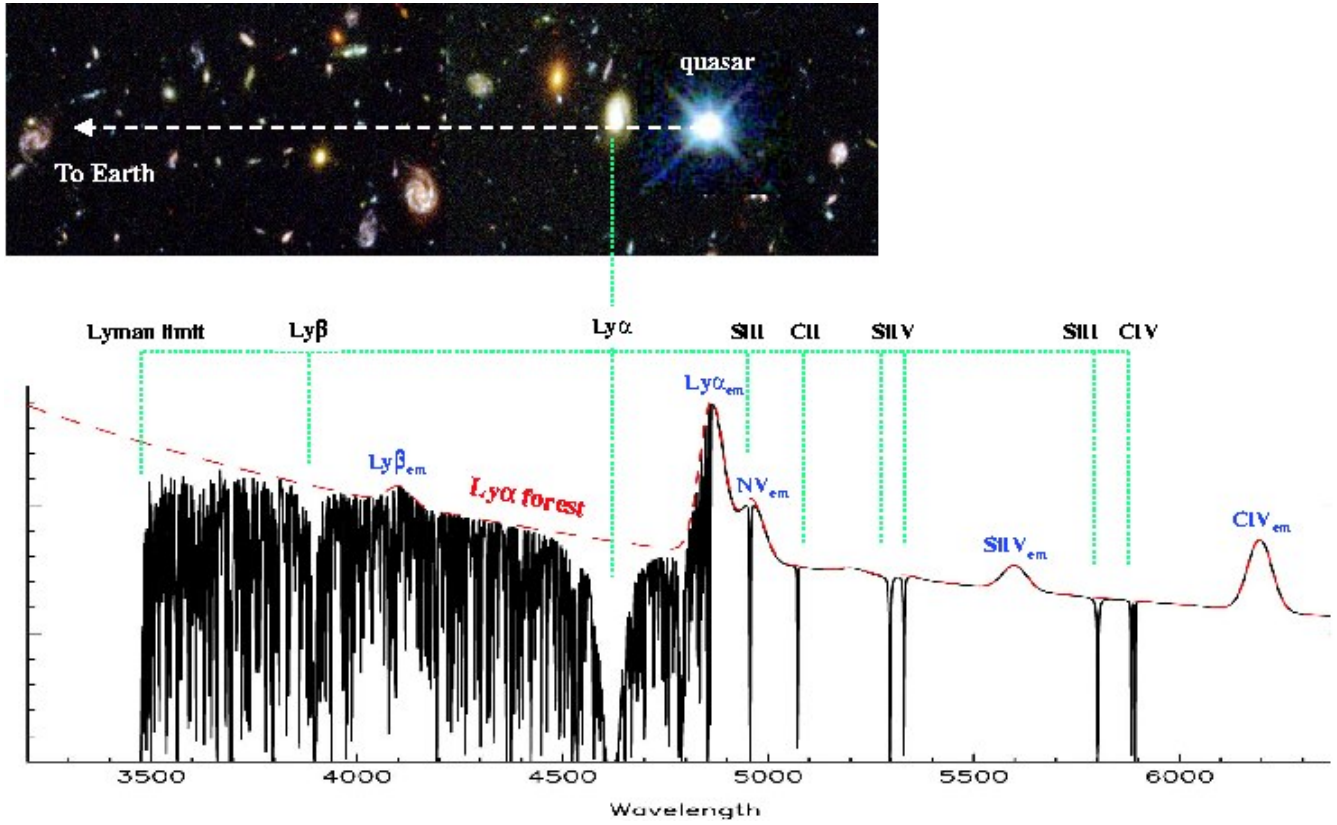
Unravelling the element abundances and ionization structure in intervening QSO absorbers.

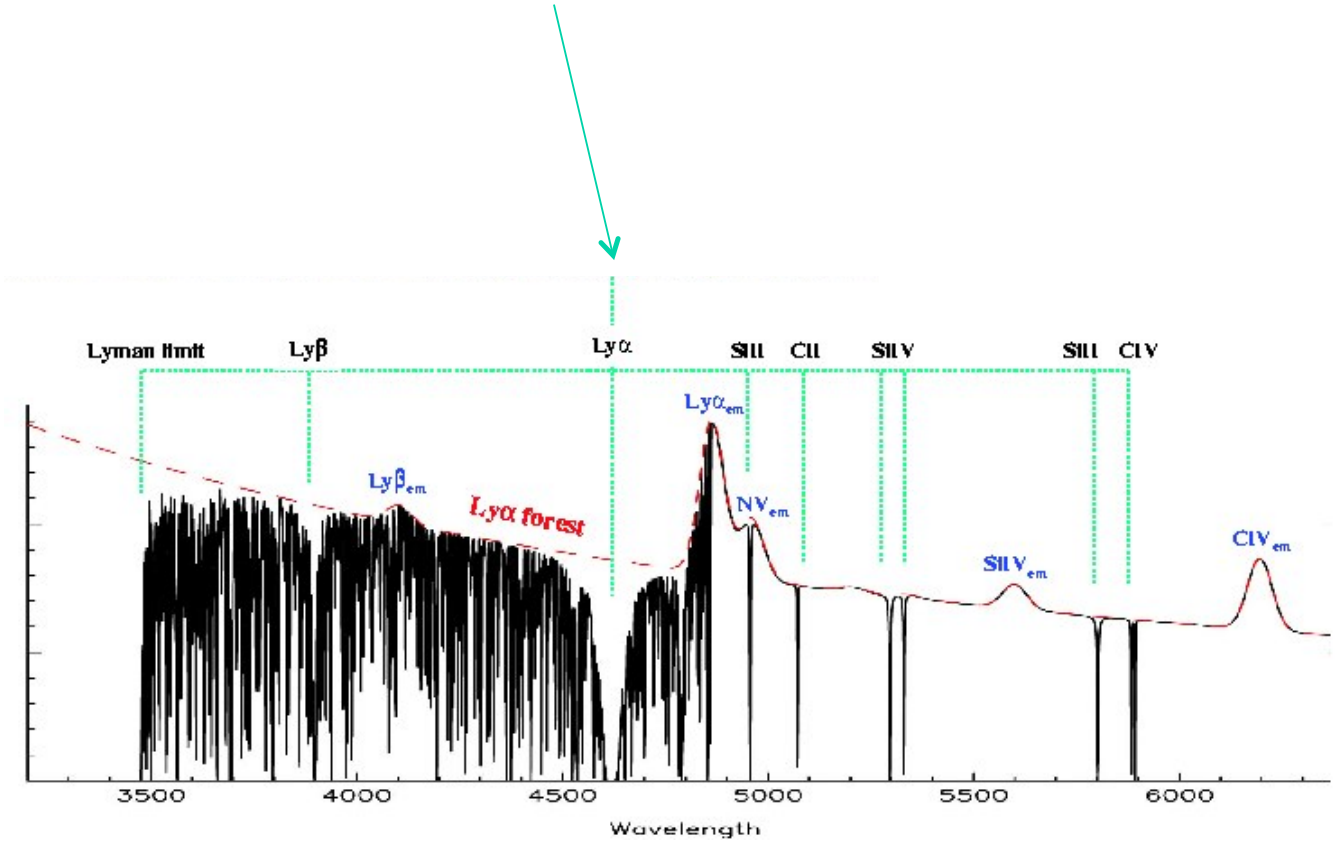
Bob Carswell (IoA, Cambridge, UK)

Quasar absorption from intervening galaxies, and intergalactic medium



from John Webb

Aim here is to investigate heavy element abundances relative to hydrogen (and each other) in the interstellar medium in high redshift galaxies using absorption lines in the spectra of background QSOs, so we shall concentrate on systems roughly like this.



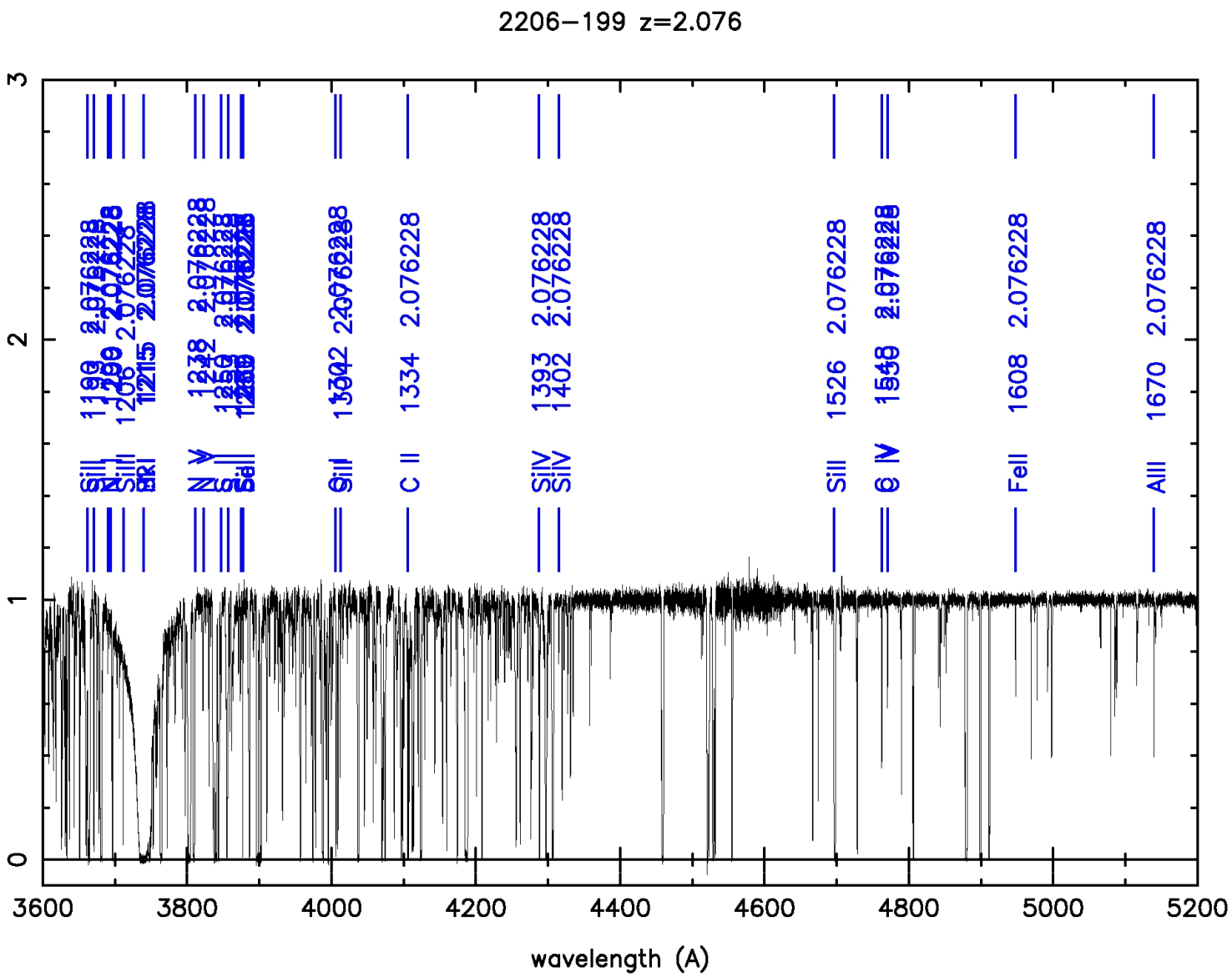
from John Webb

Aim here is to investigate heavy element abundances
relative to hydrogen (and each other) in the interstellar medium in high redshift galaxies using absorption lines in the spectra of background QSOs, so we shall concentrate on systems roughly like this.

Outline:

1. Simple system where no ionization corrections are needed to illustrate the methods
2. Realistic case with velocity structure to get integrated abundances for the whole complex
3. An attempt to divide into plausible components to get the range heavy element abundances
4. Then compare these with the integrated values
5. ..and see if they tell us anything worthwhile.

A real example:



Use the strengths of the lines for each ion to estimate the numbers (cm^{-2}) of each along the sightline at the redshift of interest.

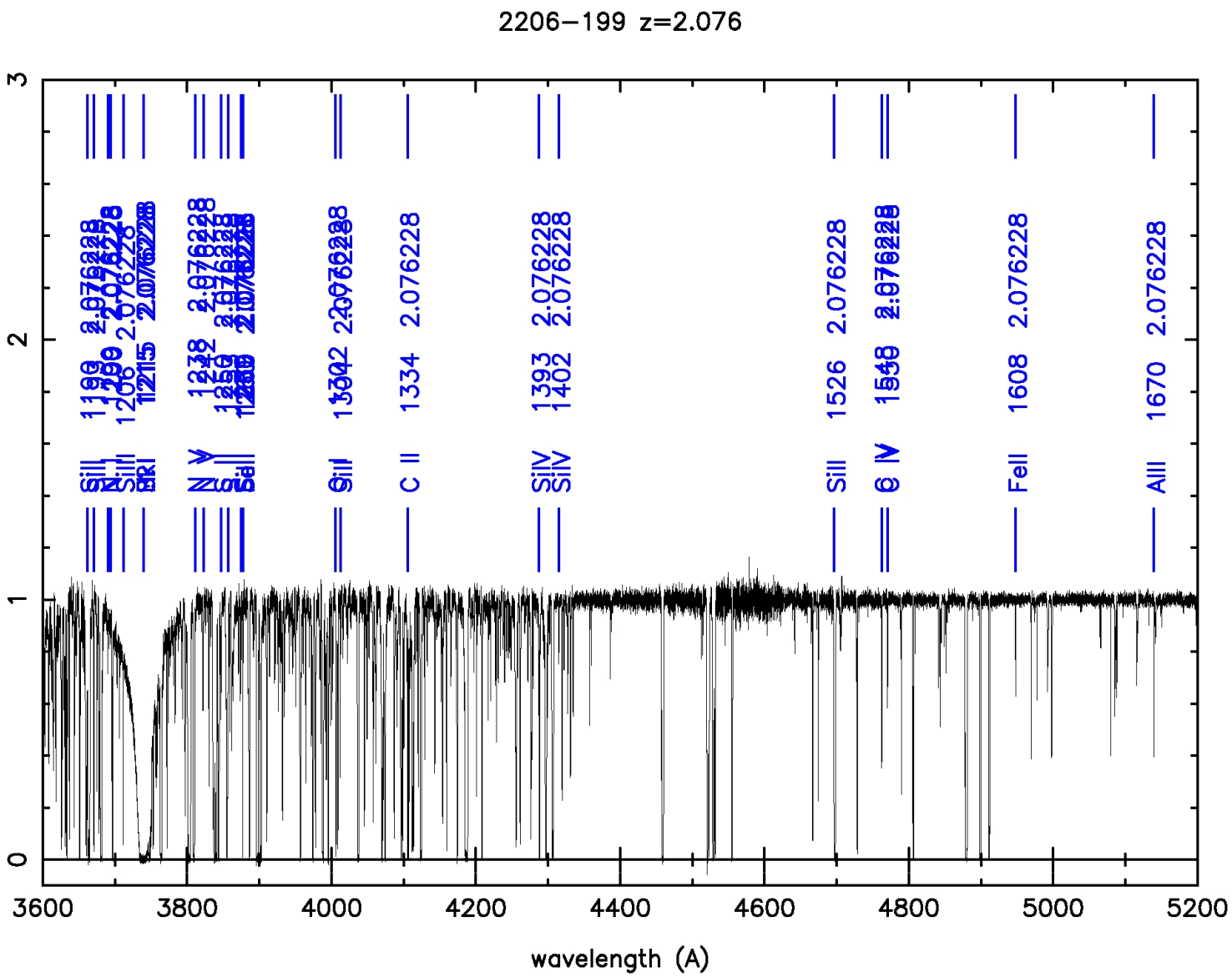
Notation:

H I = H^0

SiII = Si^+

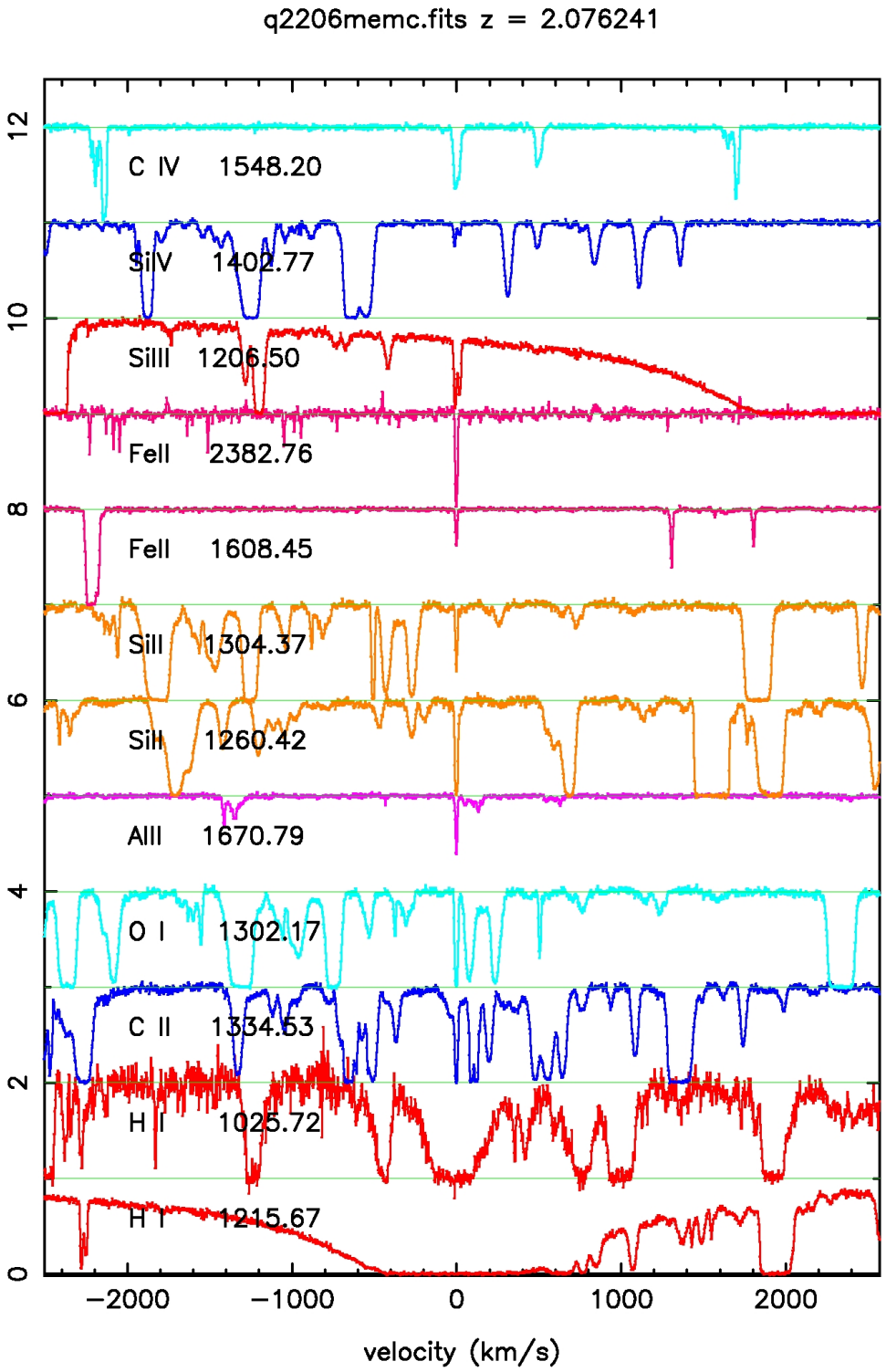
SiIV – Si^{+++}

etc.



View reduced to a common velocity scale relative to the low ionization lines:

Note the dominance of Lyman-α (HI 1215.67), as hydrogen is by far the most abundant element.



Metal lines:

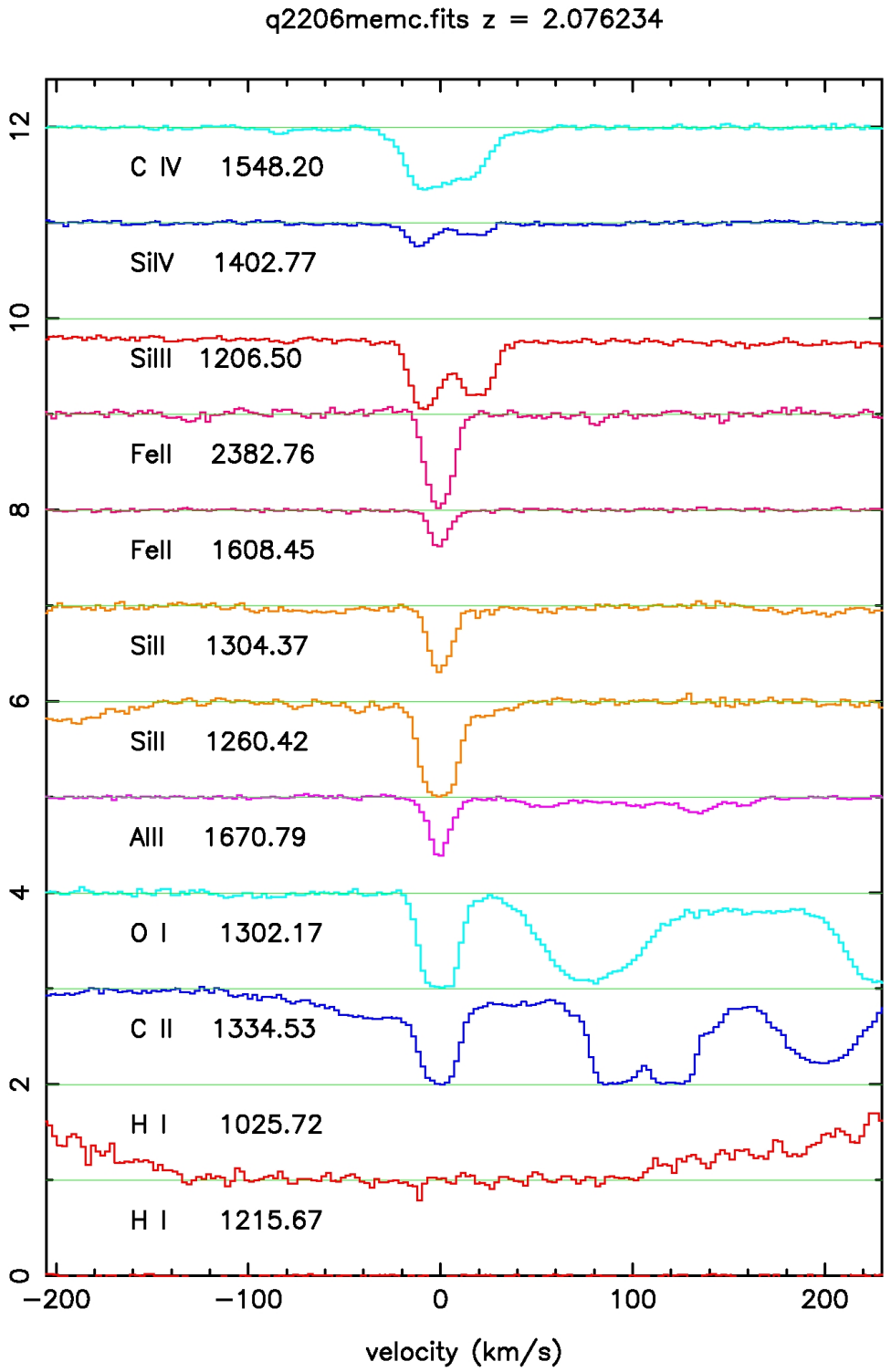
CII, OI, AlII, SiII, FeII all have same structure. Higher ionization (SiIII etc) different.

Reason: CII etc all in regions where hydrogen is neutral. CIV etc are high ionization, hydrogen mostly ionized, so arise somewhere else.

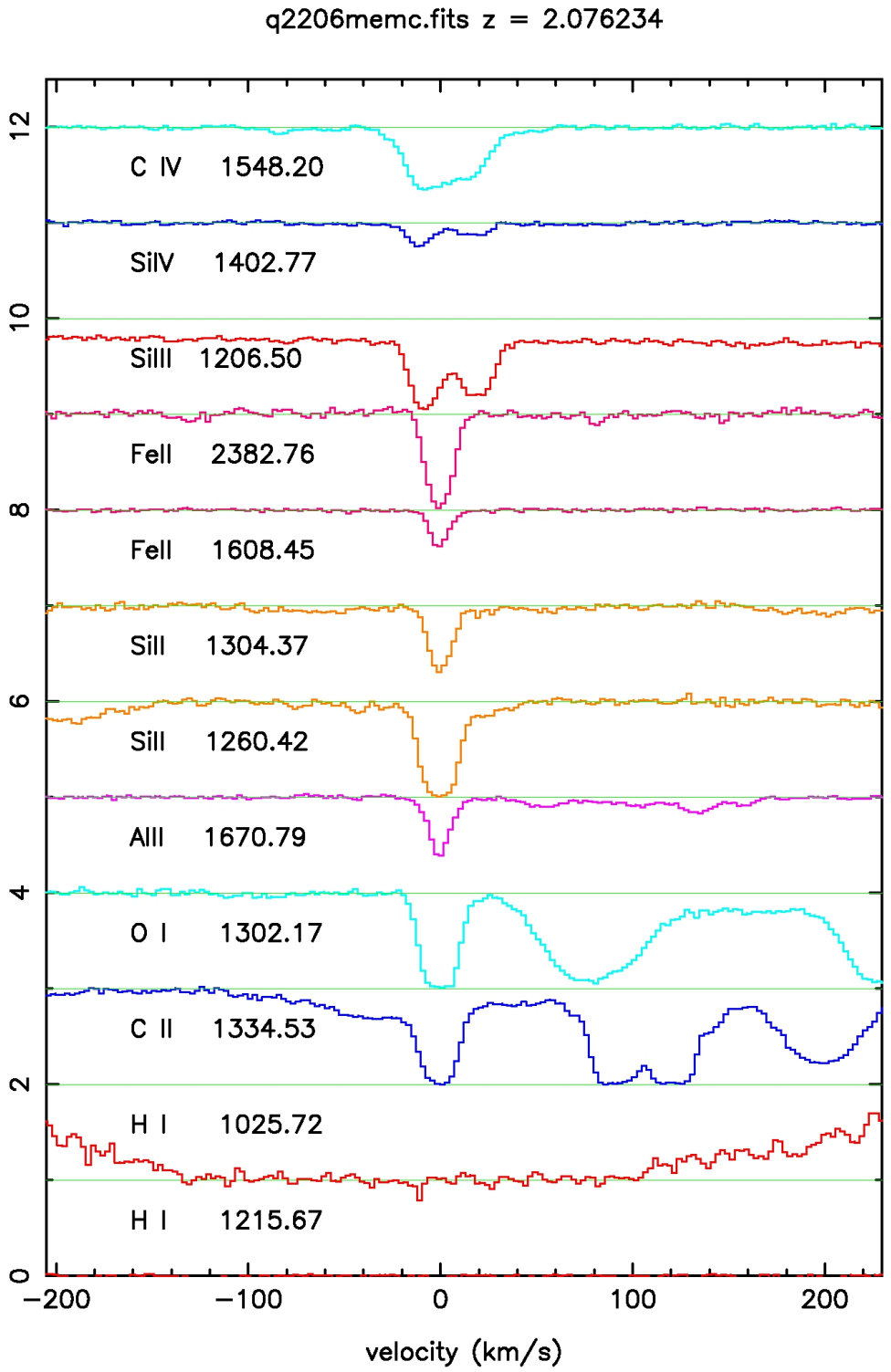
In neutral zone numbers C/H ~ CII/HI, O/H ~ OI/HI, Si/H ~ SiII/HI etc.

Note also eg FeII 1608, 2382 not equally deep. Line strengths depend on 'oscillator strength' *f* for the particular transition. Lab measurements give these.

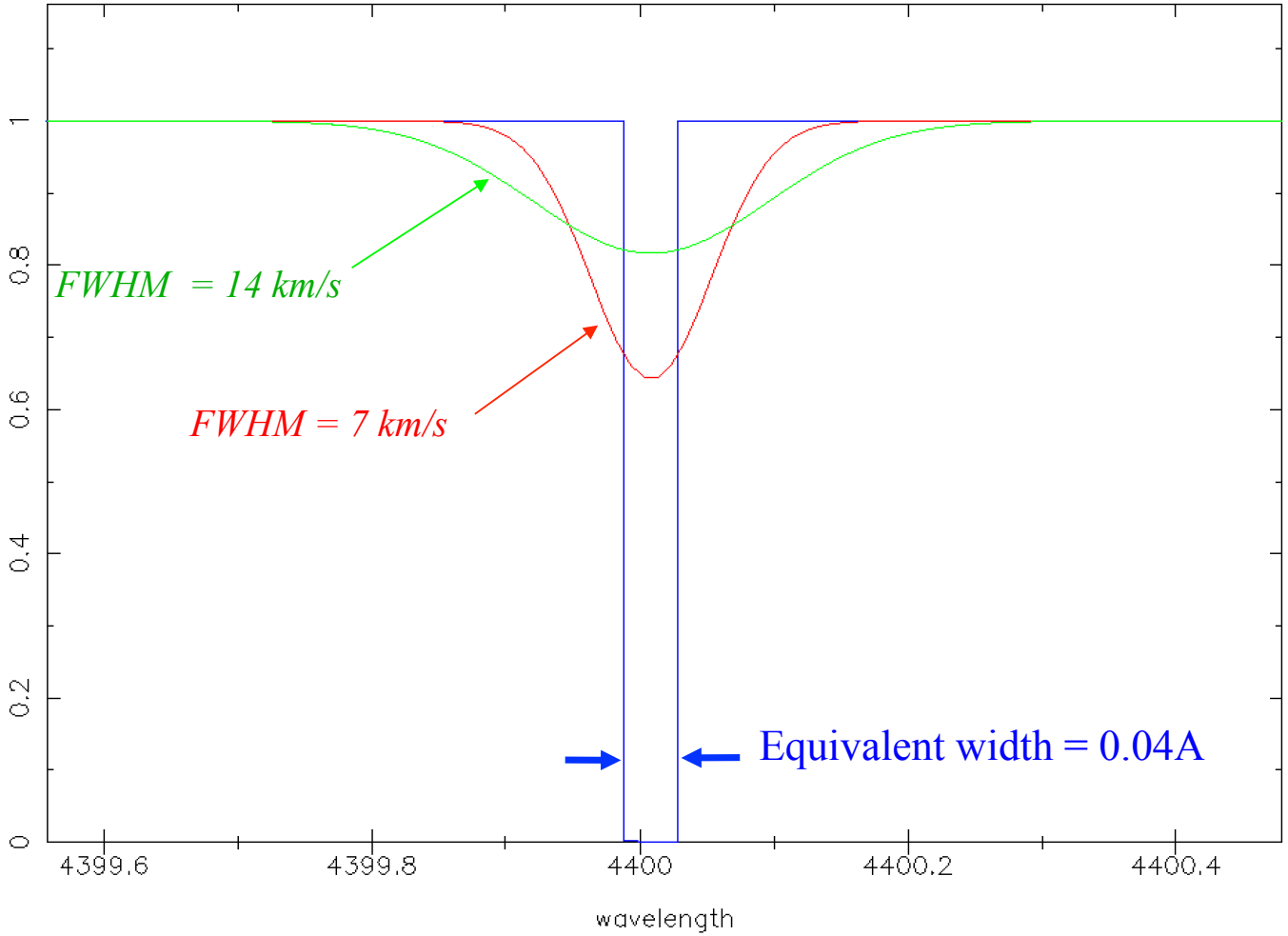
FeII 1608 *f*=0.058
FeII 2382 0.320.



To get ion column densities
(= number of ions cm^{-2})
fit model profiles to all the
available lines for the species
you are interested in.



Area between a given absorption line and unit continuum is independent of the instrument spectral resolution, and is called the equivalent width of the line. It is a common measure of line strength



If you care about the background:

Assume number vs velocity ξ is Gaussian, so

$$n(\xi) \propto \exp(-\xi^2 / b^2)$$

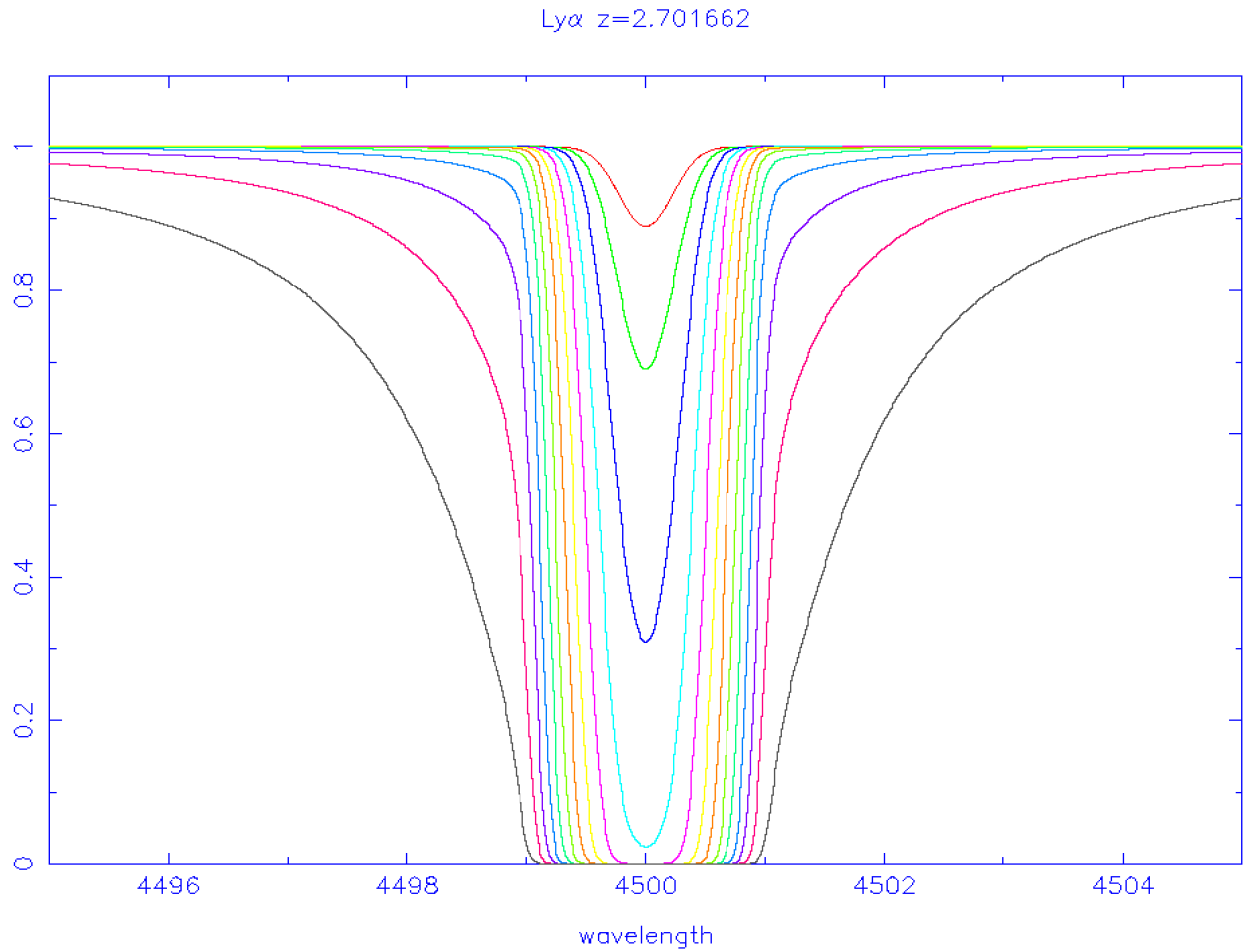
True if thermal, and OK if there are random bulk motions as well.

Then absorption coefficient α_ν at frequency ν is *f* times some function (call it *G*) of *b*, ν and atomic parameters which comes from convolving that Gaussian with the natural line spread function (a Lorentzian). The line profile measured is then exp(-*NfG)* convolved with the instrument profile.

If you are desperately interested the first bit is called the Voigt function. The Wikipedia description is fine, and there are several good approximations to it. I'm just going to show you what it looks like.

Note the use of Doppler parameter $b = \sqrt{2}\,\sigma$ rather than the usual Gaussian σ

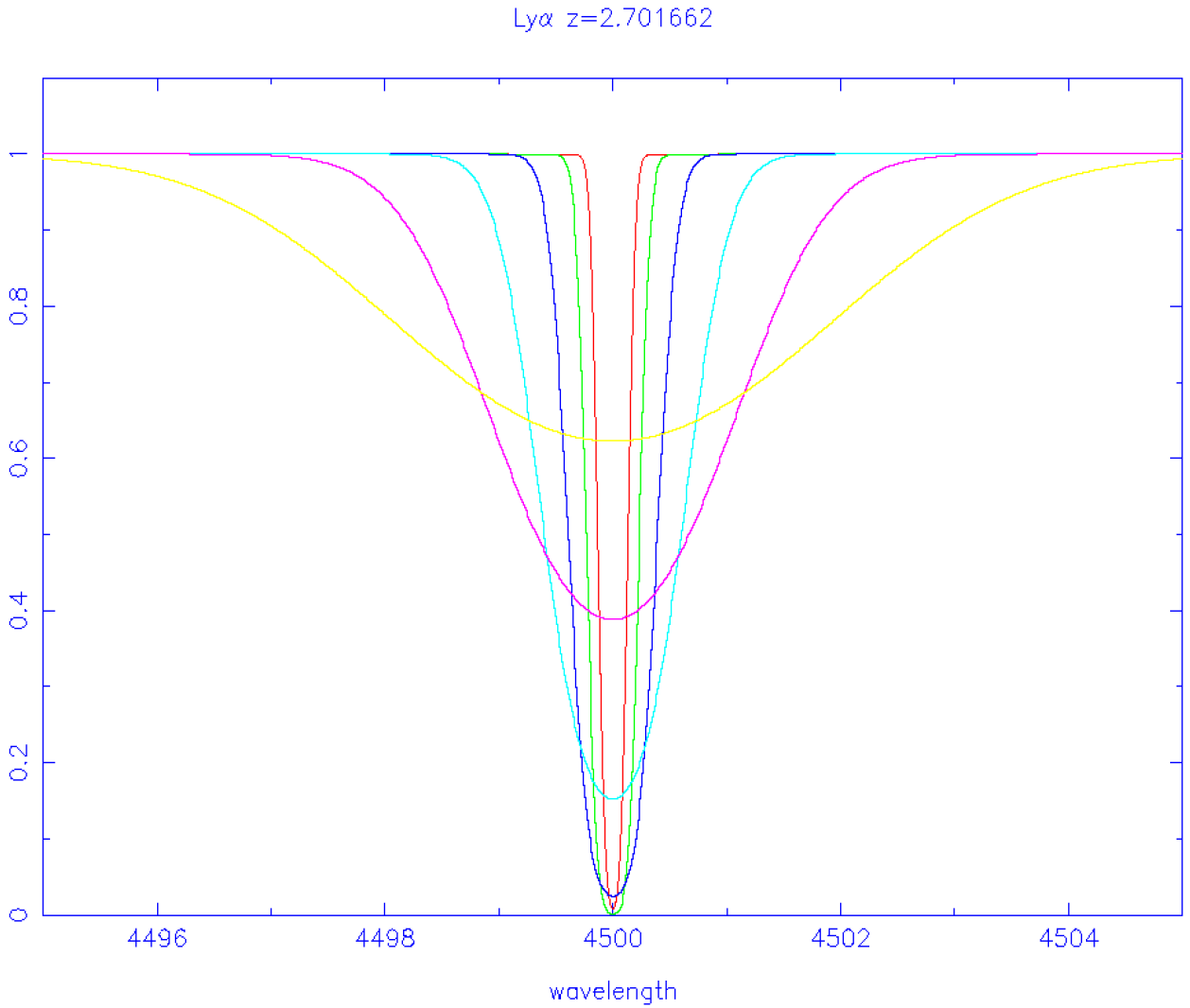
Same line with column densities N (number of HI /sq cm) from log$N$ = 12.5 - 18.5 in 0.5 steps



b = 20 km/s

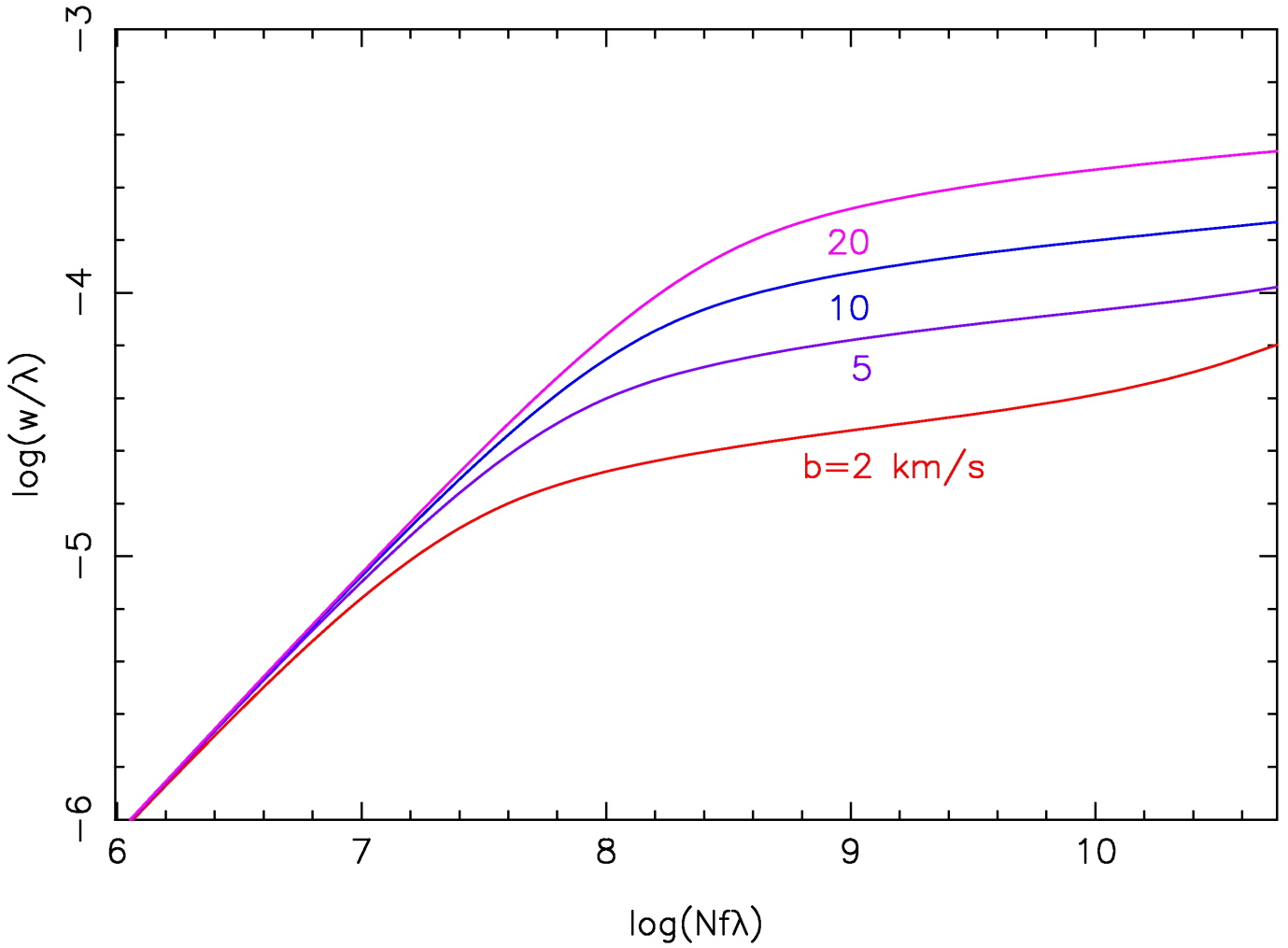
Equivalent width w (= area in A taken out of spectrum by the absorption line) is an increasing function of N (and oscillator strength f)

Doppler parameter b (= √2 s) 5, 10, 20, ... 160 km/s

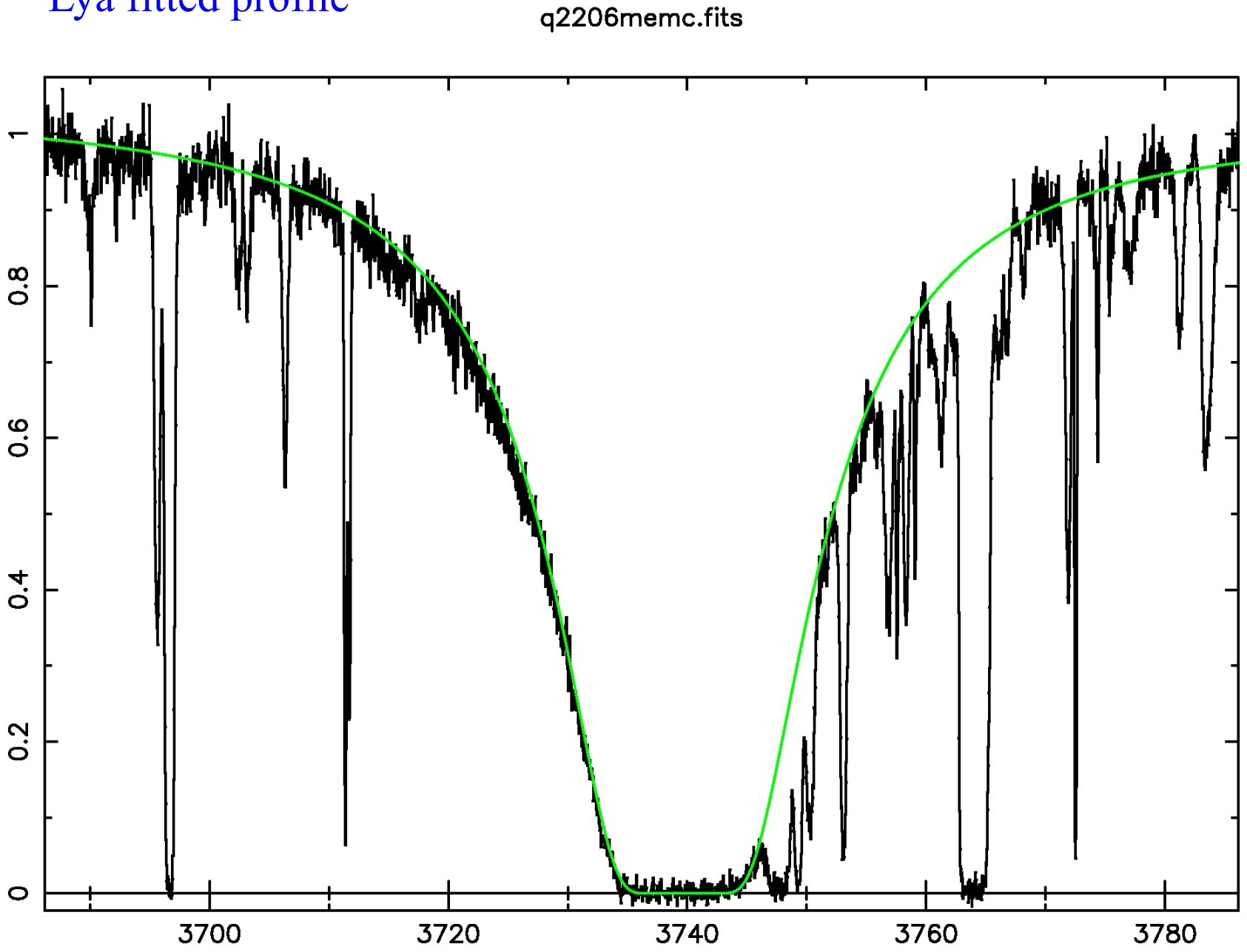


log$N$ = 14.0

Equivalent width w increases with b until self-shielding becomes unimportant


−3
−4
−5
−6
log(w/λ)
6
7
8
9
10
log(Nfλ)
20
10
5
b=2 km/s

Lya fitted profile



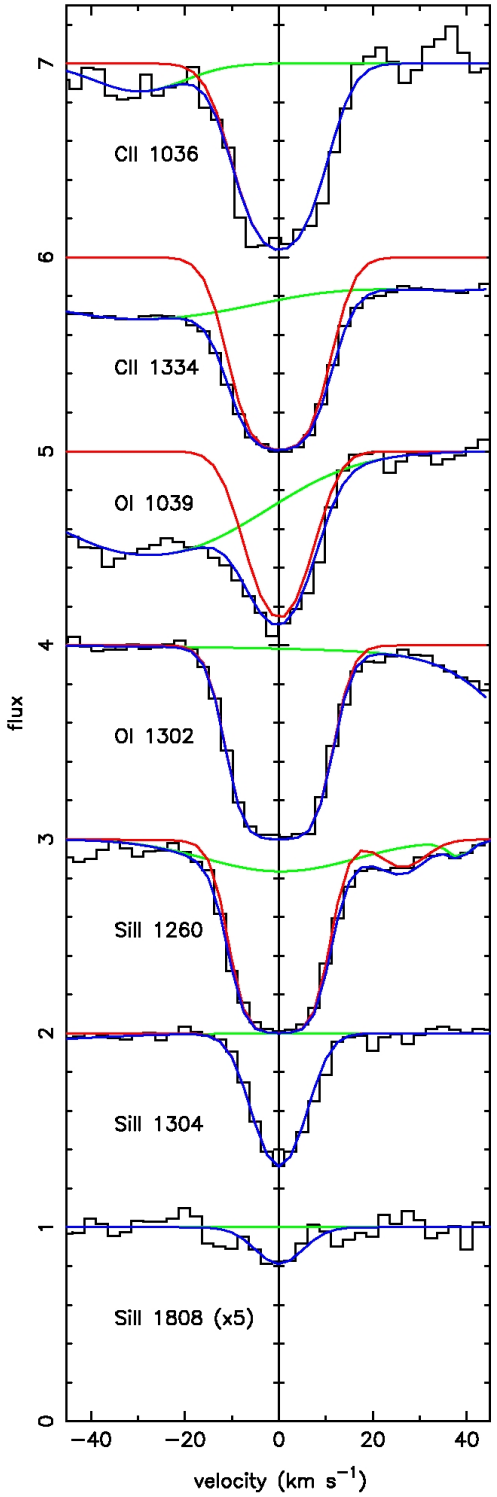
Fit model profiles, varying redshift, width and ion column density to get best fit.

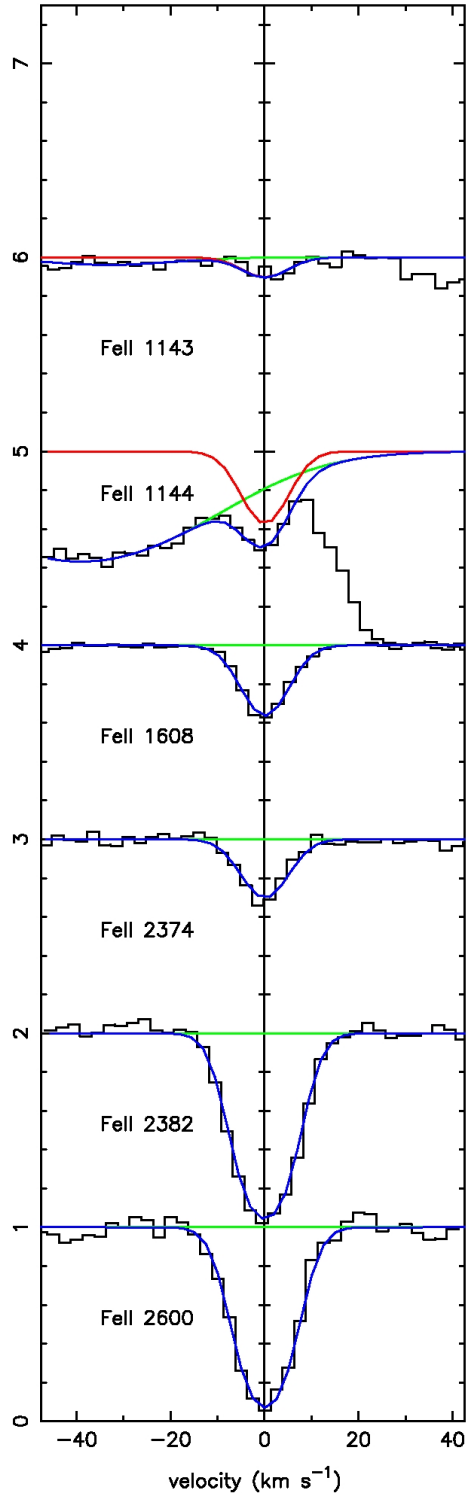
Blue = fit profile
Red = ion only
Green = blend or continuum

=>

Ion	log*N*	+/-	[N/H]*
H I	20.44	0.05	
[C II	14.24 – 14.35]		
O I	15.08	0.05	-2.28
SiII	13.69	0.01	-2.29
FeII	13.35	0.01	-2.59

* Log abundance relative to solar.





Fit model profiles, varying width and ion column density to get best fit.

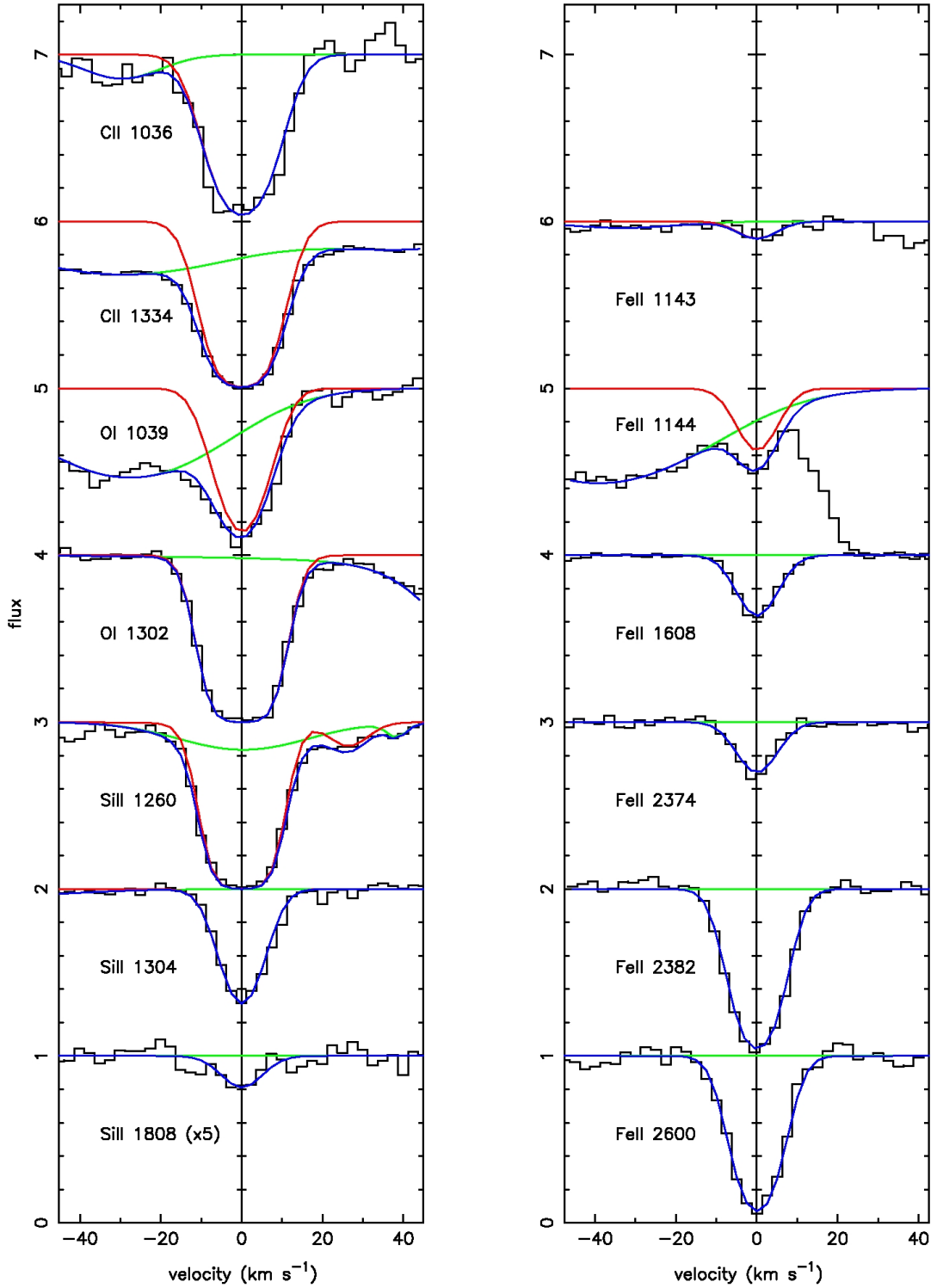
Blue = fit profile
Red = ion only
Green = blend or continuum

=>

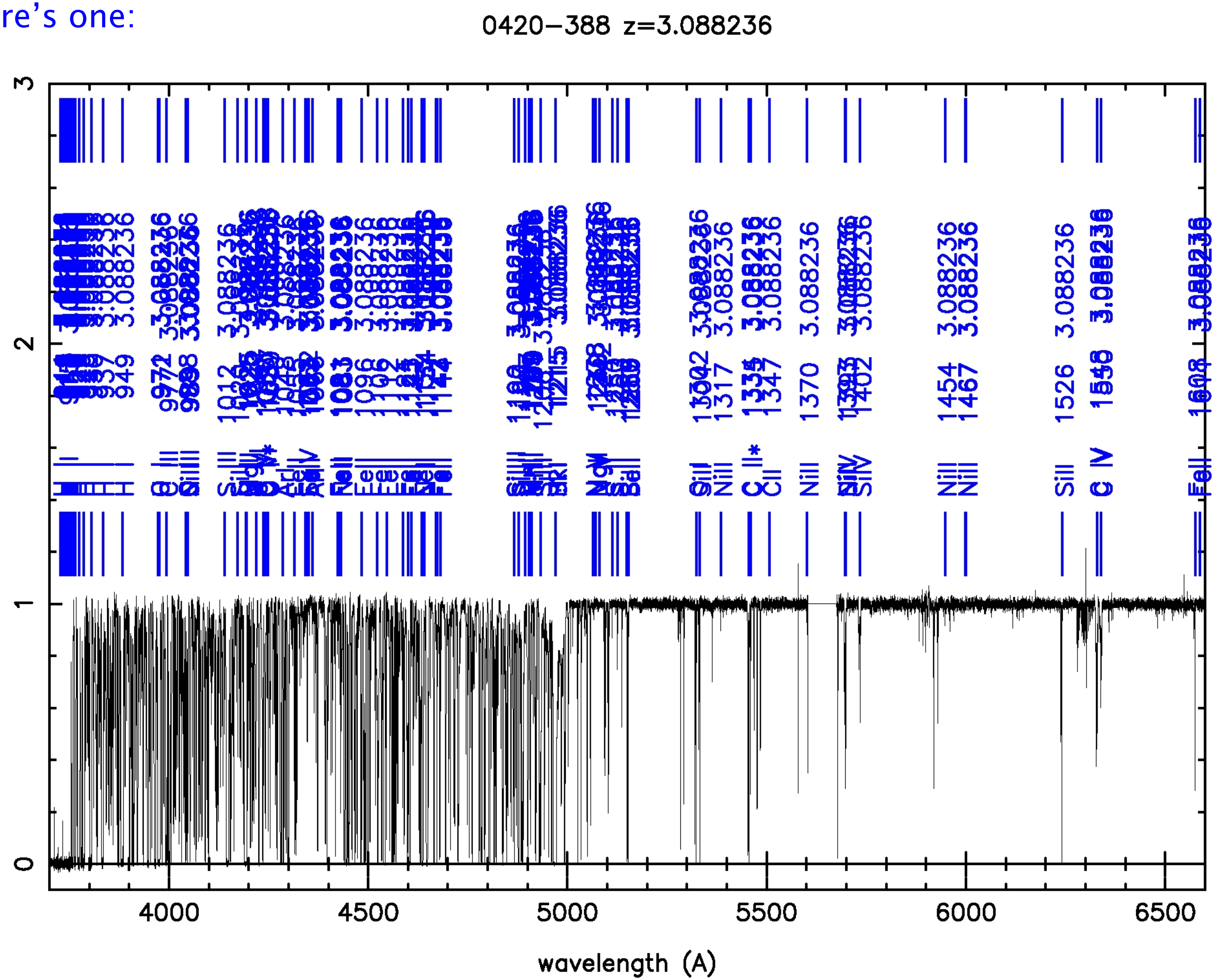
Ion	log*N*	+/-	[N/H]*
H I	20.44	0.05	
[C II	14.24 – 14.35]		
O I	15.08	0.05	-2.28
SiII	13.69	0.01	-2.29
FeII	13.35	0.01	-2.59

* Log abundance relative to solar.

That was a carefully chosen example. How about something with more typical velocity structure?



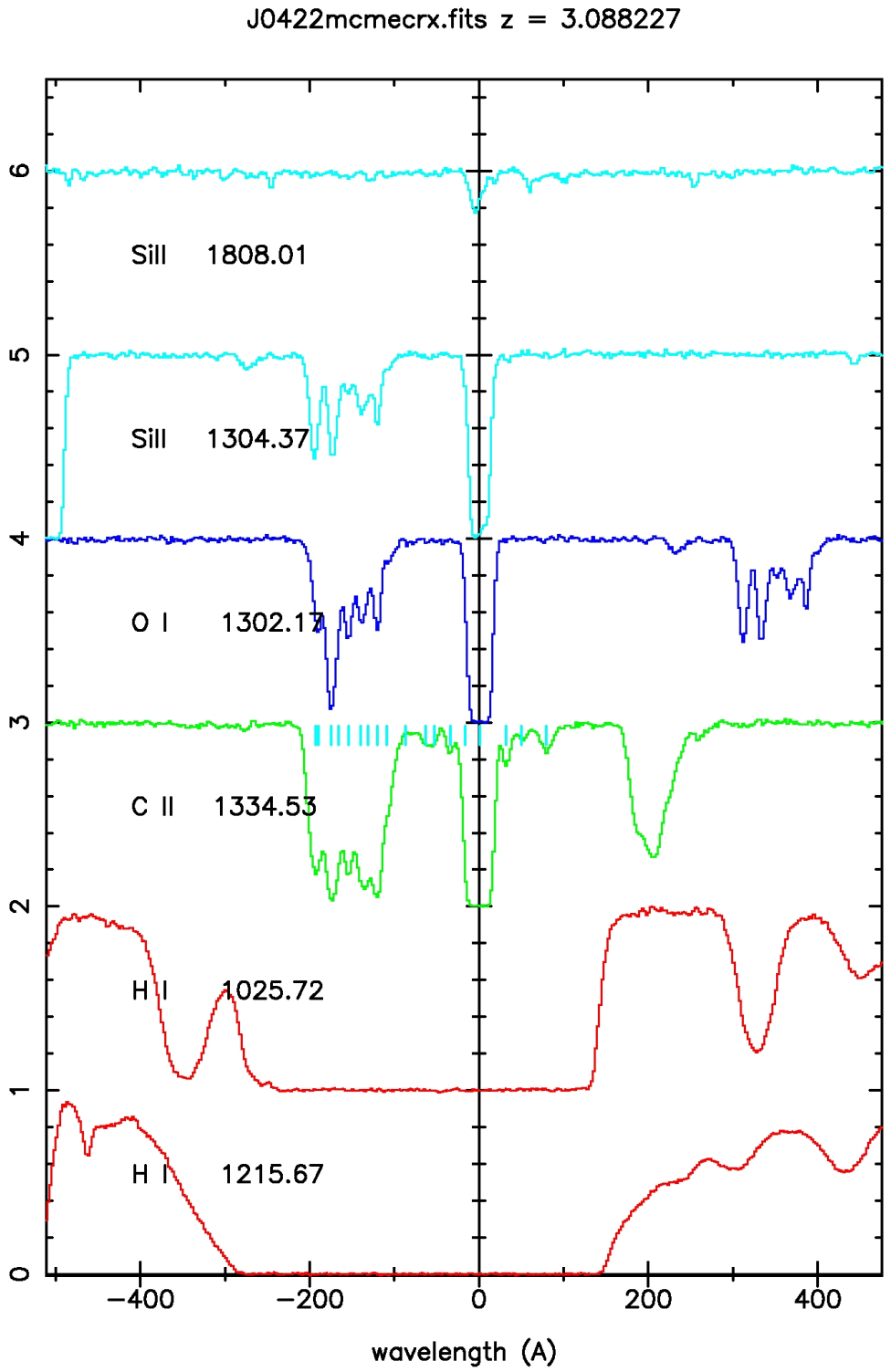
Here’s one:

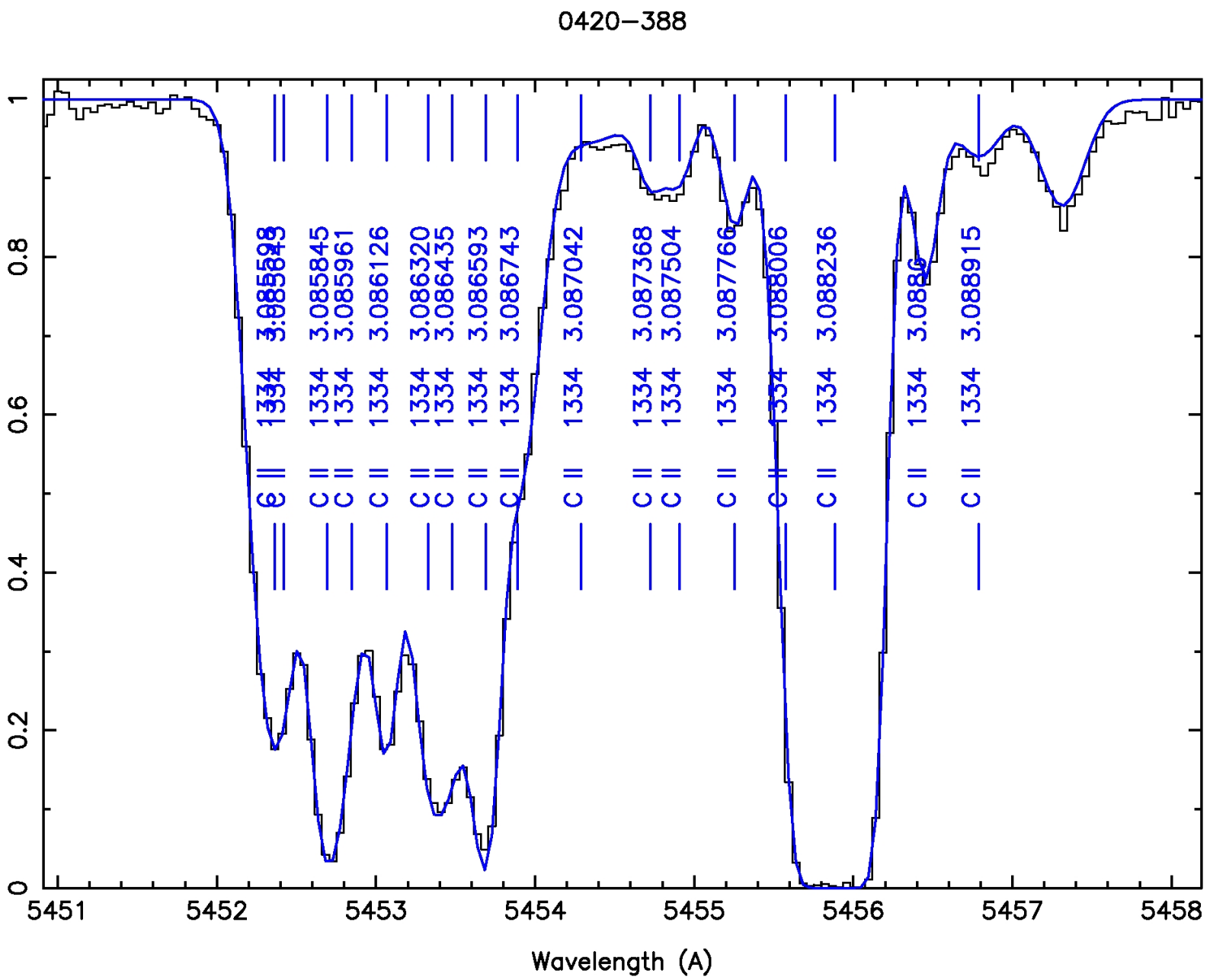

0420−388 z=3.088236
0
1
2
3
4000
4500
5000
5500
6000
6500
wavelength (A)

Many components spread out over a few 100 km/s.
Can no longer associate each one with an HI, but can get integrated abundances.

Note: HI Ly-α not as strong in this example, and not a great deal wider than the overall metal line spread. Also, the system is near the *z*=3.12 QSO - it is about 7.3 Mpc away.

The QSO flux dominates the integrated background and any other known local sources of ionizing radiation, so ionization corrections should hopefully be less ambiguous than usual.

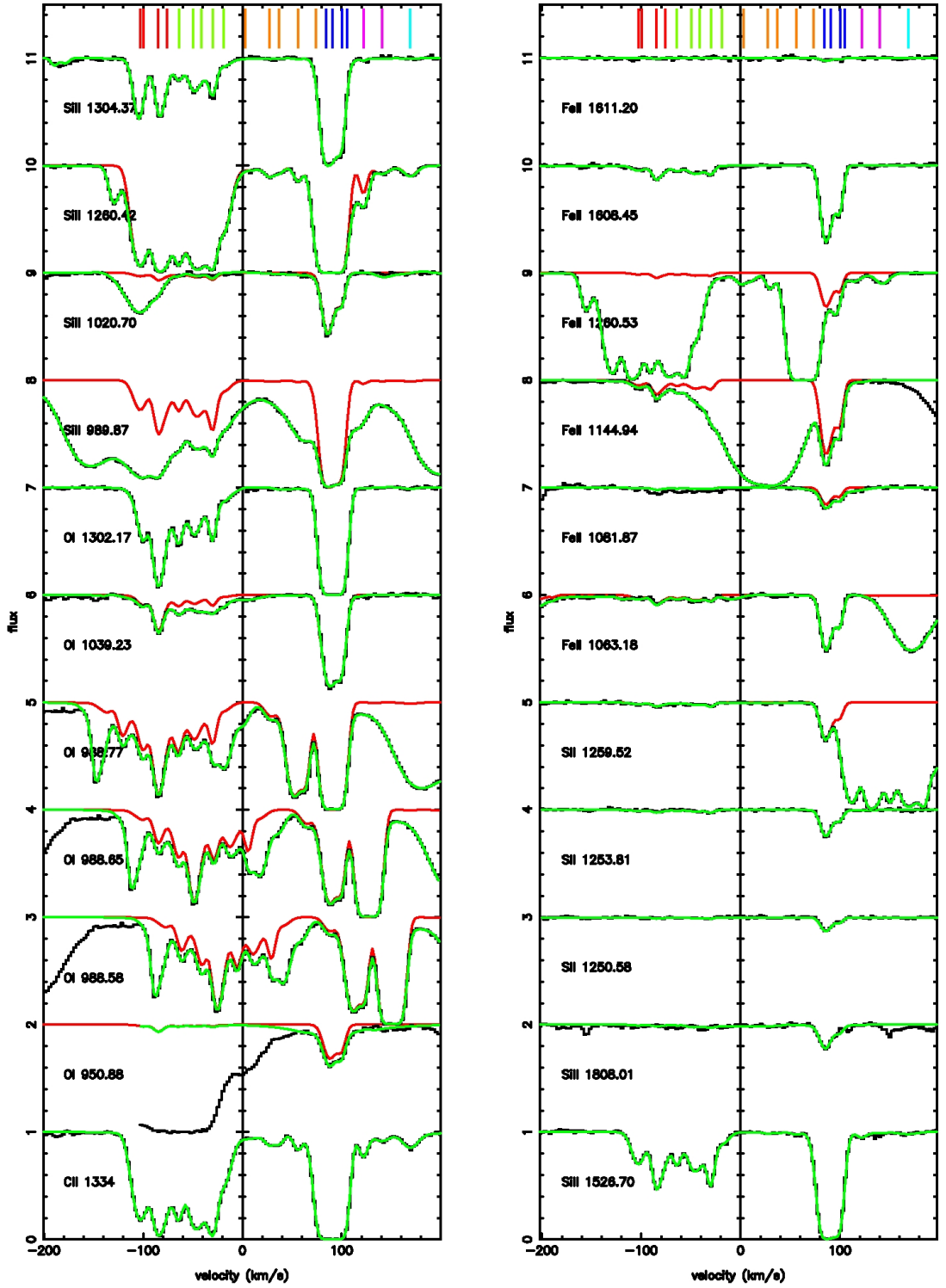



0420−388
C II 1334 3.085845
C II 1334 3.085961
C II 1334 3.086126
C II 1334 3.086320
C II 1334 3.086435
C II 1334 3.086593
C II 1334 3.086743
C II 1334 3.087042
C II 1334 3.087368
C II 1334 3.087504
C II 1334 3.087766
C II 1334 3.088006
C II 1334 3.088236
C II 1334 3.088915
0
0.2
0.4
0.6
0.8
1
5451
5452
5453
5454
5455
5456
5457
5458
Wavelength (A)

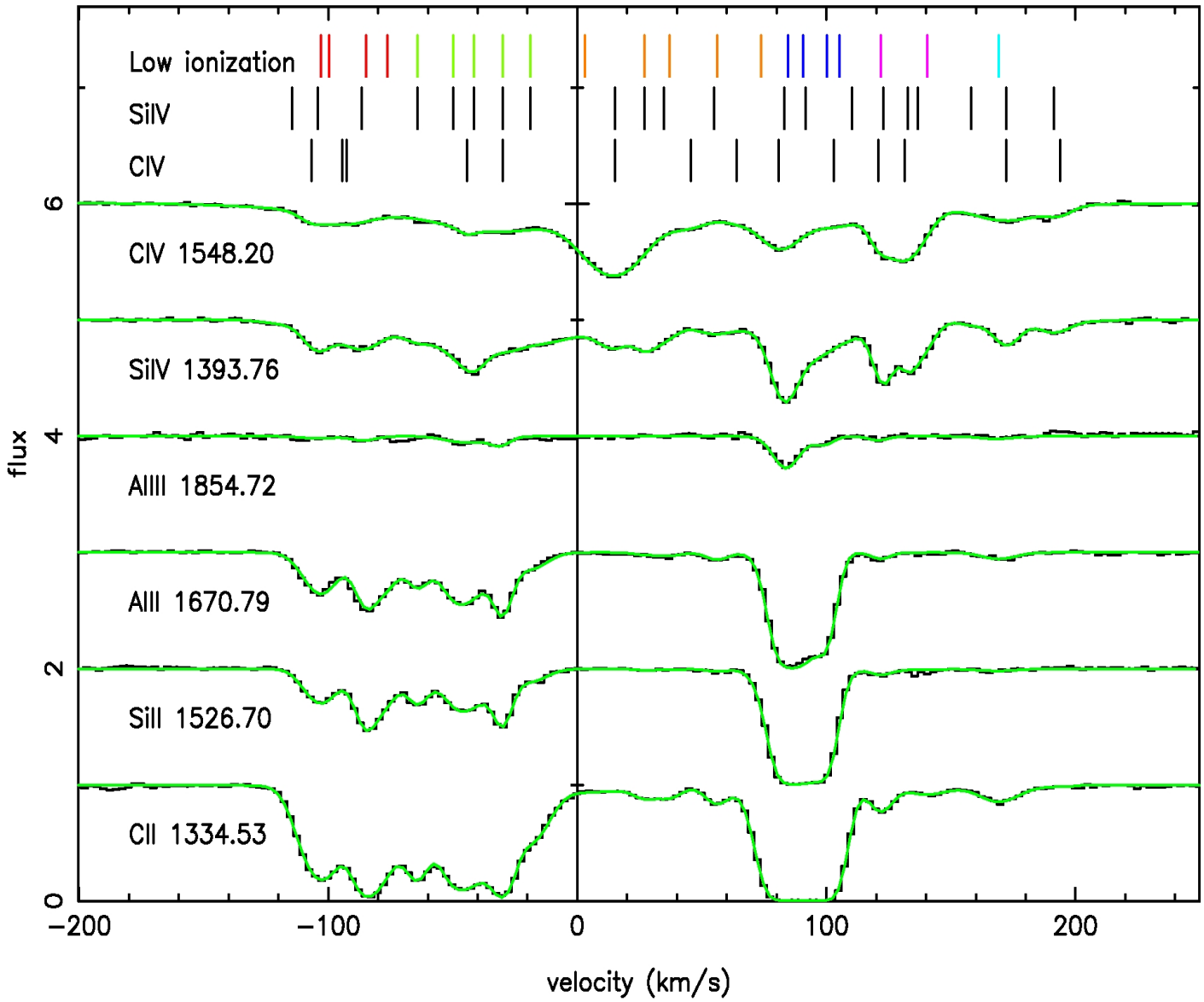
CII, OI, SiII, SII & FeII line profile fits. Green = fit, Red = fit with ion lines only (if it differs from green). Tick marks show components used.

Totals:

Ion	logN	+/-
H I	19.48	0.01
C II	<16.17	
N I	12.99	0.04
N II	14.17	0.02
O I	15.40	0.01
AlII	13.35	0.02
SiII	14.61	0.01
S II	14.21	0.01
FeII	14.03	0.01
AlIII	12.47	0.03
C IV	14.09	0.01
SiIV	13.68	0.01



As usual the strong high ionization components misaligned with low. AlIII is weak and agrees OK, SiIV agrees for green tick set only.



The CLOUDY photoionization model code (www.nublado.org) has an optimizer which we use to provide best fit solutions for density, metallicity, etc. given ionizing flux from quasar, background flux & the measured column densities.

Totals:

Ion	logN	+/-	model
H I	19.48	0.01	19.48
C II	<16.17		15.21
N I	12.99	0.04	13.45
N II	14.17	0.02	13.92
O I	15.40	0.01	15.24
AlII	13.35	0.02	13.24
SiII	14.61	0.01	14.49
S II	14.21	0.01	14.01
FeII	14.03	0.01	14.19
AlIII	12.47	0.03	12.66
C IV	14.09	0.01	14.23
SiIV	13.68	0.01	13.83

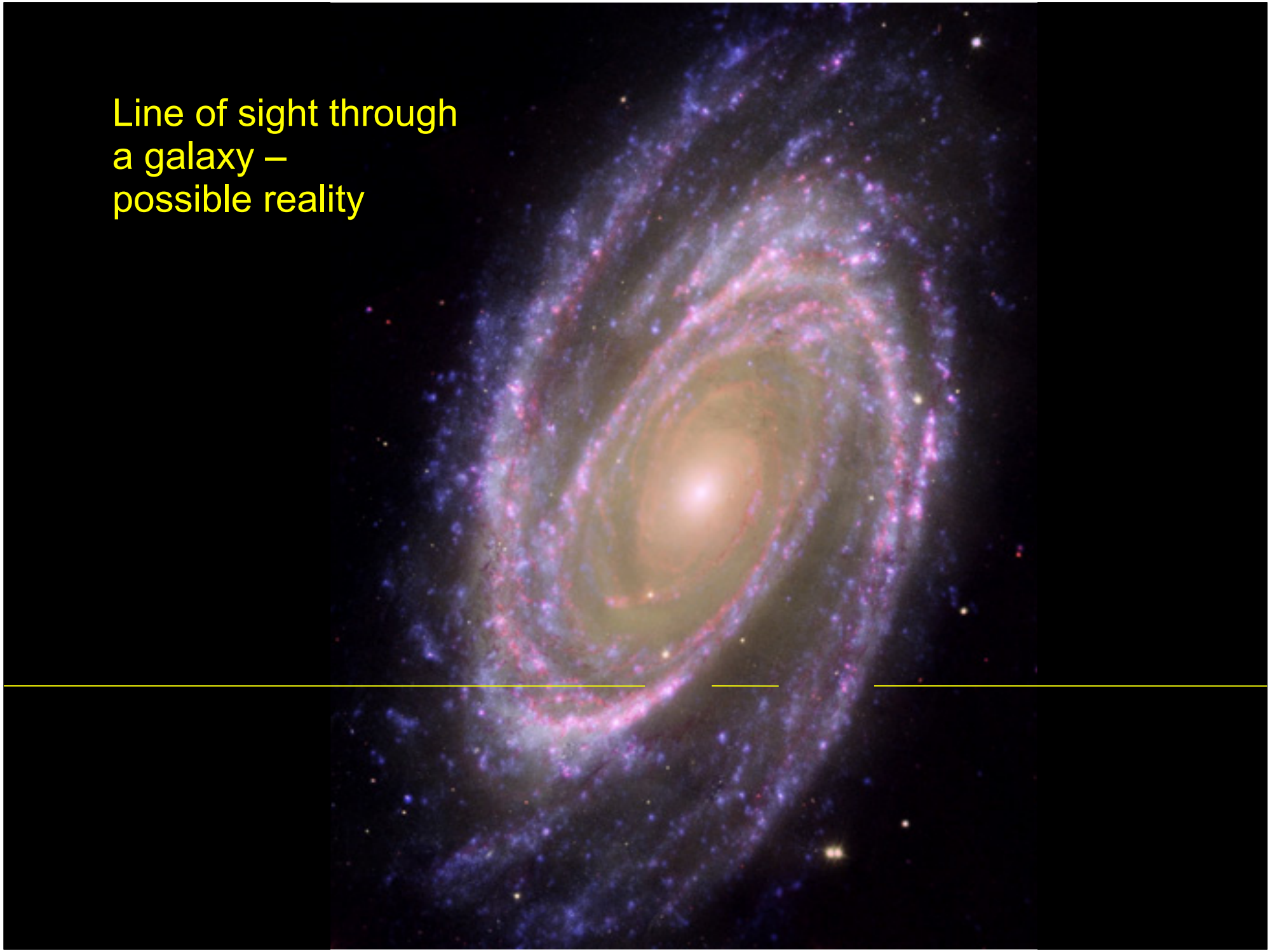
log n_H = -0.34 (cm^{-3})

[O/H] = -0.94 (=[C/H], [Si/H], [S/H])

[N/O] = -0.85

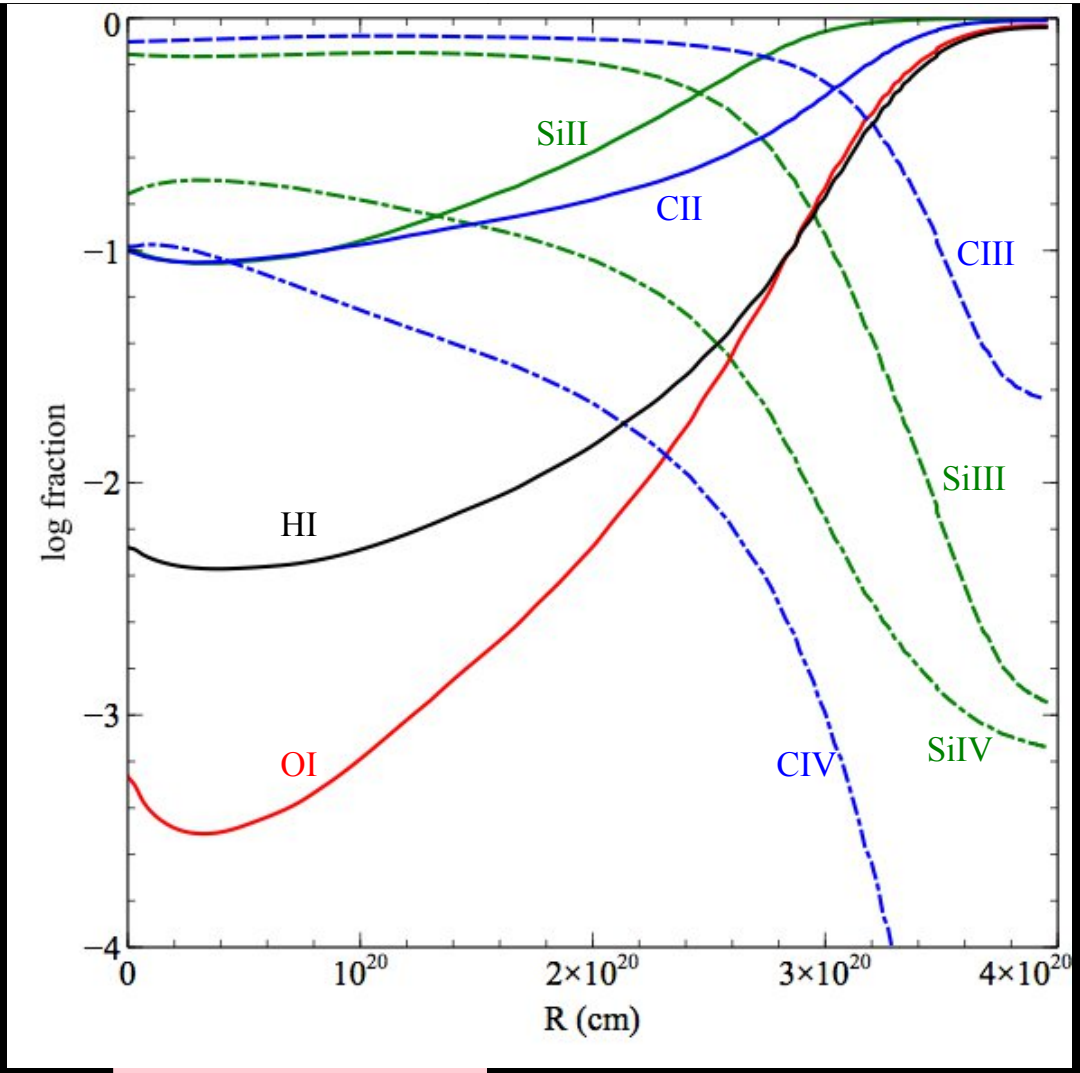
[Al/O] = -0.19

$<\chi^2>$ = 178.8 – don't expect good agreement, but that is pretty poor.


Line of sight through
a galaxy –
possible reality

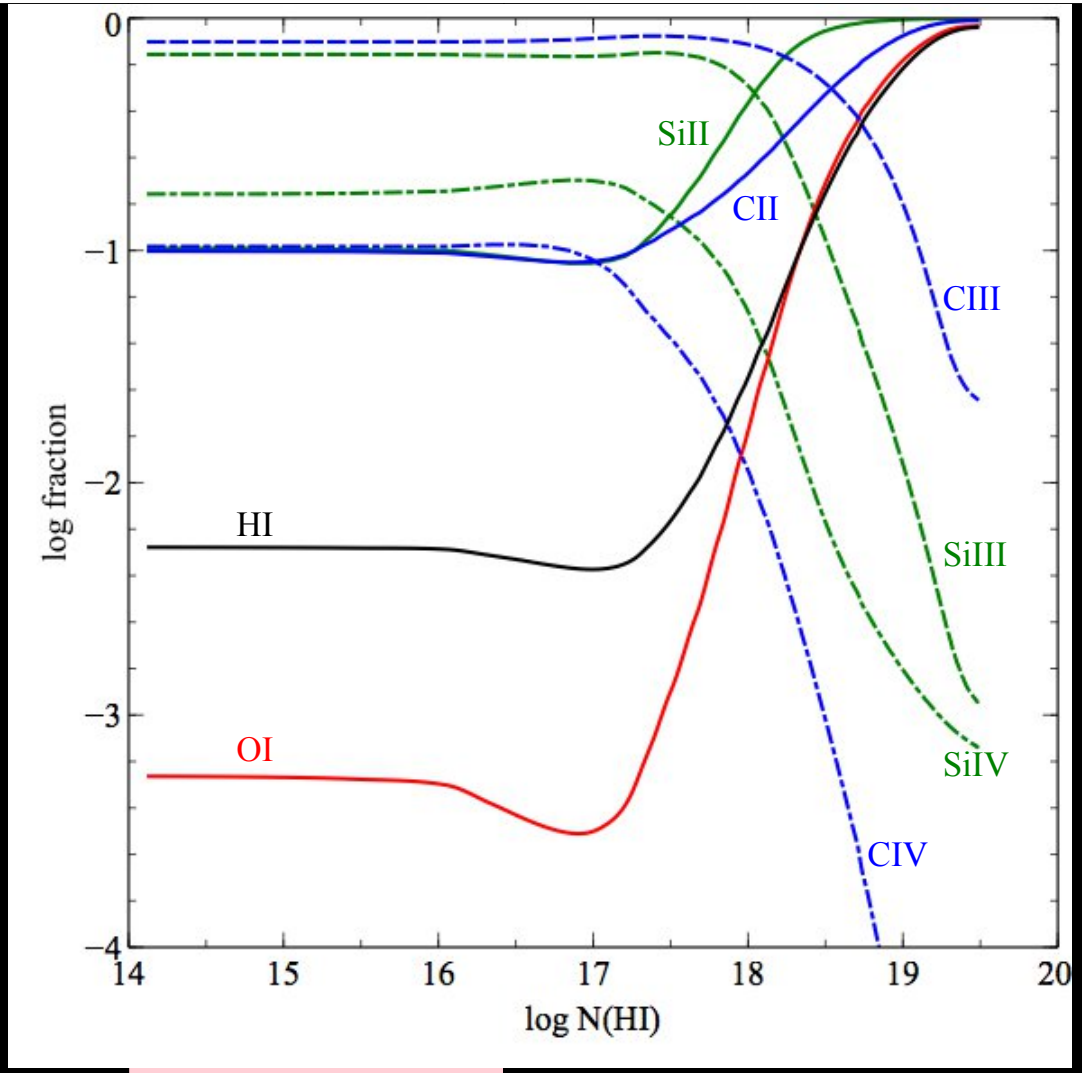

Line of sight through
a galaxy
-- as modelled
(at least in abundance terms)
QSO

Line of sight through
a galaxy
-- as modelled
(at least in abundance terms)



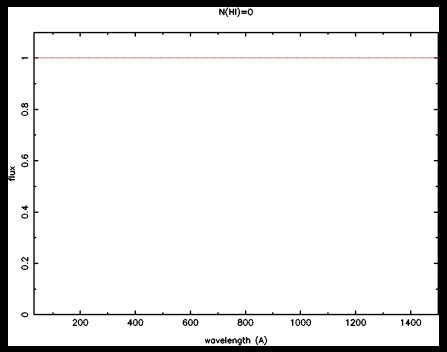
QSO

Line of sight through
a galaxy
-- as modelled
(at least in abundance terms)

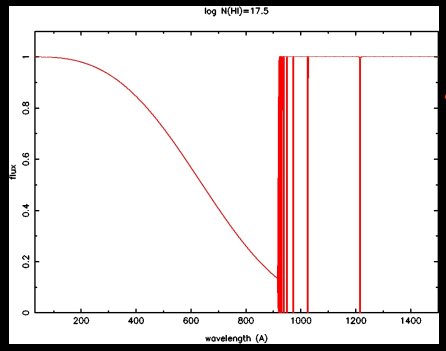


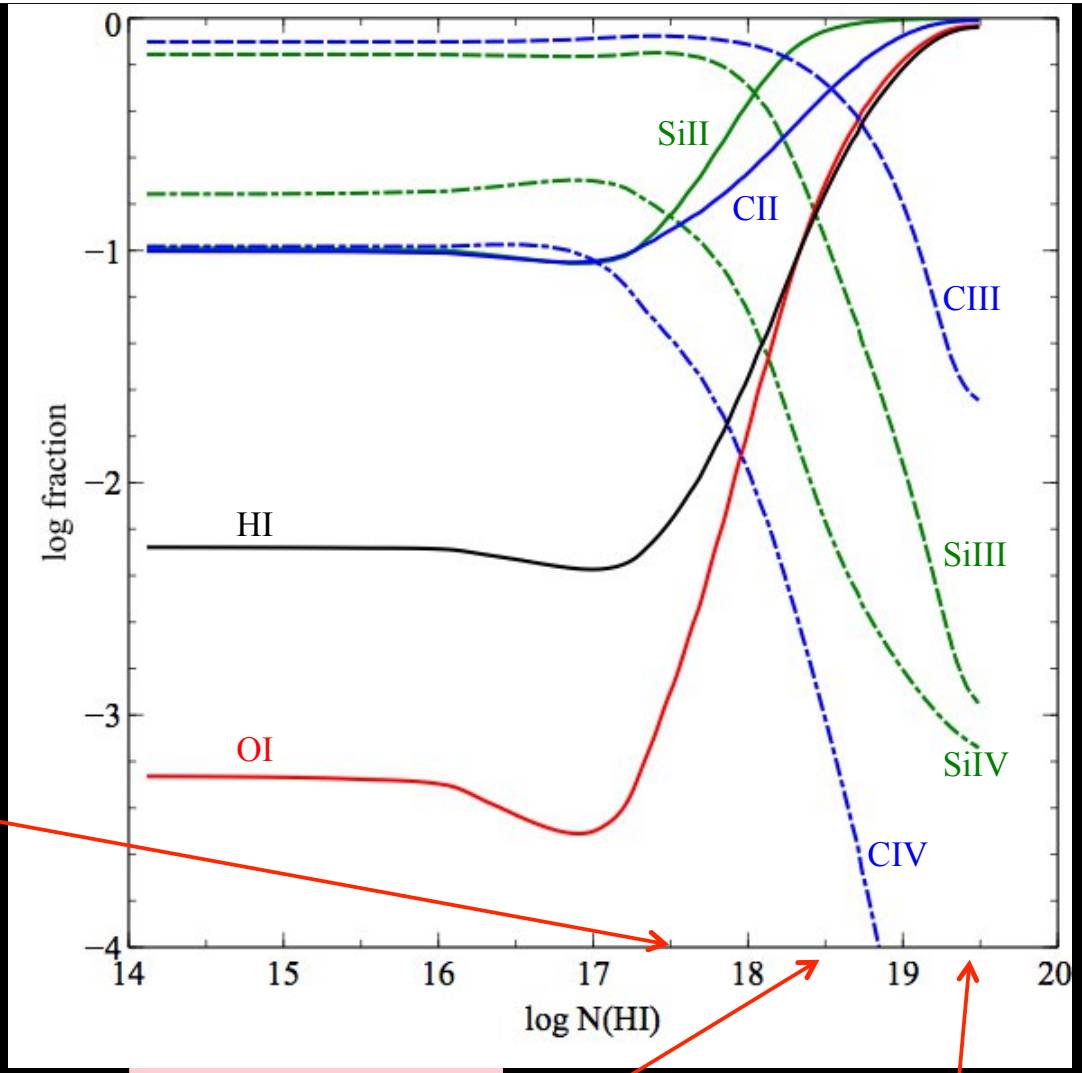
QSO

Line of sight through a galaxy -- as modelled

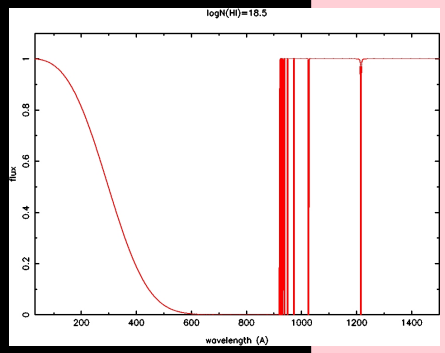


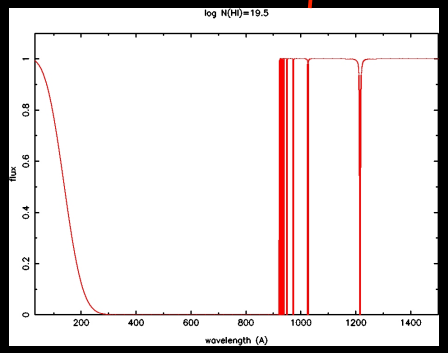
Input spectrum





QSO





Line of sight through
a galaxy
-- as modelled
(at least in abundance terms)

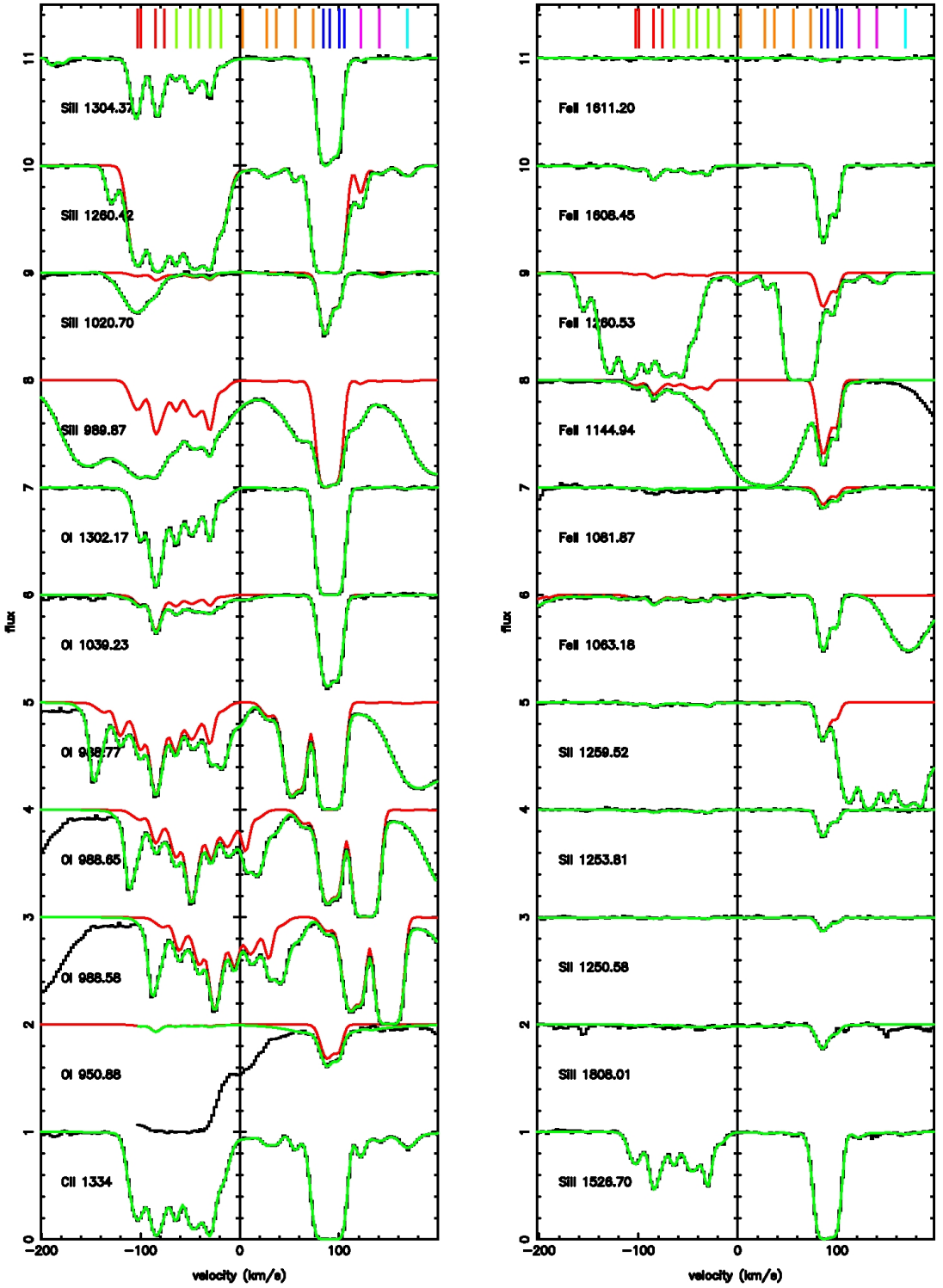
So maybe we should not be too surprised. But can we do better?

Try to break the model up into components in some way? Guided by the data hopefully….

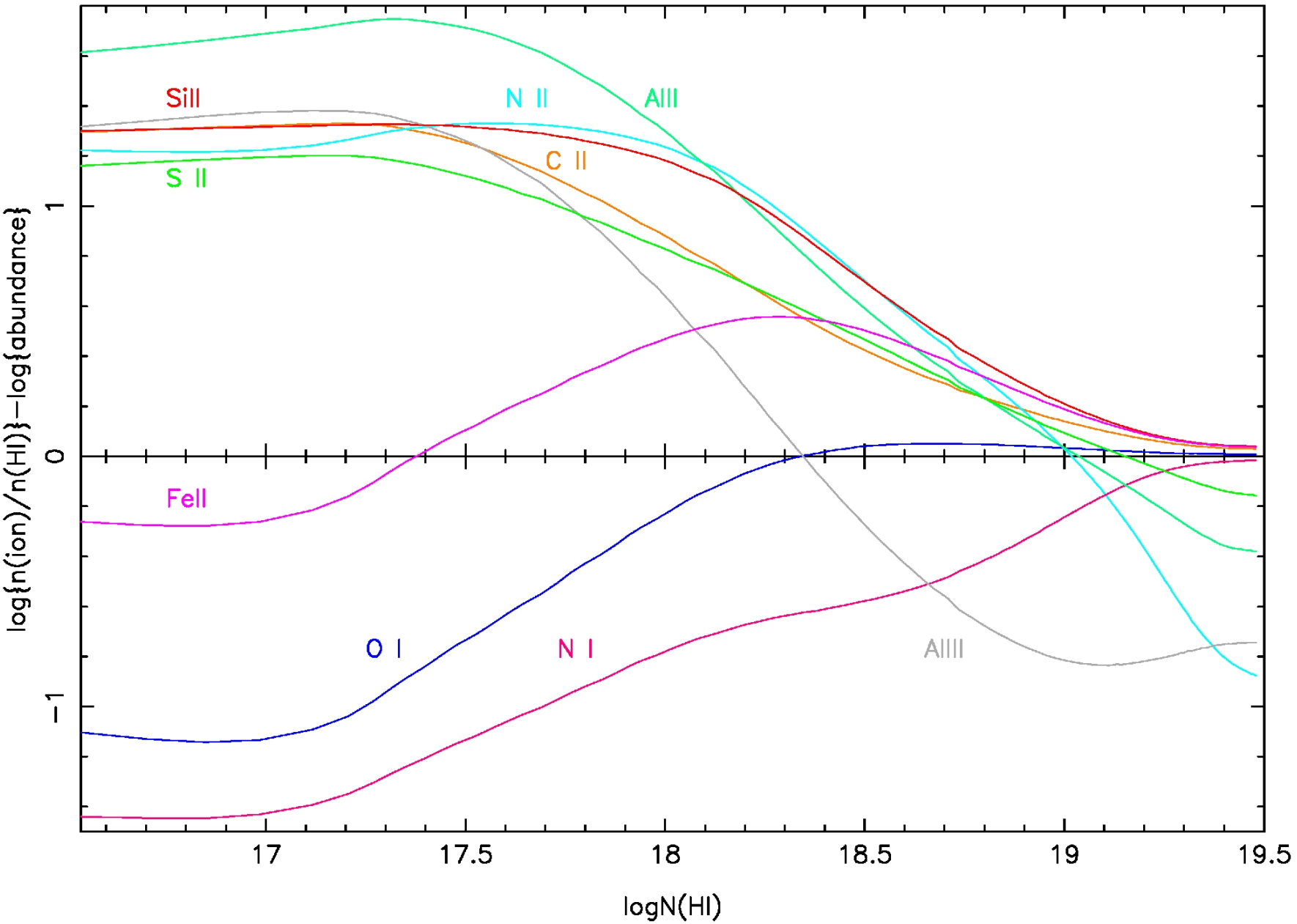
A first guide to any differences are the relative strengths of CII 1334, OI 1302 and SiII 1260. If the ions are in the solar abundance ratios of C/O/Si, then their *f*-values are such that these lines should have similar strengths. They don't always.

Coloured tick marks separate velocity groups which seem to have similar internal properties:

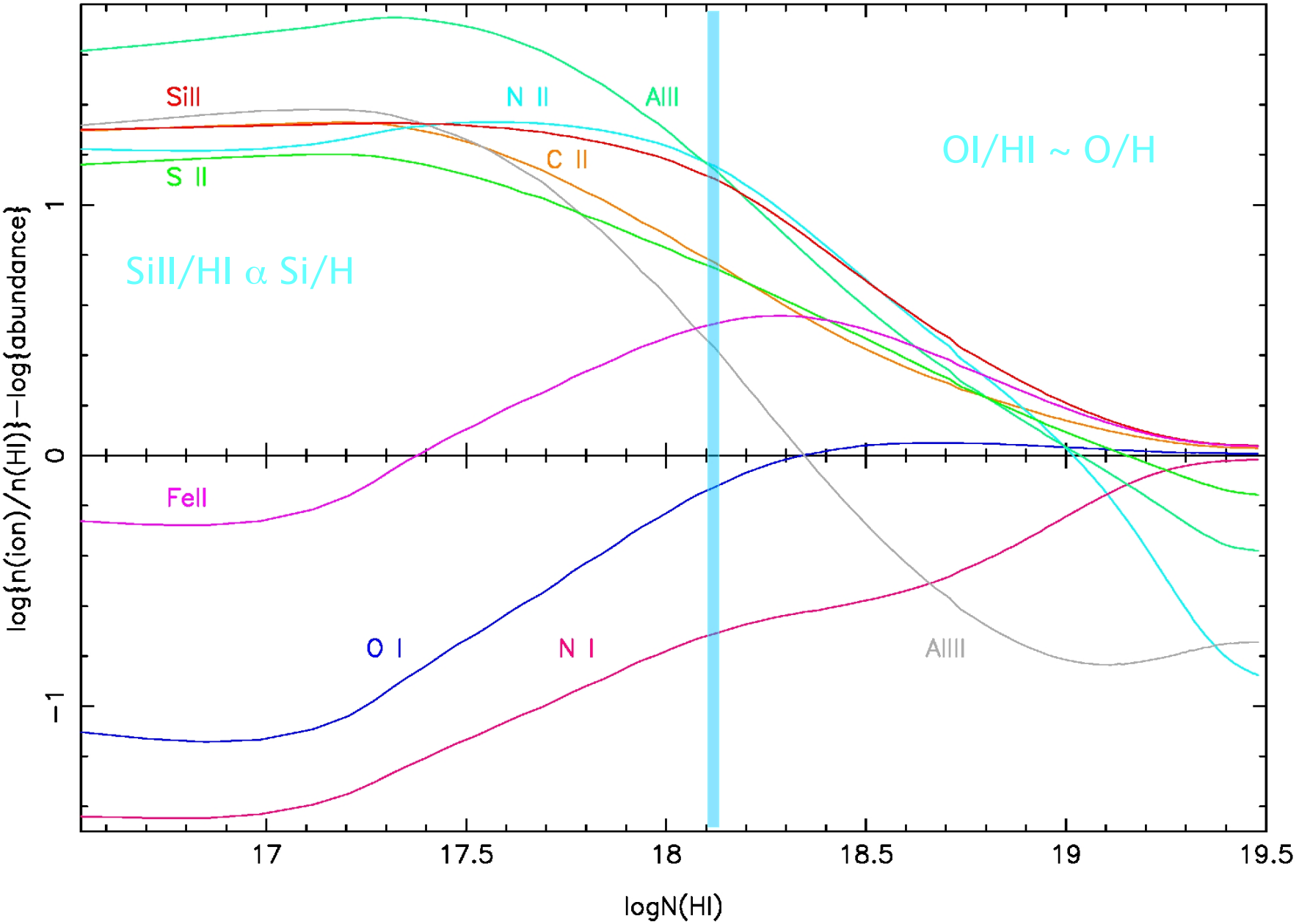
(A) Red: CII, OI, SiII present, SiIV matches poorly.
(B) Green: CII, OI, SiII seen, SiIV matches well.
(C) Orange: CII, SiII measurable, OI not seen.
(D) Blue: Strong system with small velocity range.
(E) Magenta: CII, SiII measured, no OI
(F) Turquoise: velocity outlier with CII, OI, SiII.



Relative ion abundance through a cloud ionized by the QSO

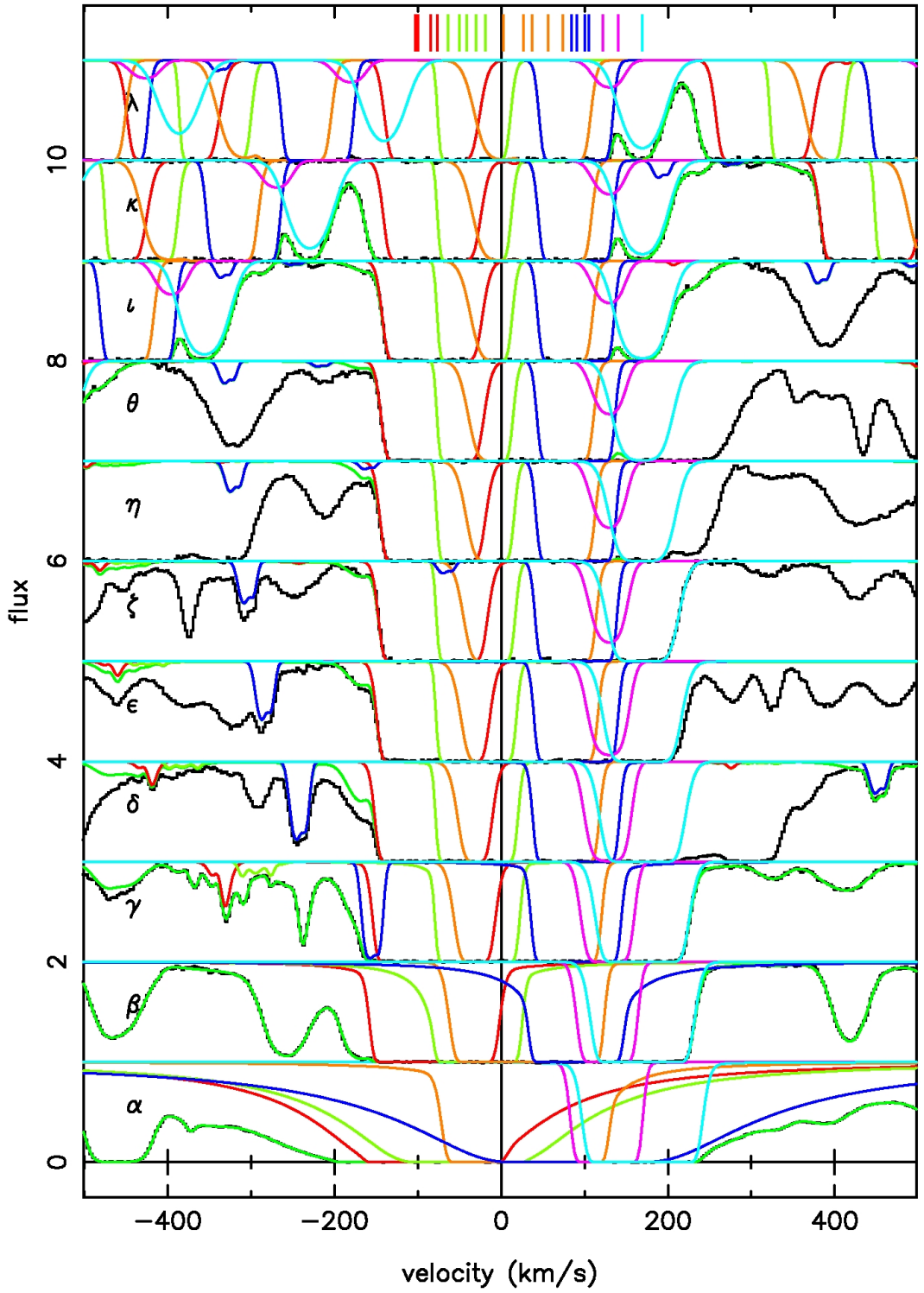


Relative ion abundance through a cloud ionized by the QSO



Assume abundances constant within a group, and so for each HI α OI where OI detected, and HI α SiII where it is not.
Then can unscramble the HI.

Black: data
Green: overall fit
Other: group Lyman lines (+ others)



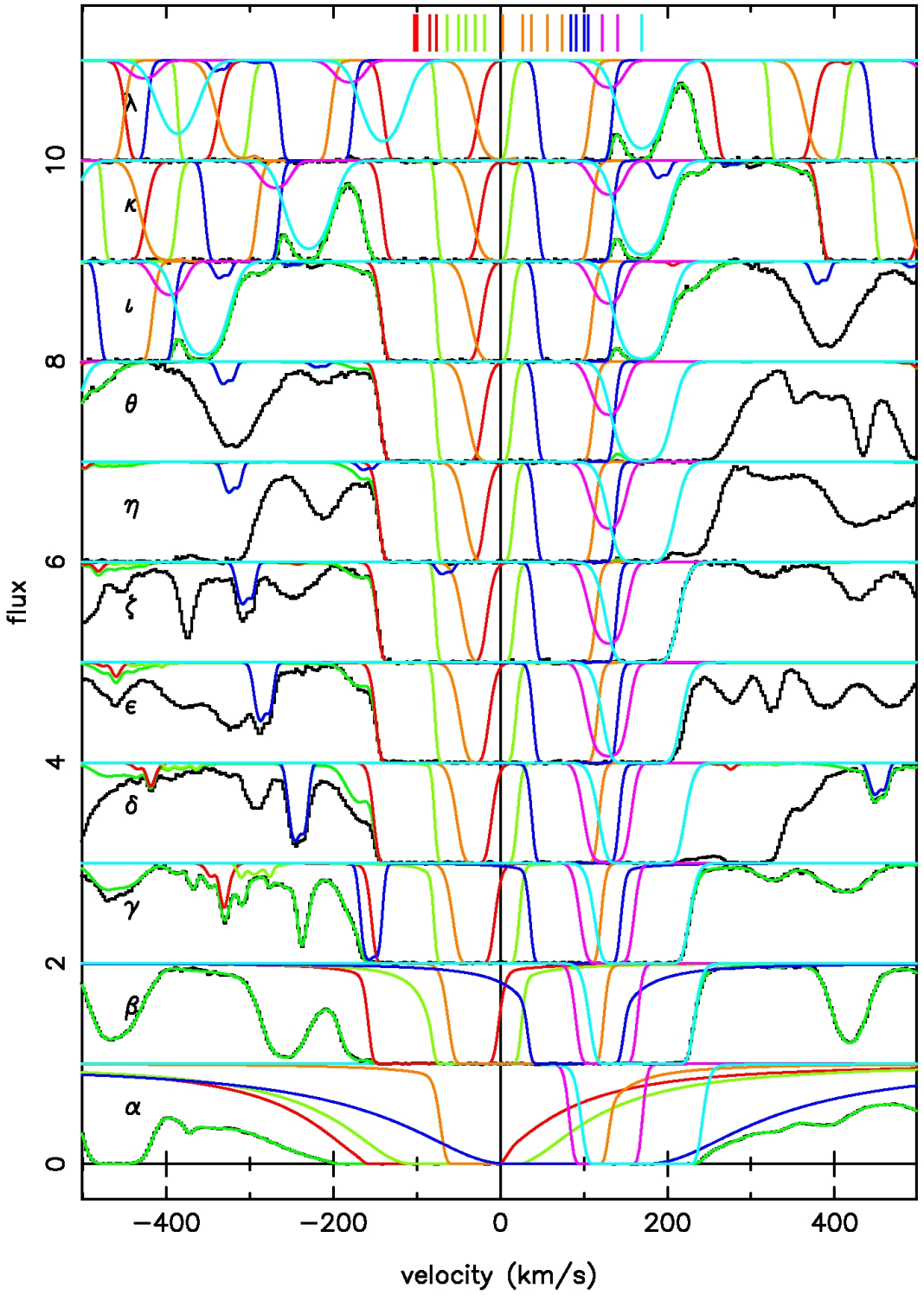
Assume abundances constant within a group, and so for each HI α OI where OI detected, and HI α SiII where it is not.
Then can unscramble the HI.

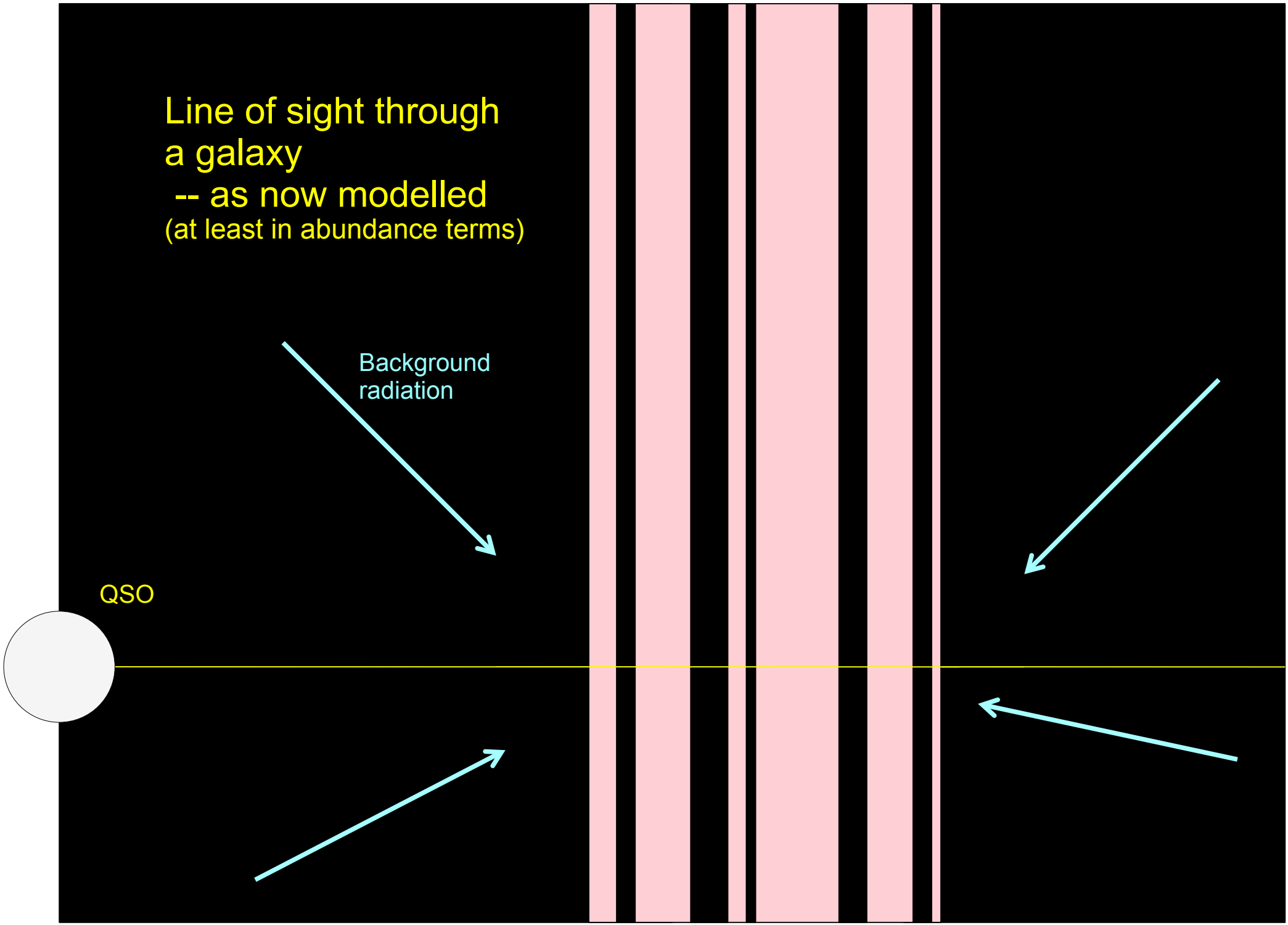
Black: data
Green: overall fit
Other: group Lyman lines (+ others)

Now we have six sets of column densities for HI, CII, NI, NII, OI, AlII, SiII, SII, FeII, AlIII, with, in one case SiIV, and no corresponding CIV.

To model these need to account for absorption of QSO radiation by whichever other components lie between the one we are interested in and the QSO.

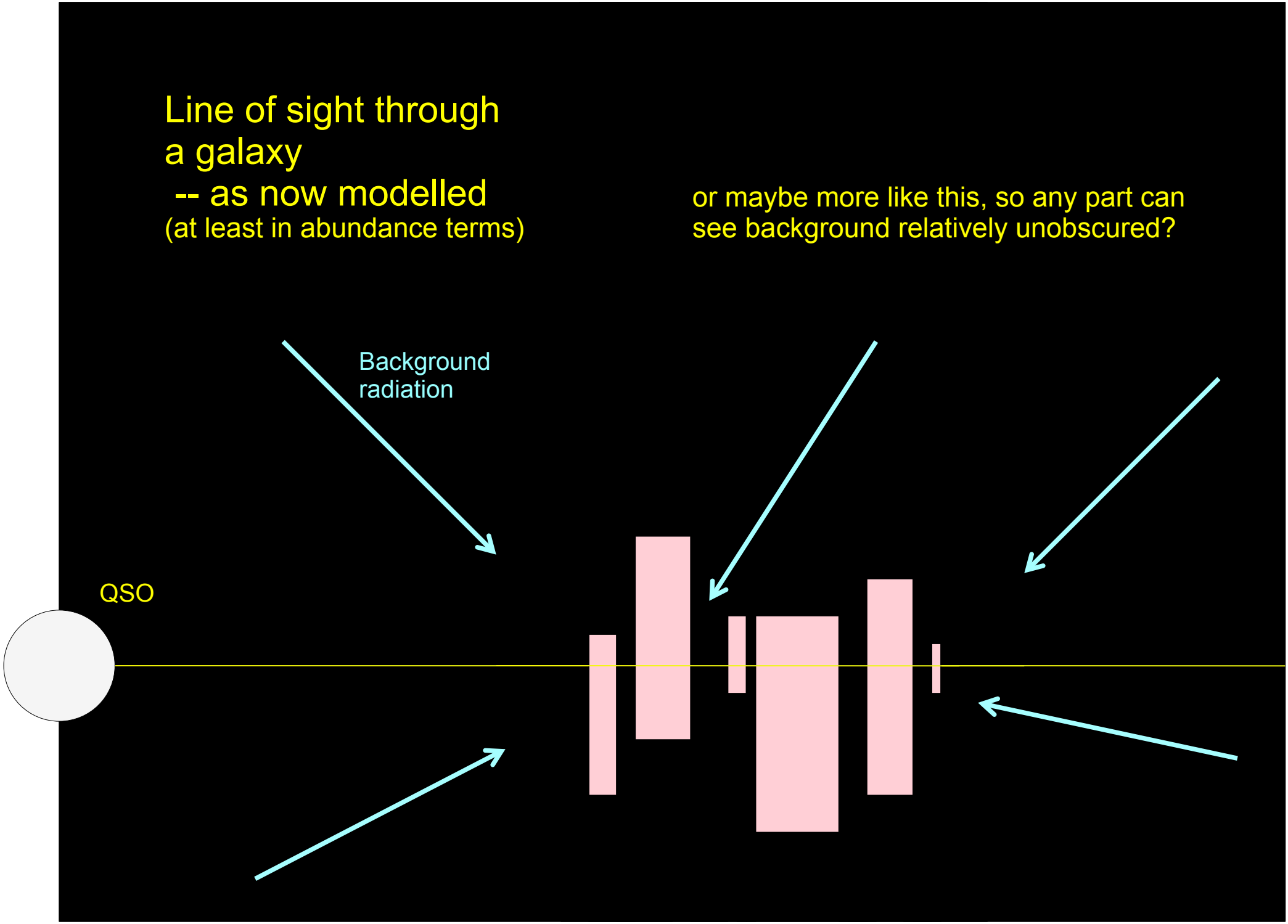
Ignore high ionization CIV etc since it is associated with ionized H, so little absorption of ionizing radiation.




Line of sight through
a galaxy
-- as now modelled
(at least in abundance terms)
Background
radiation
QSO

Line of sight through
a galaxy
-- as now modelled
(at least in abundance terms)

or maybe more like this, so any part can see background relatively unobscured?



Now have a list with column densities for various ions for the six groups we have chosen -

	HI	CII	NI	NII	NIII	OI	AlII	SiII	SII	FeII	AlIII	CIV	SiIV	CII*	NiII
A	18.80	14.28	11.95	13.46	<13.50	14.44	12.36	13.54	13.16	13.04	11.43	<13.03	<12.77	<12.88	<12.41
	0.07	0.02	0.17	0.02		0.01	0.02	0.01	0.06	0.02	0.12				
B	18.86	14.49	12.44	13.33	<13.50	14.19	12.51	13.62	13.21	13.07	11.83	<13.37	12.97	11.85	<12.75
	0.12	0.12	0.09	0.08		0.01	0.02	0.01	0.05	0.02	0.05		0.01	0.28	
C	17.87	13.41	<13.40	12.30	<13.50	<13.16	11.36	12.56	<13.53	<12.85	10.22	<13.63	<12.96	<13.62	<12.65
	0.45	0.12		0.16			0.12	0.29			1.35				
D	19.19	<16.15	12.78	13.97	<14.00	15.32	13.21	14.51	14.11	13.93	12.25	<13.36	<13.20	12.58	12.87
	0.02		0.02	0.02		0.01	0.04	0.01	0.01	0.01	0.02			0.10	0.02
E	15.75	12.96	<12.43	<12.95	<13.50	<12.73	10.84	12.02	<13.23	<11.55	11.07	<13.13	<12.74	<12.40	<11.81
	0.70	0.04					0.14	0.02			0.15				
F	16.65	12.78	<13.00	12.08	<13.50	12.24	11.09	11.63	<13.15	<11.90	11.11	<12.60	<12.15	<11.85	<12.00
	0.02	0.06		0.22		0.21	0.06	0.04			0.19				

...this table is only to show that it has been done..

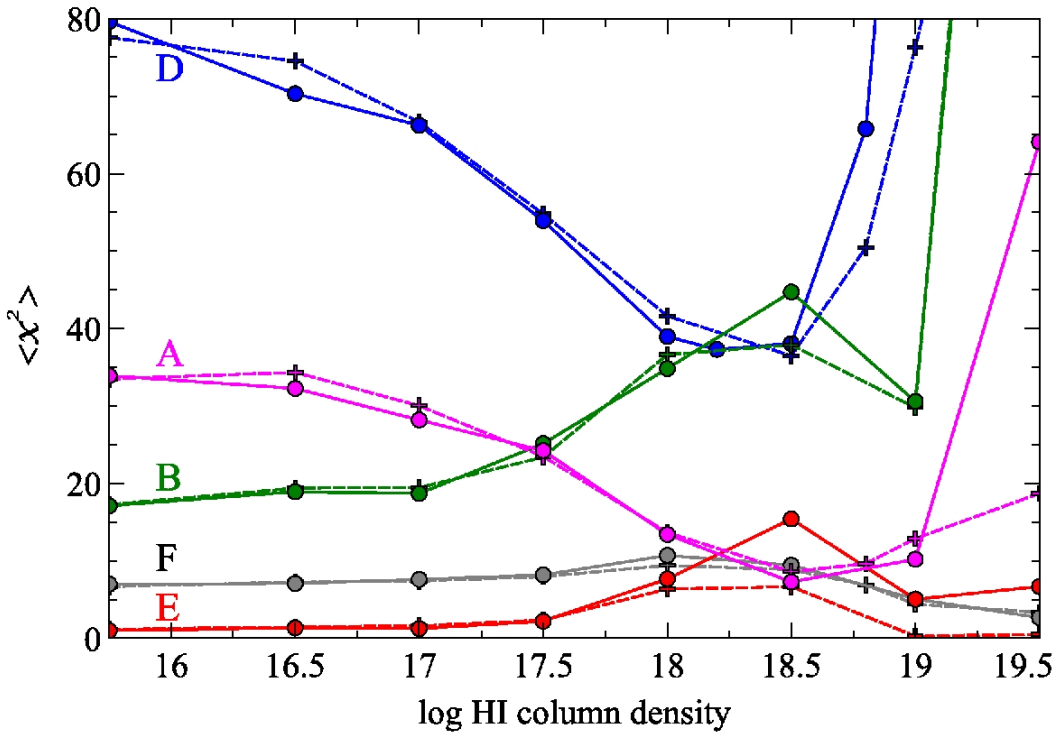
Now have a list with column densities for various ions for the six groups we have chosen -

	HI	CII	NI	NII	NIII	OI	AlII	SiII	SII	FeII	AlIII	CIV	SiIV	CII*	NiII
A	18.80	14.28	11.95	13.46	<13.50	14.44	12.36	13.54	13.16	13.04	11.43	<13.03	<12.77	<12.88	<12.41
	0.07	0.02	0.17	0.02		0.01	0.02	0.01	0.06	0.02	0.12				
B	18.86	14.49	12.44	13.33	<13.50	14.19	12.51	13.62	13.21	13.07	11.83	<13.37	12.97	11.85	<12.75
	0.12	0.12	0.09	0.08		0.01	0.02	0.01	0.05	0.02	0.05		0.01	0.28	
C	17.87	13.41	<13.40	12.30	<13.50	<13.16	11.36	12.56	<13.53	<12.85	10.22	<13.63	<12.96	<13.62	<12.65
	0.45	0.12		0.16			0.12	0.29			1.35				
D	19.19	<16.15	12.78	13.97	<14.00	15.32	13.21	14.51	14.11	13.93	12.25	<13.36	<13.20	12.58	12.87
	0.02		0.02	0.02		0.01	0.04	0.01	0.01	0.01	0.02			0.10	0.02
E	15.75	12.96	<12.43	<12.95	<13.50	<12.73	10.84	12.02	<13.23	<11.55	11.07	<13.13	<12.74	<12.40	<11.81
	0.70	0.04					0.14	0.02			0.15				
F	16.65	12.78	<13.00	12.08	<13.50	12.24	11.09	11.63	<13.15	<11.90	11.11	<12.60	<12.15	<11.85	<12.00
	0.02	0.06		0.22		0.21	0.06	0.04			0.19				

...this table is only to show that it has been done..

To model these we have to decide on the order as we go away from the QSO. Do this by calculating best fit models for various HI columns between region of interest and the QSO, and then ordering to minimize resultant $\chi 2$.

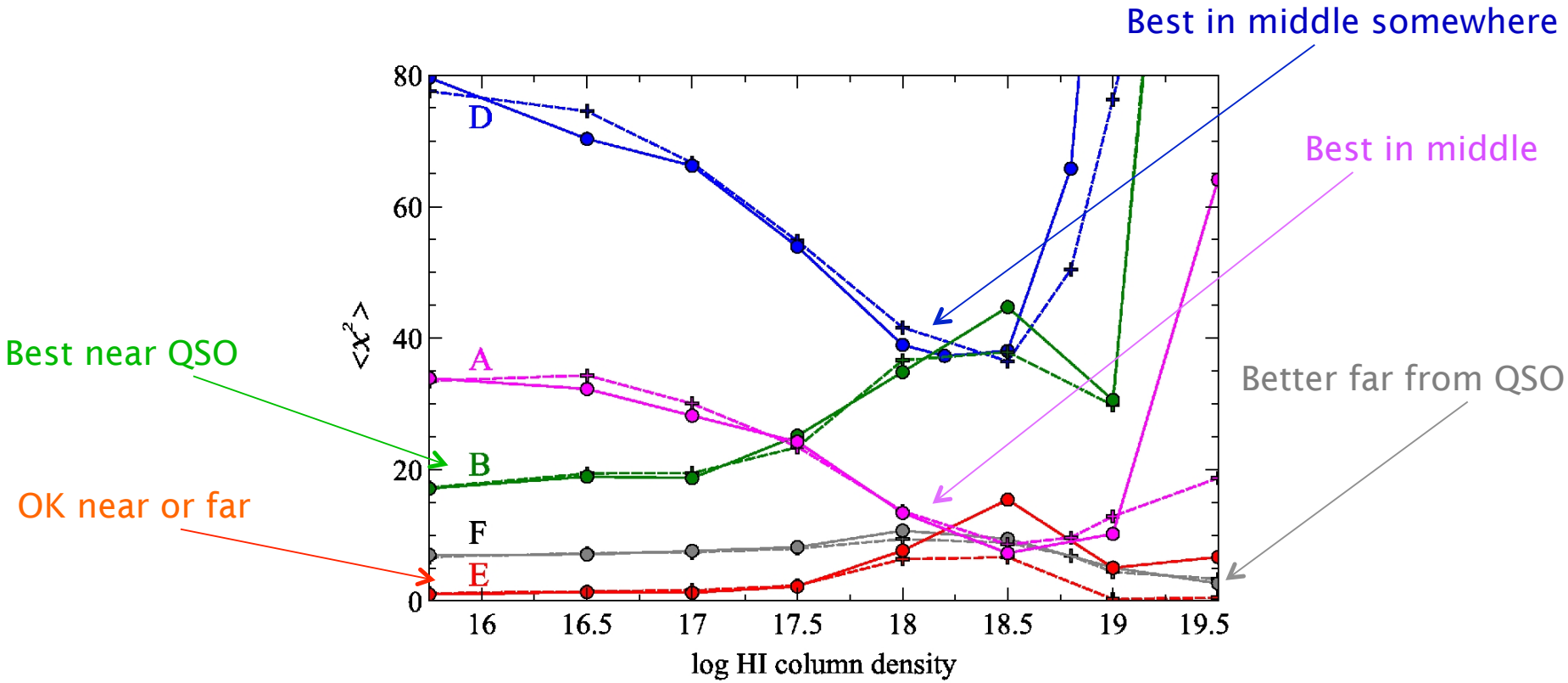
<χ2> vs intervening HI column for each component:



intervening between QSO and labelled component. Dashed lines are those with additional unobscured integrated background component.

(C is omitted because <χ2> < 1 everywhere, so you can put it wherever you like)

<χ2> vs intervening HI column for each component:



intervening between QSO and labelled component.
Dashed lines are those with additional unobscured
integrated background component.

(C is omitted because <χ2> < 1 everywhere, so you can put it wherever you like)

So a plausible [but not unique!] order, taking account of the HI columns for each component, is E B (A D) F C where A & D are left in brackets because the best fits have similar obscuration.

So a plausible [but not unique!] order, taking account of the HI columns for each component, is E B (A D) F C where A & D are left in brackets because the best fits have similar obscuration.

Two possibilities:

Live with a poorer fit for one of A or D – in which case better overall if order is EBDAFC $\Sigma<\chi 2>=95.1$

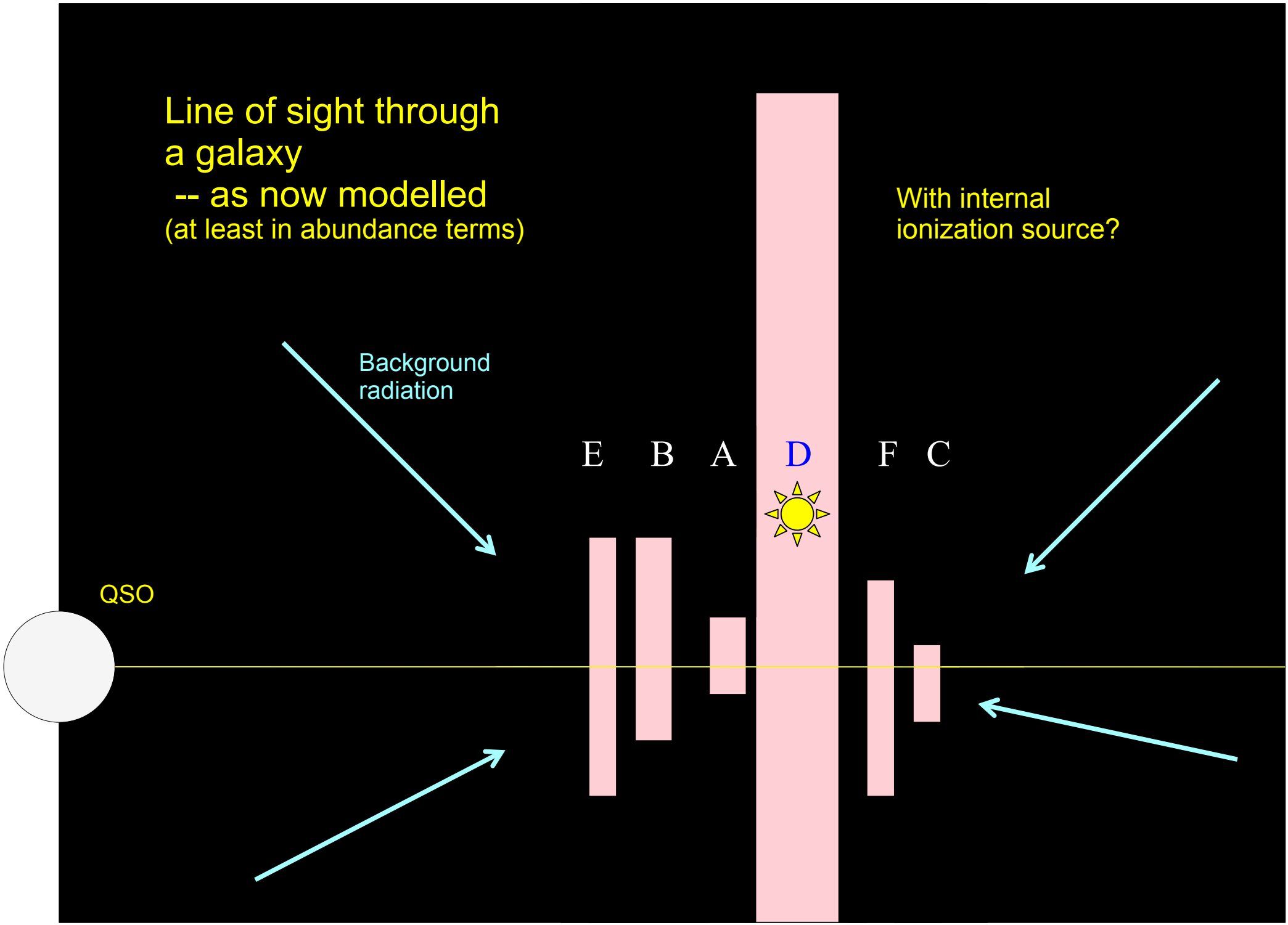
So a plausible [but not unique!] order, taking account of the HI columns for each component, is E B (A D) F C where A & D are left in brackets because the best fits have similar obscuration.

Two possibilities:

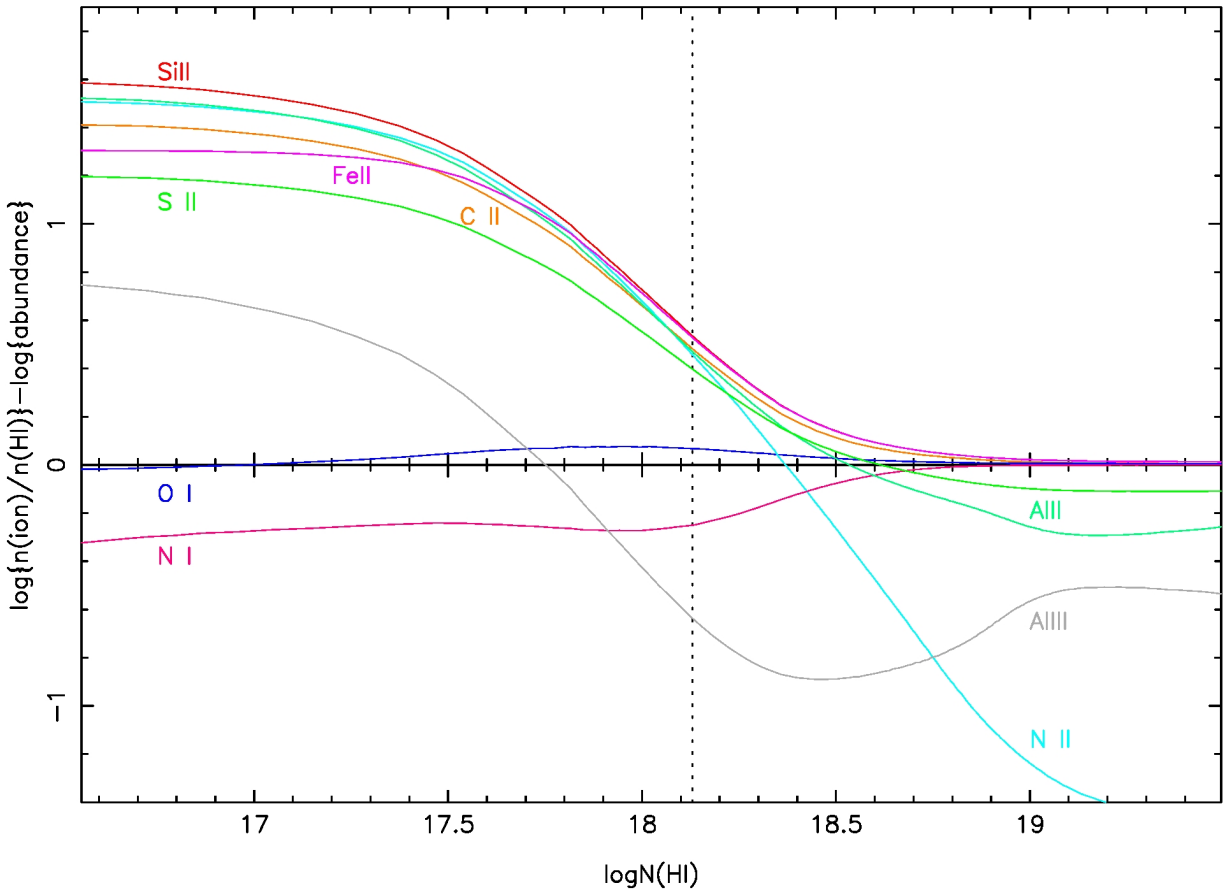
Live with a poorer fit for one of A or D – in which case better overall if order is EBDAFC $\Sigma<\chi 2>=95.1$

or

Invoke a local source of ionization in D (as the one with most HI), and then EBADFC better. A 4.10^{40} erg/s starburst 10kpc off to the side is enough. $\Sigma<\chi 2>=77.2$


Line of sight through
a galaxy
-- as now modelled
(at least in abundance terms)
With internal
ionization source?
Background
radiation
E
B
A
D
F
C
QSO

Match OI/SiII, AlII/AlIII & NI/NII as far as possible to get attenuation of starburst for D.



When you've done all this, find:

Component	log n_H	[O/H]	N/O	Al/O	logN(HI)
E	-0.43	-1.01	*	-0.15	15.75
B	-0.23	-1.46	-0.63	-0.24	18.86
A	-0.39	-1.16	-0.55	-0.02	18.80
D	unknown	-0.65	-1.15	-0.17	19.19
F	-1.29	-1.61	-0.38	0.72	16.65
C	-0.64	-1.50	-0.69	-0.05	17.87
HI average	?	-0.73	-0.80	-0.14	
mass average	?	-0.95	-0.72	-0.16	
Fitting total	-0.34	-0.94	-0.85	-0.19	19.48

When you've done all this, find:

Component	log n_H	[O/H]	N/O	Al/O	logN(HI)
E	-0.43	-1.01	*	-0.15	15.75
B	-0.23	-1.46	-0.63	-0.24	18.86
A	-0.39	-1.16	-0.55	-0.02	18.80
D	unknown	-0.65	-1.15	-0.17	19.19
F	-1.29	-1.61	-0.38	0.72	16.65
C	-0.64	-1.50	-0.69	-0.05	17.87
HI average	?	-0.73	-0.80	-0.14	
mass average	?	-0.95	-0.72	-0.16	
Fitting total	-0.34	-0.94	-0.85	-0.19	19.48

So, unsurprisingly:
Metallicities [O/H] range from -1.6 to -0.6 log relative to solar
Dominant component D has highest metallicity
Mass average very close to estimate from treating all as one system

Odd elements (N & Al) have different underabundances. Really?
NI/NII lower than models, AlII/AlIII higher: spectral shape problem?

Having come up with a prescription for separating regions of a carefully chosen QSO absorber to establish the abundance structure, we have found:

There is abundance structure, ranging over ~ a factor 10 (not surprising)

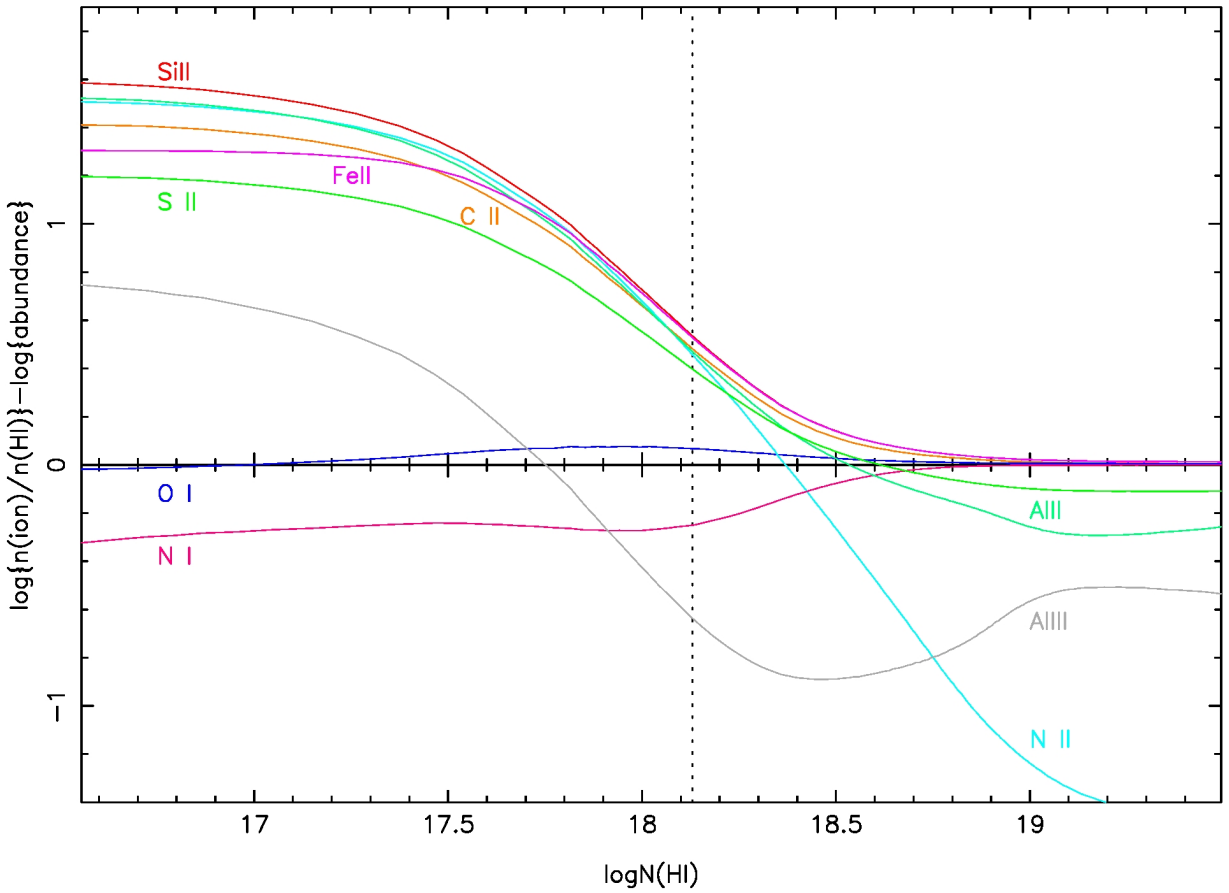
The average abundance overall is close to that which we obtained by the simplest possible model fitting (so we need not have bothered)

A local source of ionization is preferred for one of the components, the one with the most HI (which is not a surprising place to put it)

OI/HI good estimator O/H for starburst ionization (widely known), not for AGN ionized (sometimes ignored). Other metals less reliable.

The odd number elements are odd i.e strange. Al/N is quite large.
(lines optically thin, and hard to escape this conclusion. So how can it happen? I don't know, but there is a Mg-Al-Si cycle analogous to the C-N-O cycle for taking H -> He in some stars, so maybe?)

And finally:



For log N(HI) < 19.5 or so there is the possibility that ionizing sources off the sightline will give overabundances of e.g. Si, Fe (and others, like Zn) by anything up to a factor 10 in extreme cases. This may have been noted, and misinterpreted, already. OI/HI ~ O/H everywhere.

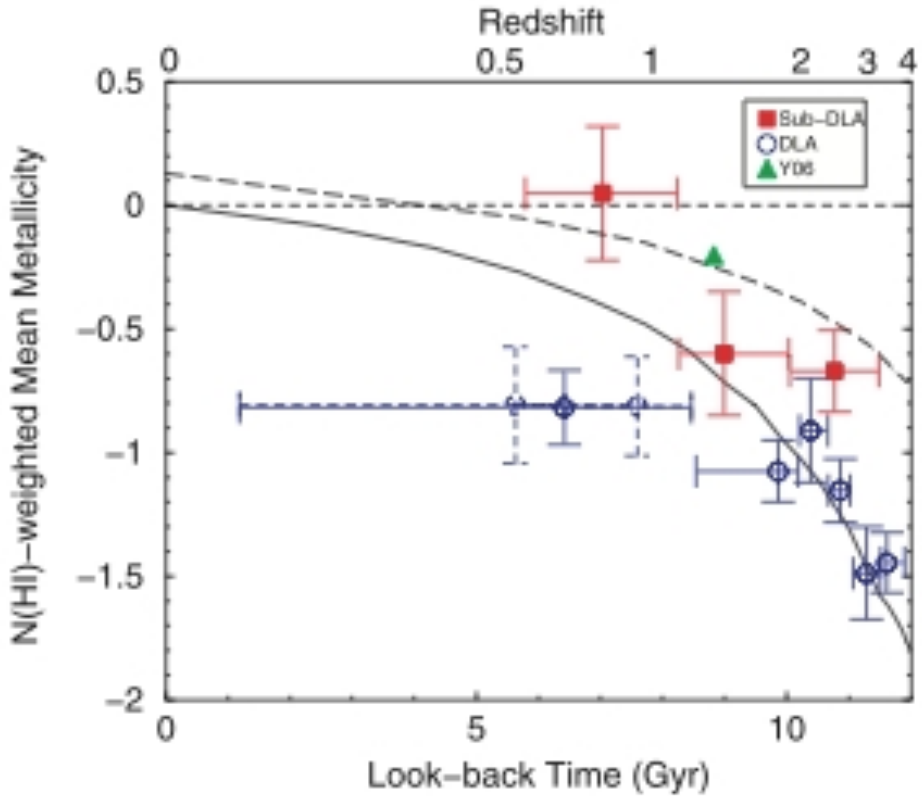


FIG. 1.—Logarithmic $N_{H\,I}$-weighted mean Zn metallicity plotted vs. look-back time for DLAs and sub-DLAs. Dashed circles refer to the lowest time bin split into two bins with 10 DLAs each. The triangle denotes the formal lower limit to the average [Zn/ H] for a composite spectrum from 698 absorbers with average log $N_{H\,I} \sim 20$ (sample 24) from York et al. (2006). The solid and long-dashed curves show, respectively, the mean metallicities in the chemical evolution models of Pei et al. (1999) and Somerville et al. (2001).

Sub-DLAs have lower HI column densities along sightline, an so probably in other directions, so possibility of local ionization from off-sightline sources might be higher.