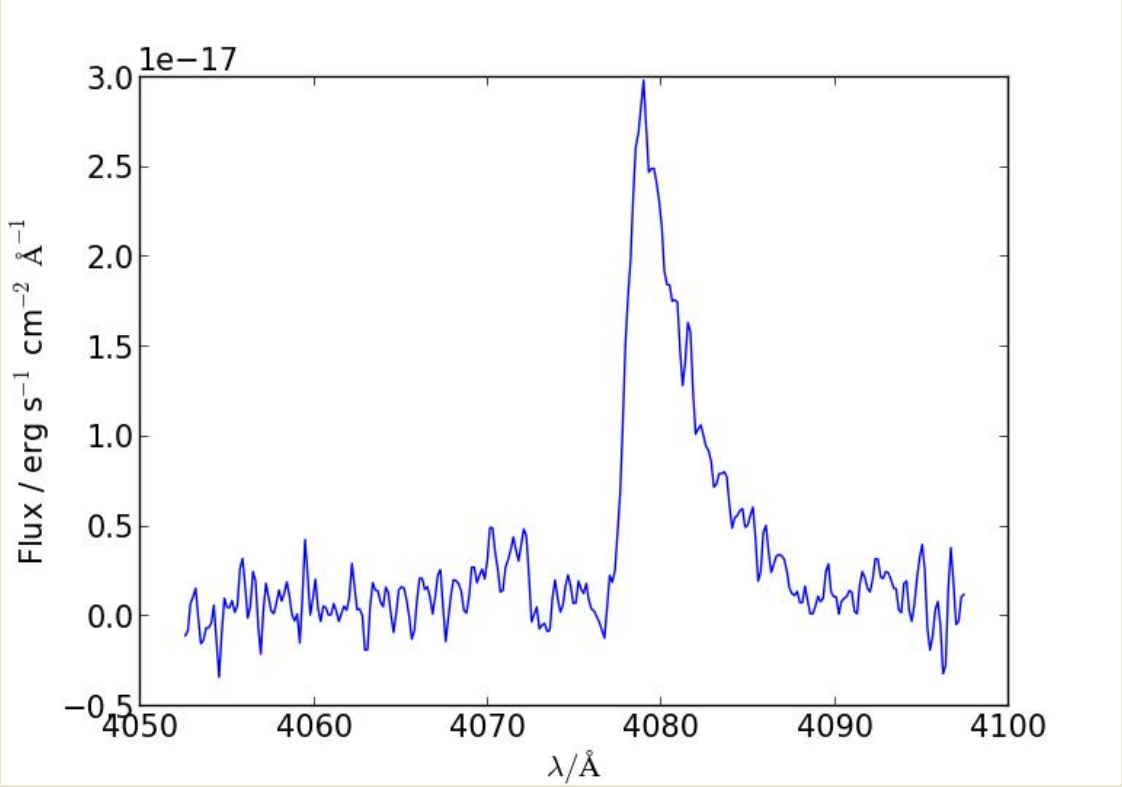
HST/UVIS with the F606W filter

QSO2222-0946



VLT/X-Shooter (UVB arm)

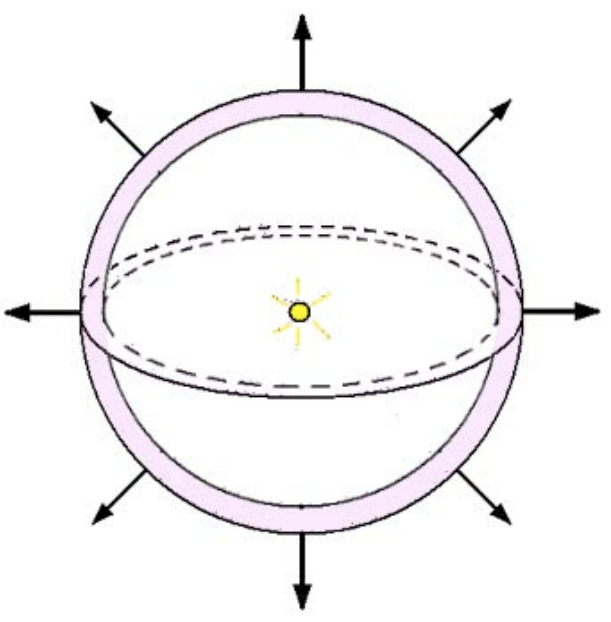
QSO2222-0946



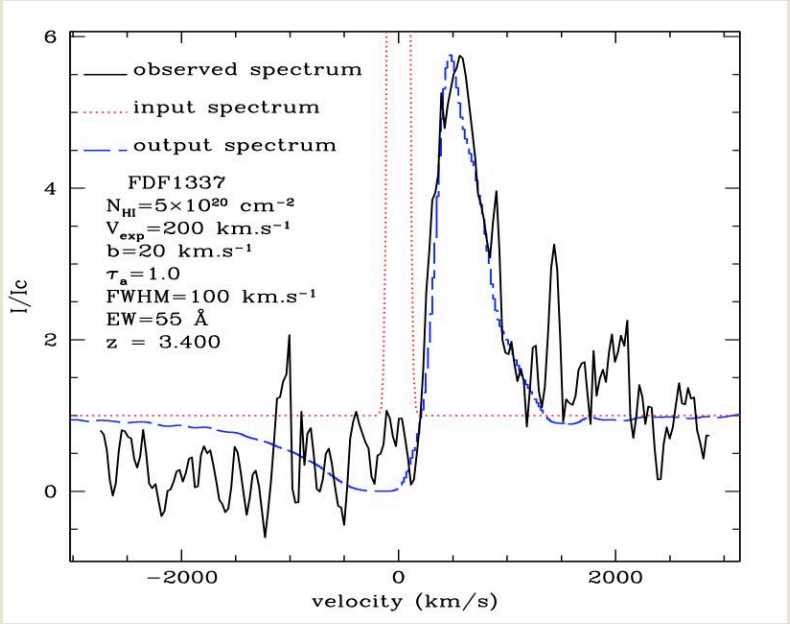
VLT/X-Shooter (UVB arm)

Modeling Lyα lines

...has been done before

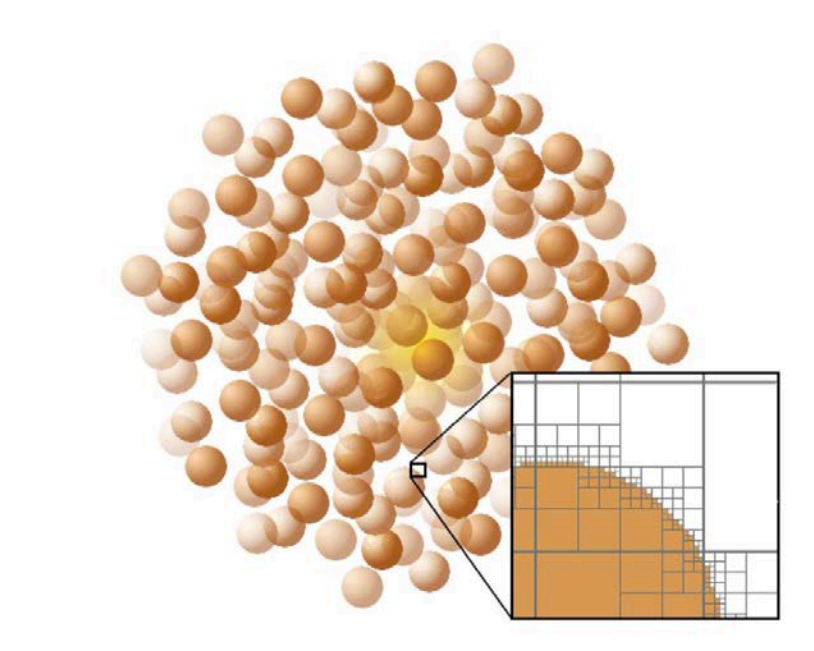


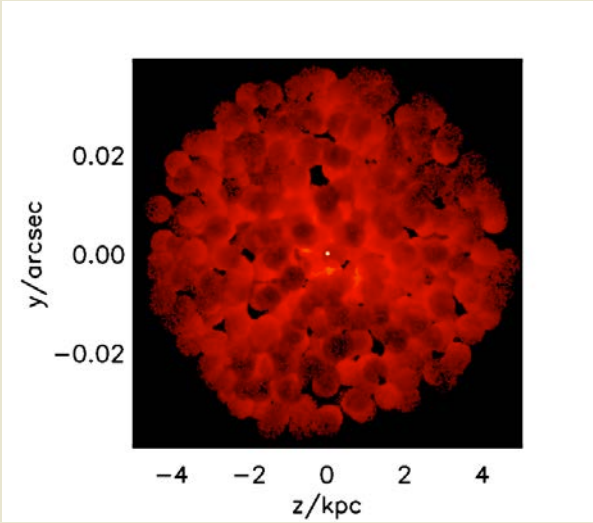
Verhamme et al. (2008) with MCLya

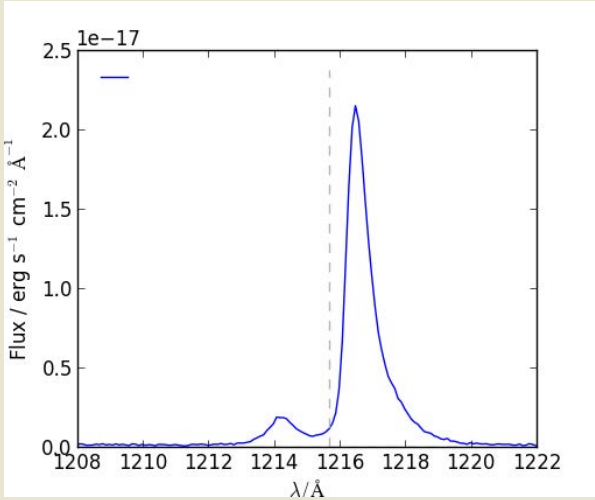


The model

MoCaLaTA

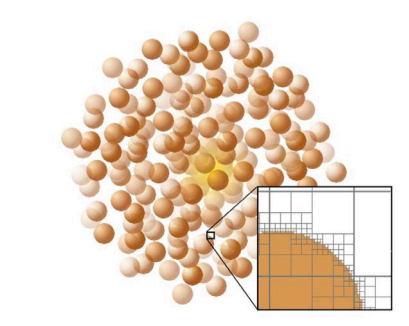






Input parameters

MoCaLaTA



Geometry:

- Radius $r_{\rm gal}$
- Number of clouds $N_{\rm cl}$
- Cloud size distribution $r_{\rm cl,min}$; $r_{\rm cl,max}$; β

State of the clouds and the intercloud medium:

- Neutral hydrogen density $n_{\rm HI,cl}$; $n_{\rm HI,ICM}$
- Temperature $T_{\rm HI,cl}$; $T_{\rm HI,ICM}$
- Dust density $\Leftarrow$ metallicity $Z_{\rm HI,cl}$; $Z_{\rm HI,ICM}$

Kinematics:

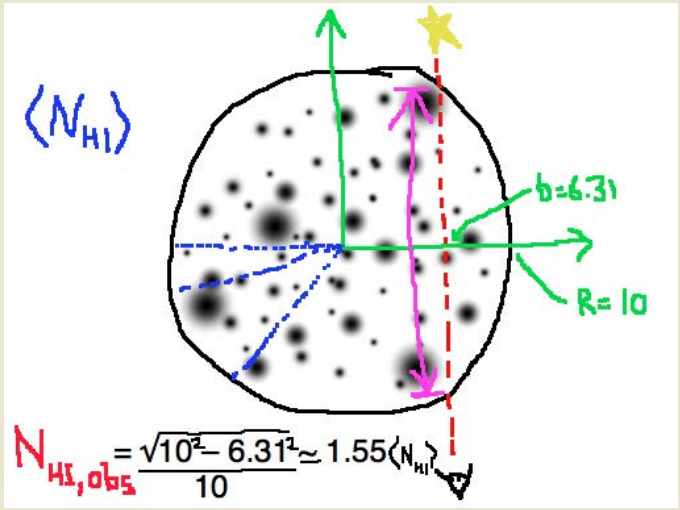
- Cloud velocity dispersion $\sigma_{V,\rm cl}$
- Outflow velocity $V_{\rm out}$

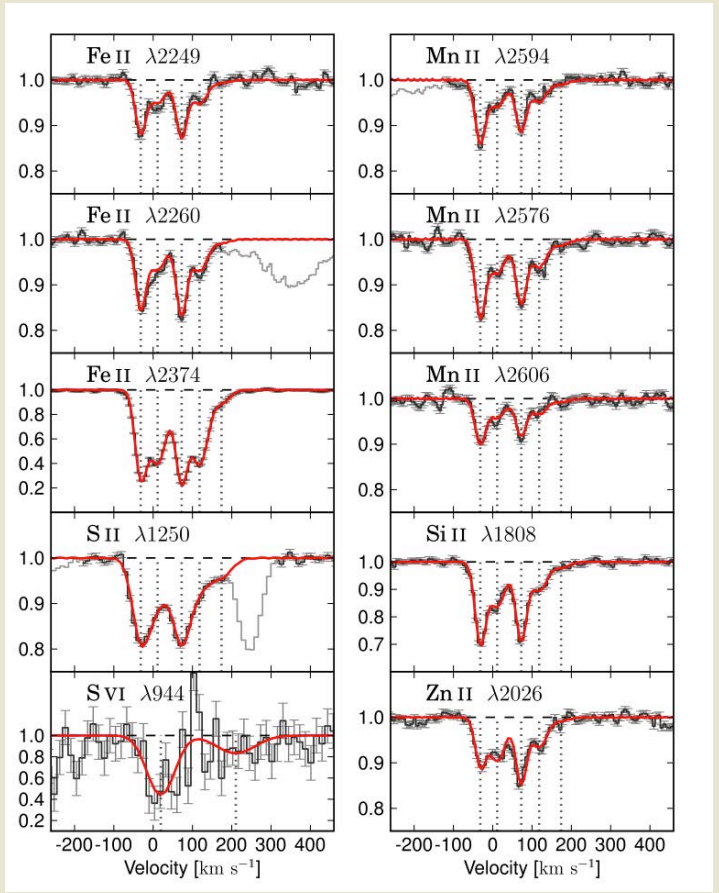
Emission:

- Intrinsic line width $\sigma_{\rm line}$
- Emission scale length $H_{\rm em}$
- Emission site/cloud correlation $P_{\rm cl}$
- Systemic redshift z

Input parameters

r_{gal}	10 kpc	Kim+ 03 (LMC)
N_{cl}	~10^5	Dickey & Garwood 89;
$r_{cl,min}$; $r_{cl,max}$; β	10–100 pc; –1.6	Williams & McKee 97
$n_{HI,cl}$; $n_{HI,ICM}$		
$T_{HI,cl}$; $T_{HI,ICM}$		
$Z_{HI,cl}$; $Z_{HI,ICM}$		
$\sigma_{V,cl}$		
V_{out}		
σ_{line}		
H_{em}		
P_{cl}		
z		





Input parameters

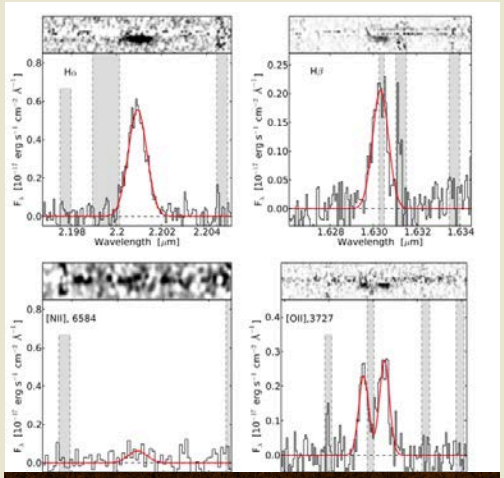
$r_{\rm gal}$	10 kpc	
$N_{\rm cl}$	~10^5	
$r_{\rm cl,min}$; $r_{\rm cl,max}$; β	10–100 pc; –1.6	
$n_{\rm HI,cl}$; $n_{\rm HI,ICM}$	0.3 cm^{-3}; 10^{-10}–10^{-5} cm^{-3}	0.2–0.5 cm^{-3} from e.g. Carilli+ 98; Ferrière 01; Gloeckler & Geiss 04 (MW)
$T_{\rm HI,cl}$; $T_{\rm HI,ICM}$	10^4 K; 10^6 K	$n_{\rm tot}$ = 10^{-3}–10^{-2} cm^{-3} (Dopita & Sutherland 03; Ferrière 01), $x_{\rm HI,ICM}$ ~ 10^{-8}–10^{-5} (House 64; Sutherland & Dopita 93), plus residual diffuse HI clouds.
$Z_{\rm HI,cl}$; $Z_{\rm HI,ICM}$	0.31 $Z_\odot$	e.g. Brinks+ 00; Tüllmann+ 06,08
		From Zn, Si, and Fe abs. lines, as well as from [OII]/[OIII] and [NII]/Hα (R_{23} and N2 methods)
$\sigma_{V,\rm cl}$		
$V_{\rm out}$		
$\sigma_{\rm line}$		
$H_{\rm em}$		
$P_{\rm cl}$		
z		

Input parameters

$r_{\rm gal}$	10 kpc	
$N_{\rm cl}$	~10^5	
$r_{\rm cl,min}$; $r_{\rm cl,max}$; β	10–100 pc; –1.6	
$n_{\rm HI,cl}$; $n_{\rm HI,ICM}$	0.3 cm^{-3}; 10^{-10}–10^{-5} cm^{-3}	
$T_{\rm HI,cl}$; $T_{\rm HI,ICM}$	10^4 K; 10^6 K	
$Z_{\rm HI,cl}$; $Z_{\rm HI,ICM}$	0.31 $Z_\odot$	
$\sigma_{V,\rm cl}$	115±18 km s^{-1}	From abs. line widths
$V_{\rm out}$	100–200 km s^{-1}	
$\sigma_{\rm line}$		
$H_{\rm em}$		
$P_{\rm cl}$		
z		

Input parameters

$r_{\rm gal}$	10 kpc
$N_{\rm cl}$	~10^5
$r_{\rm cl,min}$; $r_{\rm cl,max}$; β	10–100 pc; –1.6
$n_{\rm HI,cl}$; $n_{\rm HI,ICM}$	0.3 cm^{-3}; 10^{-10}–10^{-5} cm^{-3}
$T_{\rm HI,cl}$; $T_{\rm HI,ICM}$	10^4 K; 10^6 K
$Z_{\rm HI,cl}$; $Z_{\rm HI,ICM}$	0.31 $Z_\odot$
$\sigma_{V,\rm cl}$	115±18 km s^{-1}
$V_{\rm out}$	100–200 km s^{-1}
$\sigma_{\rm line}$	130 km s^{-1}
$H_{\rm em}$	2.1 kpc
$P_{\rm cl}$	0.2–0.5
z	2.35



From [OII], [OIII], Hα, and Hβ

From *HST* imaging ($r_{\rm eff}$ = 1.09 kpc)

From [OII], [OIII], Hα, and Hβ

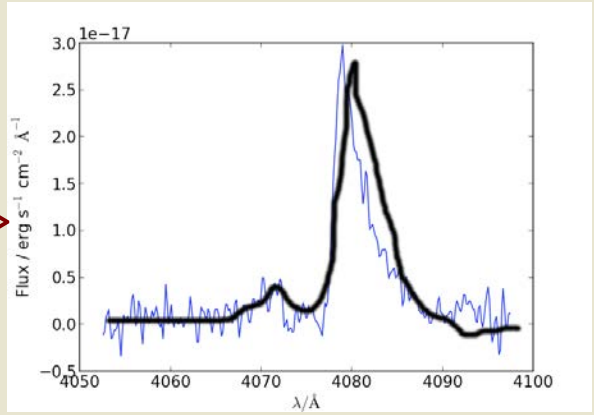
Input parameters

$r_{\rm gal}$	10 kpc	Set by observations
$N_{\rm cl}$	~10^5	Standard values
$r_{\rm cl,min}$; $r_{\rm cl,max}$; β	10–100 pc; –1.6	Fitted for
$n_{\rm HI,cl}$; $n_{\rm HI,ICM}$	0.3 cm^{-3}; 10^{-10}–10^{-5} cm^{-3}	
$T_{\rm HI,cl}$; $T_{\rm HI,ICM}$	10^4 K; 10^6 K	
$Z_{\rm HI,cl}$; $Z_{\rm HI,ICM}$	0.31 $Z_\odot$	
$\sigma_{V,\rm cl}$	115±18 km s^{-1}	
$V_{\rm out}$	100–200 km s^{-1}	
$\sigma_{\rm line}$	130 km s^{-1}	
$H_{\rm em}$	2.1 kpc	
$P_{\rm cl}$	n/a	
z	2.35	

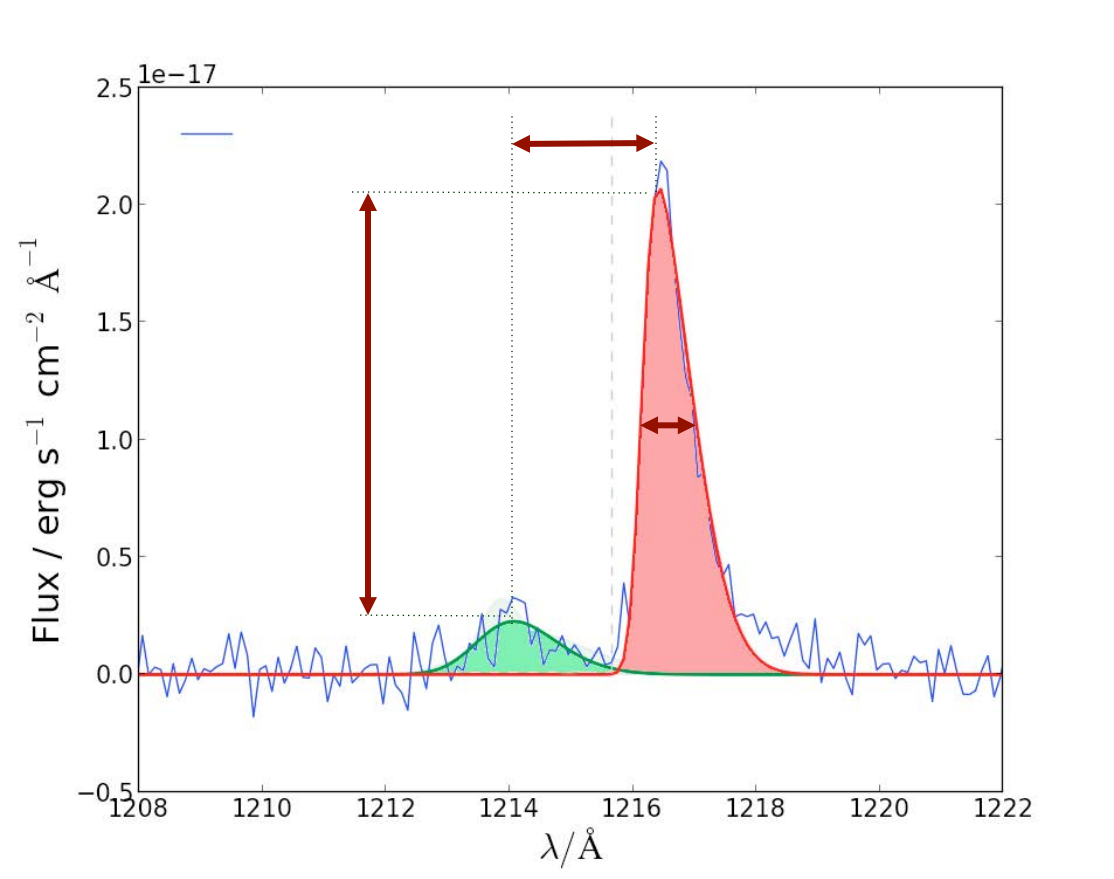
Finding the best fit

Model #	N_cl	n_HI_cl	Z	n_HI_ICM	P_cl	V_out	SFR	Features	Notes	Rating
18	3e5	.3	.31	1e-5	FF	175	8	Peaks are both 2/3 Å too separate		
19	-	-	-	1e-6	-	-	10.3	B better, Rnear almost fine, Rfar side too broad		
20	-	-	.51	-	-	-	10.8	Except for SFR, id to 18		
21	-	-	.31	-	.5	-	10.5	-		
22	-	-	.51	-	-	-	12	Slightly broader Rcent		
23	-	.2	.31	1e-5	FF	-	6.6	Slightly narrower R/B far sides, comp. to 18	id18 x n_HI_cl	
24	-	-	-	1e-6	-	-	8	Rnear is closer, but Rfar is the same		
25	2e5	.3	-	1e-5	-	-	5.8	Narrower R. Comp to 18, [BR]far is narrower (better)	id18 x N_cl	
26	-	-	-	1e-6	-	-	7.5	Rnear almost fine. Comp to 19, [BR]far is narrower (better)	id19 x N_cl	
27	1e5	-	-	1e-5	-	-	4	Comp. to 25, [BR]far is narrower		
28	-	-	-	1e-6	-	-	4.9	Comp. to 26, [BR]far is narrower (almost perfect)		
29	-	-	-	3e-7	-	-	5.2	Perfect, except for B peak which must be higher		10
30	-	-	1	1e-6	-	-	5.2	id28 x slightly lower Bcent	id28 x Z	
31	-	-	-	3e-7	-	-	5.2	id29 x SFR	id29 x Z	
32	-	-	1	-	-	200	5.5	32-34 are id x for B	id29 x V_out	
33	-	-	-	-	-	150	5.2			
34	-	-	-	-	-	125	5.1	This is the best of the three. [BR] needs to be a little broader	id29 x V_out	10
35	-	-	-	5.6e-7	-	-				
36	-	-	-	1e-6	-	-				
37										

1. Run trial models to get a rough fit $\Rightarrow N_{cl} \sim 10^5$; $V_{out} \sim 150$ km s^{-1}
2. Run grid with $N_{cl} \in [10^{4.5},10^{5.5}]$ and $V_{out} \in [100,200]$ km s^{-1}



Finding the best fit



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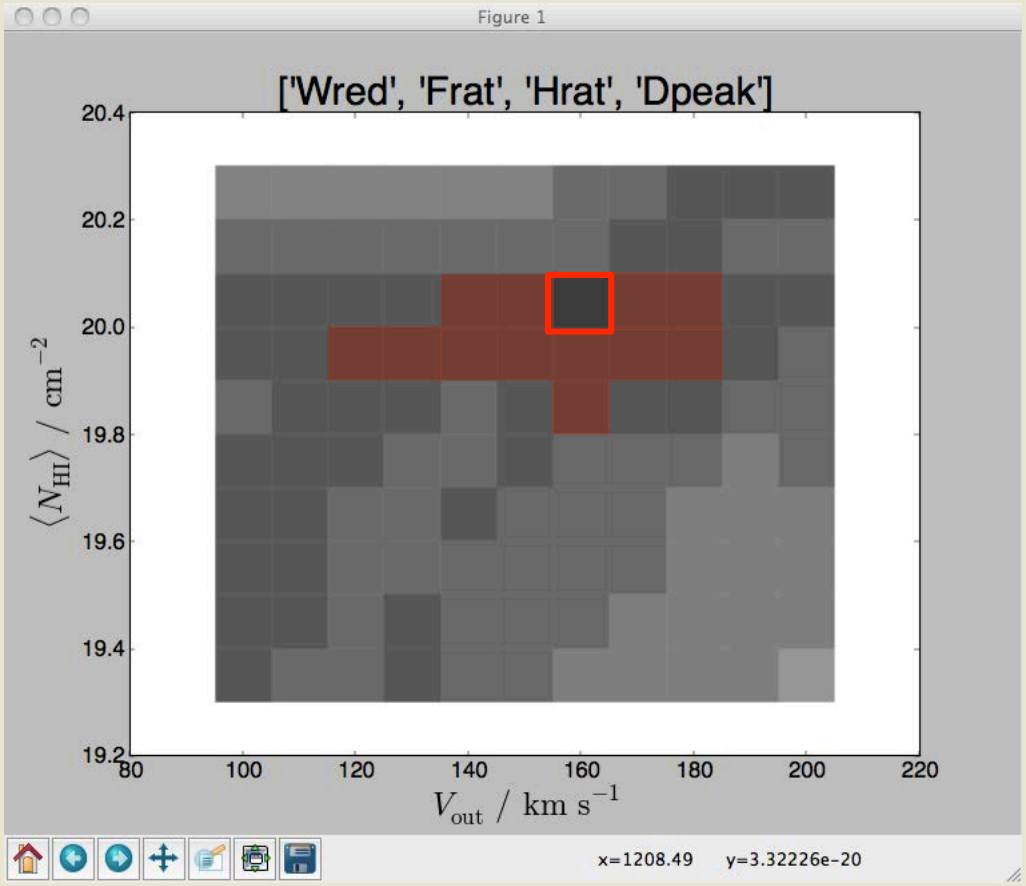
3. Fit skewed Gaußians
   $f(x) = 2\phi(x)\Phi(\alpha x)$.
   $\phi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \quad \Phi(x) = \int_{-\infty}^{x} \phi(t)\, dt$
4. Measure
   a) Red peak FWHM
   b) Peak separation
   c) Peak height ratio
   d) Peak flux ratio

Finding the best fit



1. Run trial models to get a rough fit
   $\Rightarrow N_{\rm cl} \sim 10^5$; $V_{\rm out} \sim 150$ km s^{-1}
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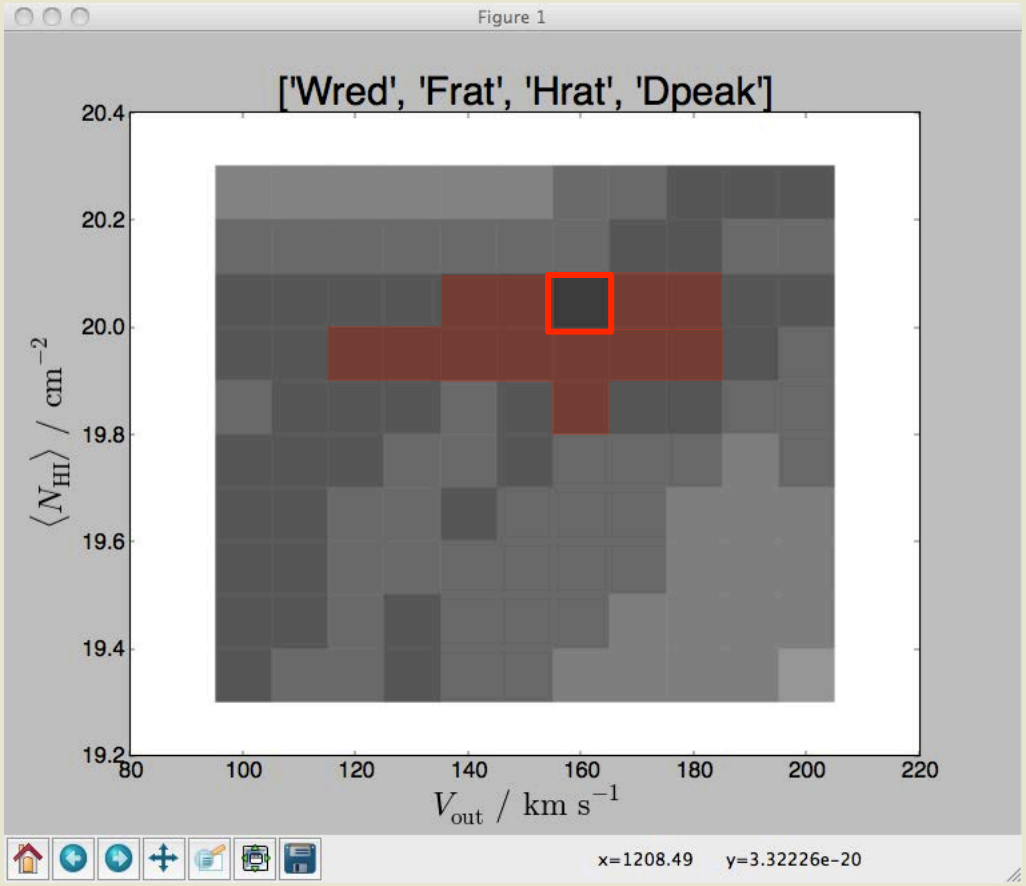
4. Measure
   a) Red peak FWHM
   b) Peak separation
   c) Peak height ratio
   d) Peak flux ratio
5. Calculate number of std. dev.s between synthetic and observed spectra
6. Identify best fitting model and those for which all four fitting parameters fall within 1σ

Results



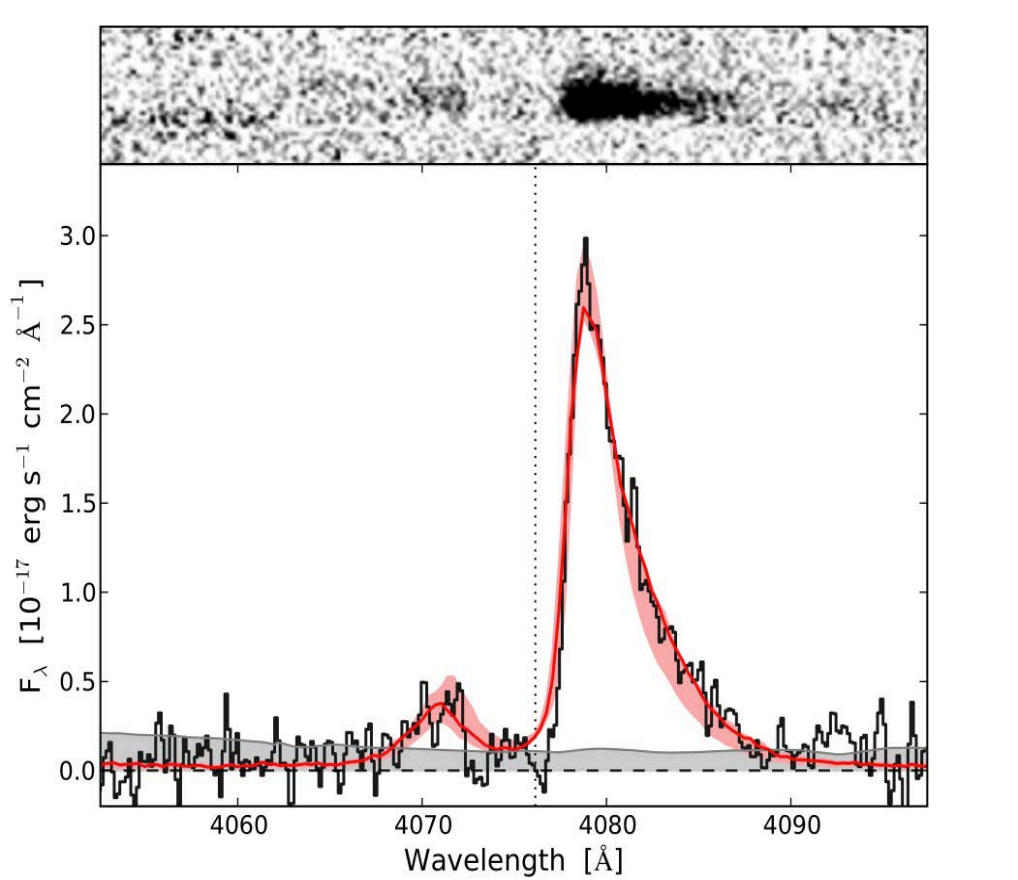
Best-fitting models give:

$$V_{\rm out} = 160^{+20}_{-40}\ {\rm km\ s^{-1}}$$

$$\log(N_{\rm HI}/{\rm cm^{-2}}) = 20.23^{+0.27}_{-1.15}$$

$$N_{\rm cl} = 2 \pm 1$$

Results



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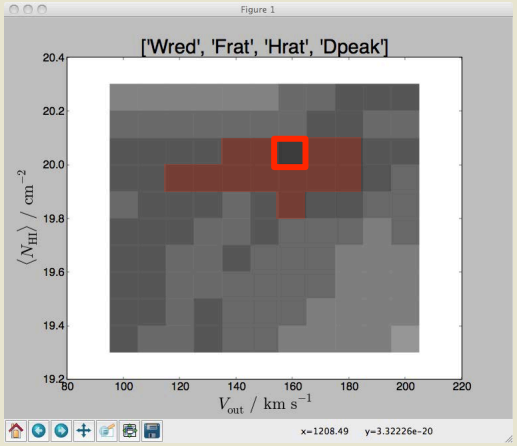

Conclusion

- Fitting Lya lines requires information about several parameters. A simple spectrum isn't really enough.