Was $\alpha = e^2/\hbar c$ different at high redshift?

DESY 2004

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Why our particular values of the constants?

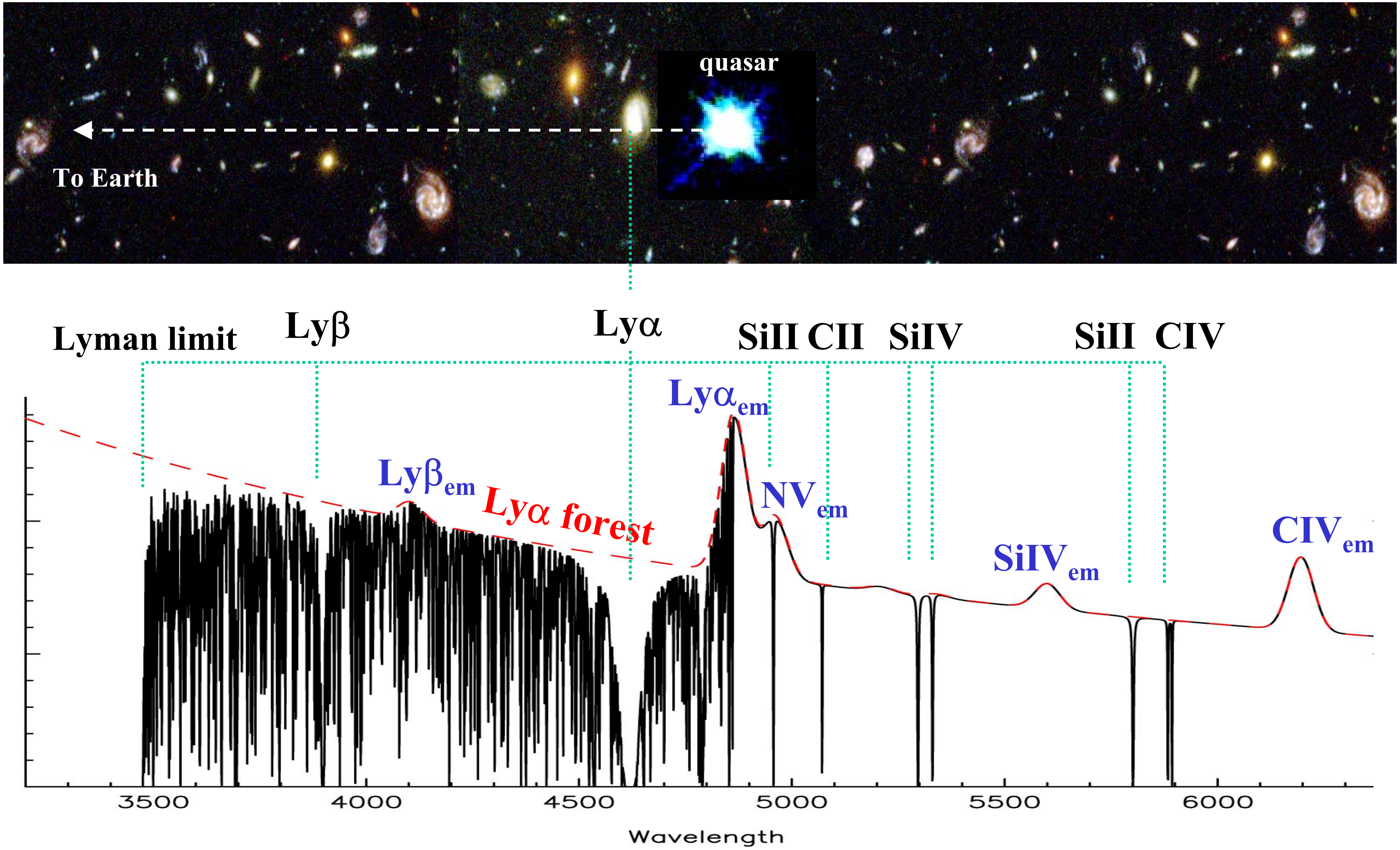
- **History:** Milne, Dirac : 1937. The first to ask “Do the constants of Nature vary?”

- **“Fine tuning”:** Our existence owes itself to the “fortuitous” values of the fundamental parameters of physics and cosmology; $\alpha = 1/137$, $m_n - m_p = 1.3$ MeV , expansion rate, $\Lambda = \ldots$

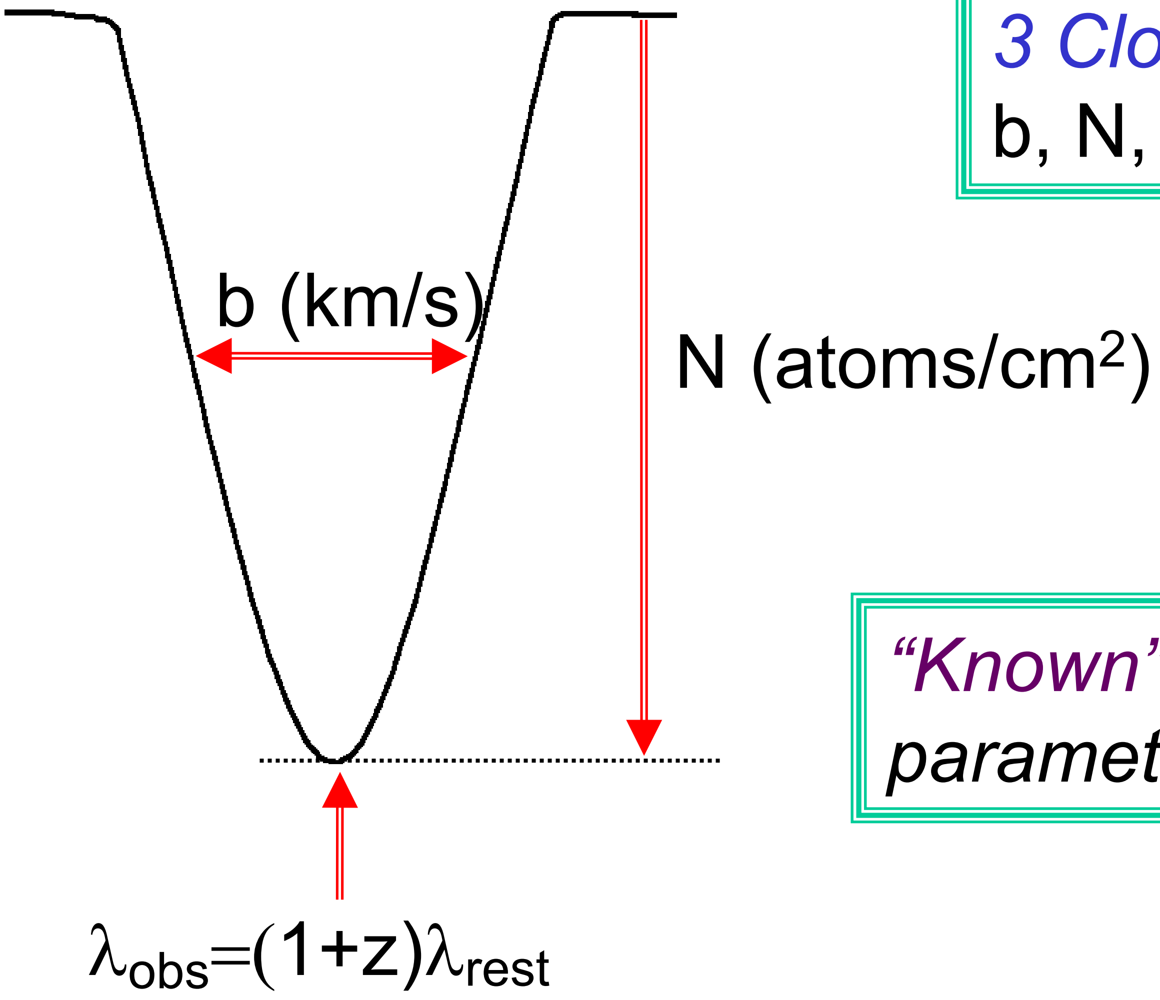
- **Anthropic principle:** But, we *are* here, so we should not be surprised that physics appears to be “fine-tuned” for our existence

- **Recent motivation:** Theories of unification of gravity and other interactions, higher dimensional theories, etc. Lengthy review by Uzan ’02.

Quasars: physics laboratories in the early universe



Parameters describing ONE absorption line



b (km/s)

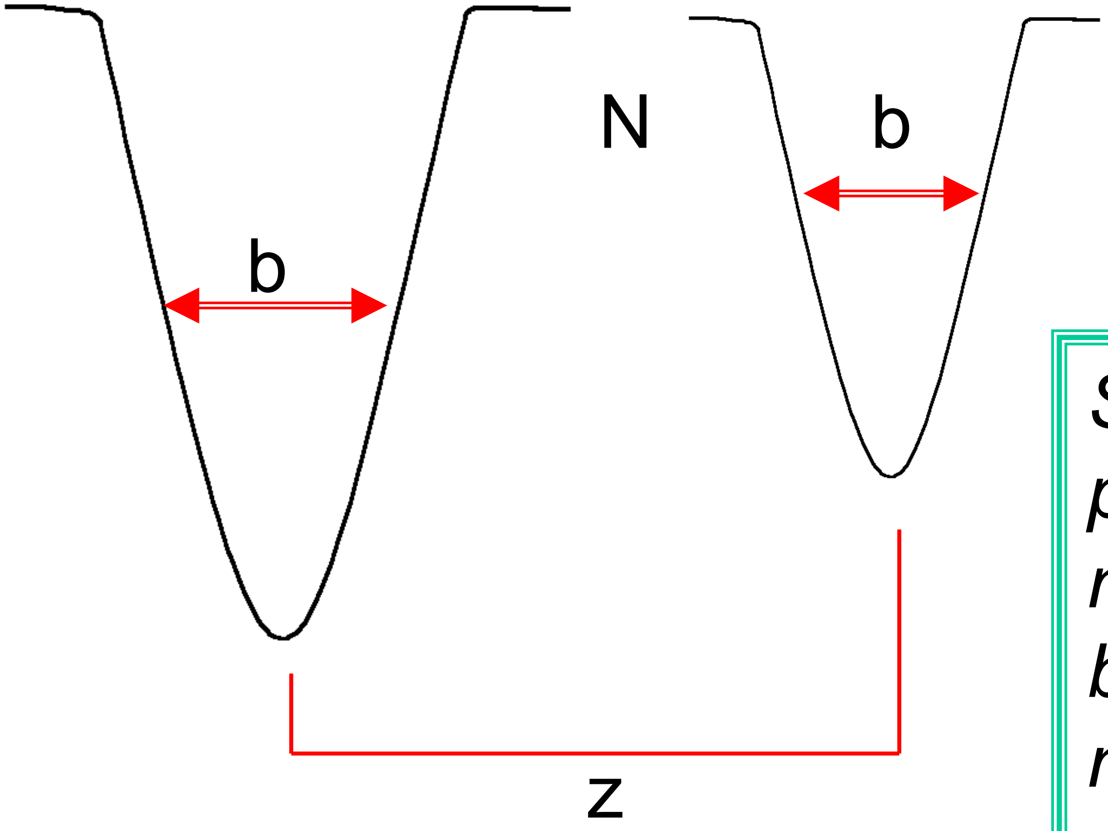
N (atoms/cm^2)

$\lambda_{obs} = (1+z)\lambda_{rest}$

3 Cloud parameters:
b, N, z

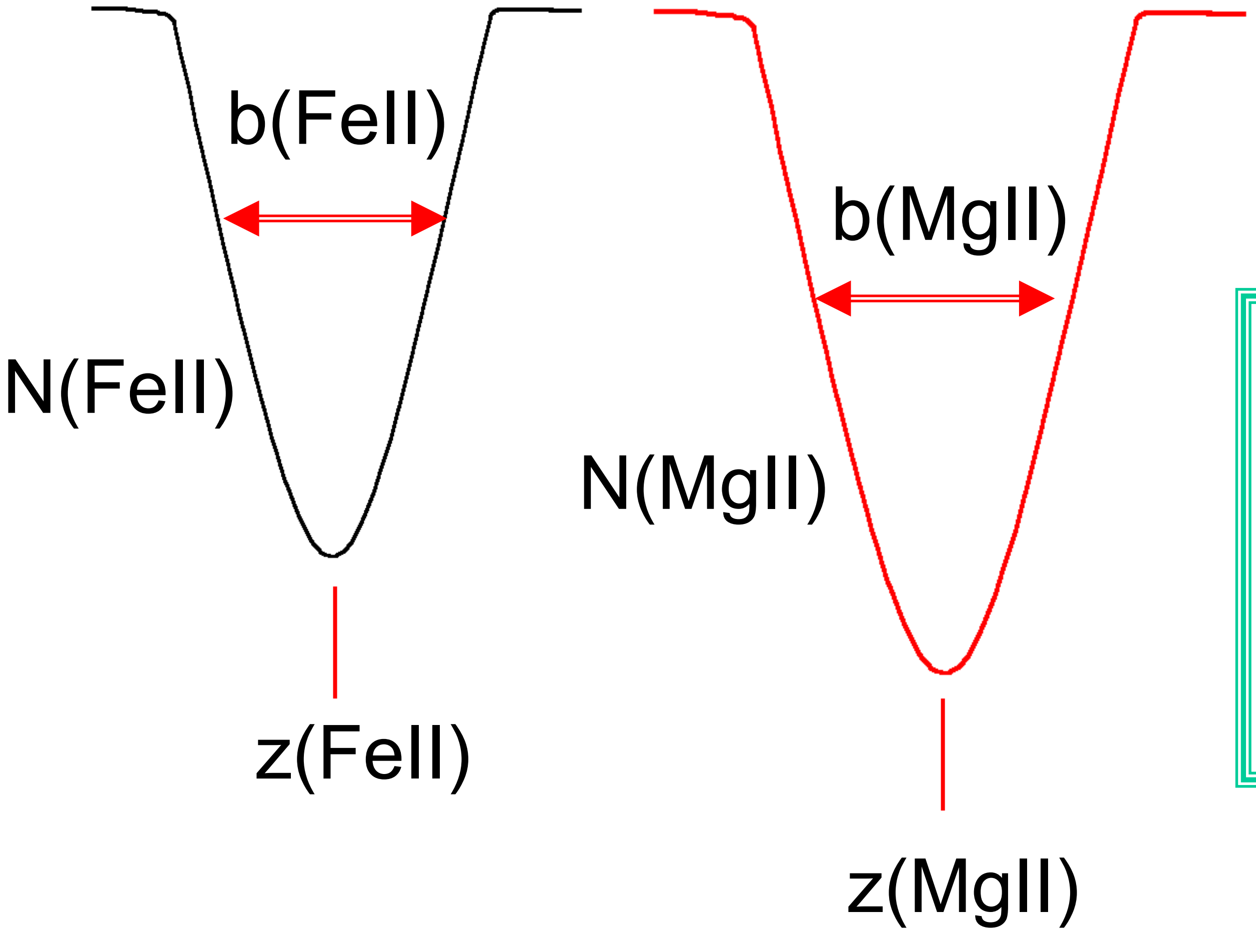
"Known" physics parameters: λ_{rest}, f, Γ, α_{EM}…

Cloud parameters describing TWO (or more) absorption lines from the same species (eg. MgII 2796 + MgII 2803 A)



Still 3 cloud parameters (with no assumptions), but now there are more physics parameters

Cloud parameters describing TWO absorption lines from *different* species (eg. MgII 2796 + FeII 2383 A)



i.e. a maximum of 6 cloud parameters, without any assumptions

However…

$$b^2_{\mathrm{observed}} = \mathbf{b}^2_{\mathbf{thermal}} + \mathbf{b}^2_{\mathbf{bulk}} = \frac{2\mathbf{kT}}{\mathbf{m}} + \mathbf{constant}$$

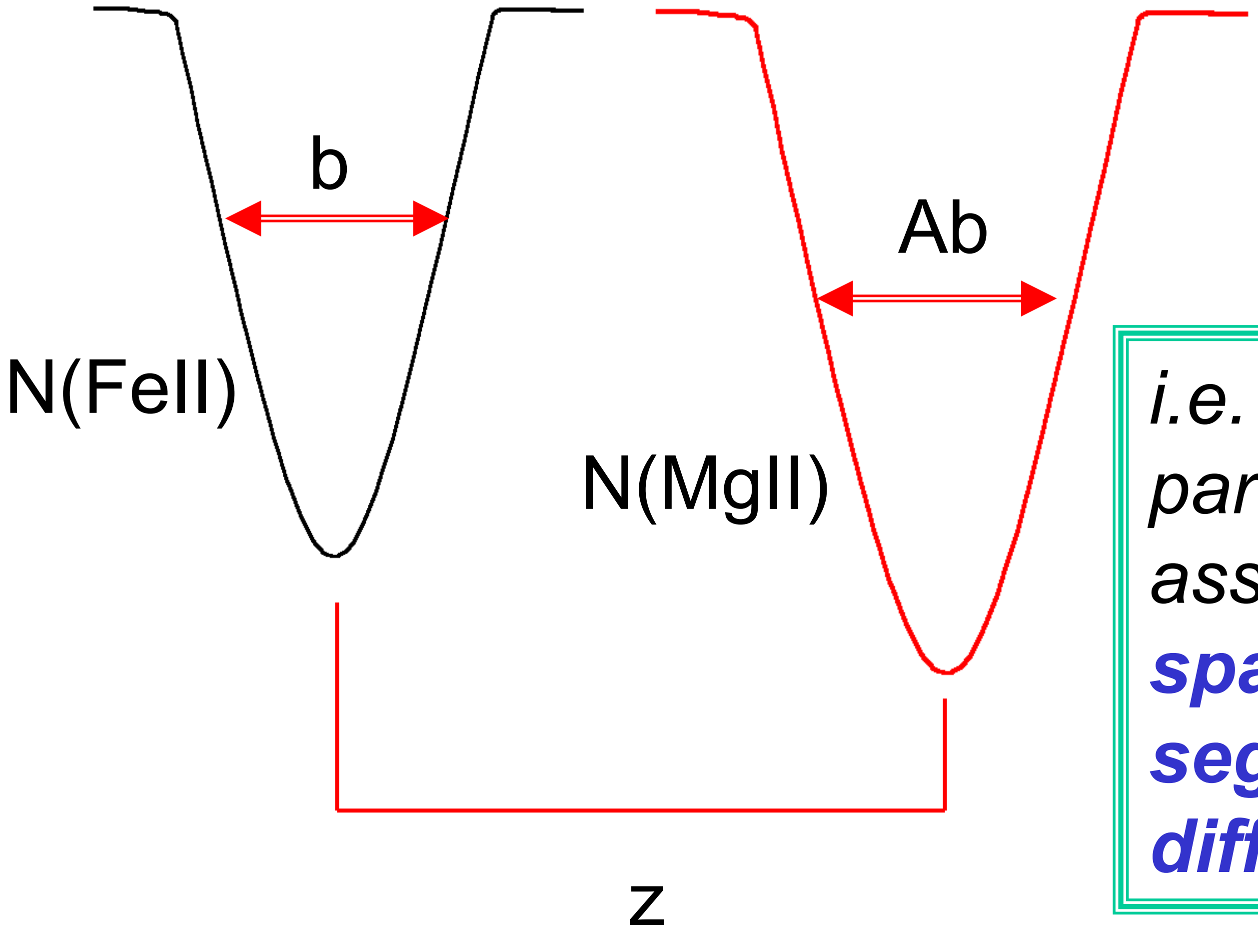
T is the cloud temperature, m is the atomic mass

So we understand the relation between (eg.) b(MgII) and b(FeII). The extremes are:

A: totally thermal broadening, bulk motions negligible, $\mathbf{b(MgII)} = \sqrt{\frac{\mathbf{m(Fe)}}{\mathbf{m(Mg)}}}\left(\mathbf{b(FeII)}\right) = \mathbf{Kb(FeII)}$

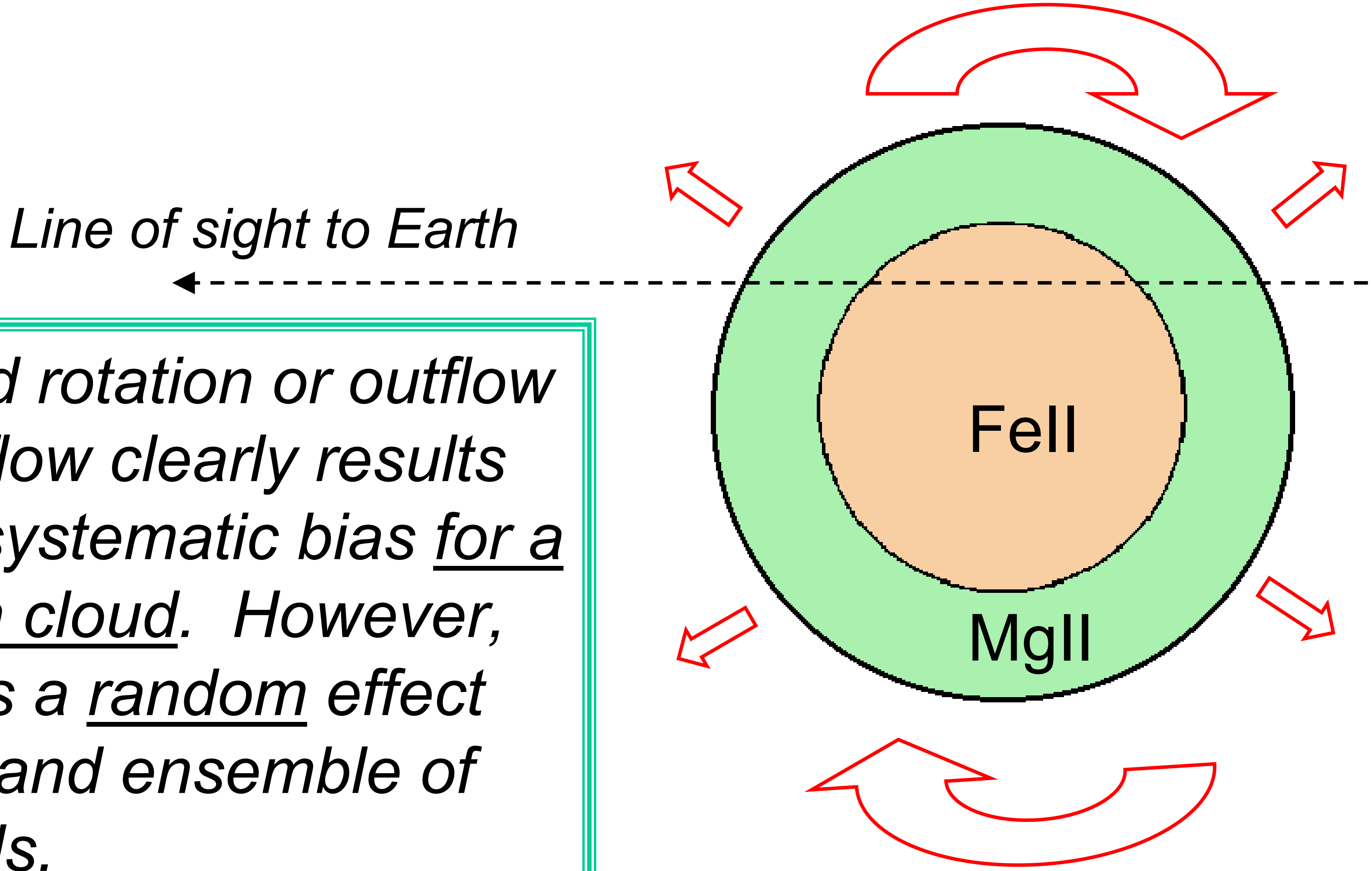
B: thermal broadening negligible compared to bulk motions, $\mathbf{b(MgII)} = \mathbf{b(FeII)}$

We can therefore reduce the number of cloud parameters describing TWO absorption lines from *different* species:



i.e. 4 cloud parameters, with assumptions: ***no spatial or velocity segregation for different species***

How reasonable is the previous assumption?

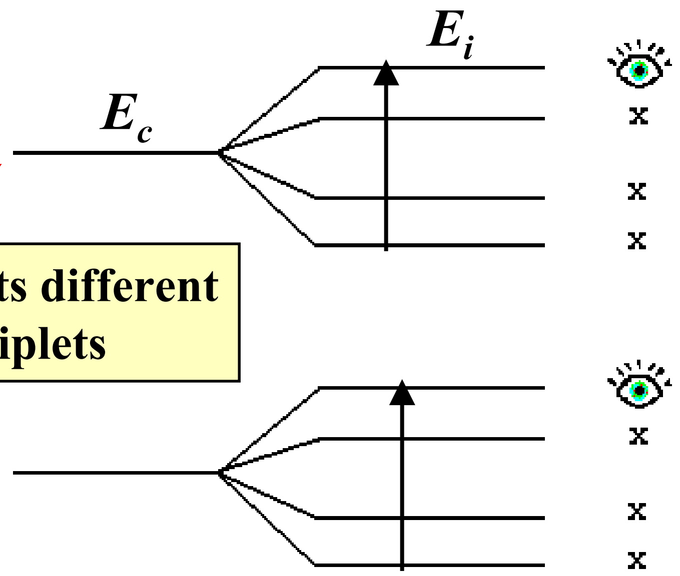


Cloud rotation or outflow or inflow clearly results in a systematic bias for a given cloud. However, this is a random effect over and ensemble of clouds.

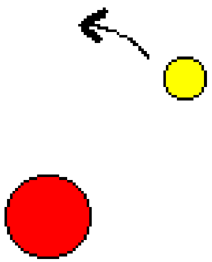
The reduction in the number of free parameters introduces no bias in the results

The “Many-Multiplet method” (Webb et al. PRL, 82, 884, 1999; Dzuba et al. PRL, 82, 888, 1999) - use different multiplets simultaneously - order of magnitude improvement

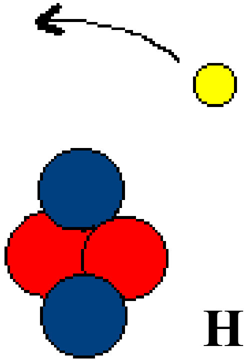
In addition to alkali-like doublets, many other more complex species are seen in quasar spectra. Note we now measure relative to *different* ground states



Represents different FeII multiplets



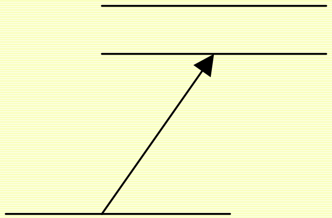
Low mass nucleus
Electron feels small potential and moves slowly: small relativistic correction



High mass nucleus
Electron feels large potential and moves quickly: large relativistic correction

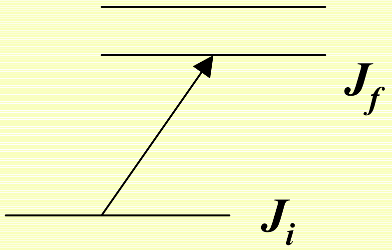
Advantages of the Many Multiplet method

1. **Includes the total relativistic shift of frequencies (e.g. for s-electron) i.e. it includes relativistic shift in the ground state**



(Spin-orbit method: splitting in excited state - relativistic correction is smaller, since excited electron is far from the nucleus)

2. **Can include many lines in many multiplets**



(Spin-orbit method: comparison of 2-3 lines of 1 multiplet due to selection rule for E1 $|J_i - J_f| \leq 1$ transitions - cannot explore the full multiplet splitting)

3. **Very large statistics - all ions and atoms, different frequencies, different redshifts (epochs/distances)**
4. **Opposite signs of relativistic shifts helps to cancel some systematics.**

Parameterisation:

$$w_z = w_{z=0} + q\left[\left(\frac{\alpha_z}{\alpha_0}\right)^2 - 1\right]$$

This term non-zero only if α has changed. Small errors in q won't emulate varying α

Observed rest-frame frequency

Laboratory frequency (must be known very precisely)

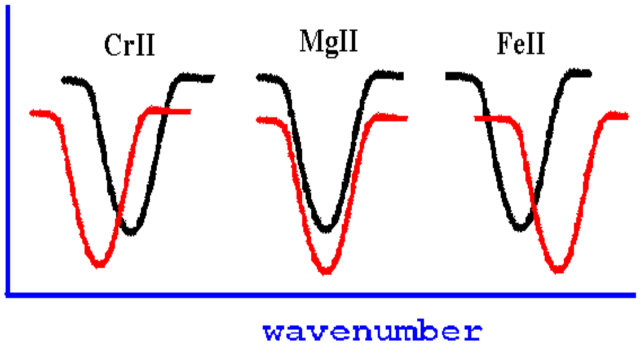
Calculated using many-body relativistic Hartree-Fock method

$$q = Q + K(L.S)$$

Relativistic shift of the multiplet configuration centre

K is the spin-orbit splitting parameter. Q ~ 10K

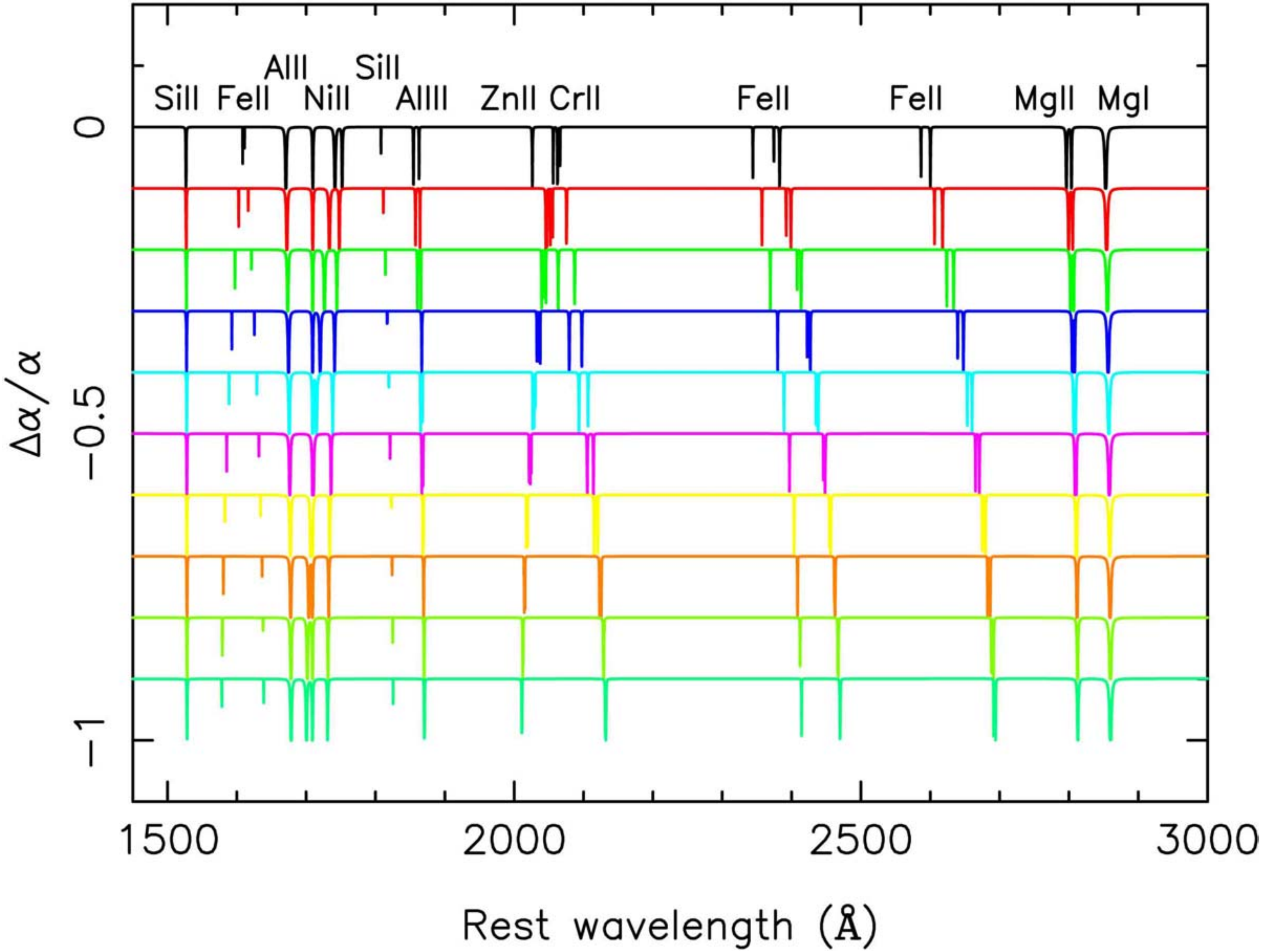
Shifts vary in size and magnitude →



Wavelength precision and q values

Ion	$\frac{\lambda_0}{\text{Å}}$	$\frac{\omega_0}{\text{cm}^{-1}}$	Ground state	Upper state	ID	$\frac{\text{IP}}{\text{eV}}$	f	$\frac{q_1}{\text{cm}^{-1}}$	$\frac{q_2}{\text{cm}^{-1}}$
Mg I	2852.96310(8)	35051.277(1)^b	$3s^2\ ^1\text{S}_0$	$3s3p\ ^1\text{P}_1$	a	—	1.810^f	106	-10
Mg II	2796.3543(2)	35760.848(2)^b	$3s\ ^2\text{S}_{1/2}$	$3p\ ^2\text{P}_{3/2}$	b	7.7	0.6295^g	211	0
	2803.5315(2)	35669.298(2)^b		$3p\ ^2\text{P}_{1/2}$	c		0.3083^g	120	0
Al II	1670.7887(1)	59851.972(4)^c	$3s^2\ ^1\text{S}_0$	$3s3p\ ^1\text{P}_1$	d	6.0	1.88^f	270	0
Al III	1854.71841(3)	53916.540(1)^c	$3s\ ^2\text{S}_{1/2}$	$3p\ ^2\text{P}_{3/2}$	e	18.9	0.268^f	464	0
	1862.79126(7)	53682.880(2)^c		$3p\ ^2\text{P}_{1/2}$	f		0.539^f	216	0
Si II	1526.70709(2)	65500.4492(7)^c	$3s^23p\ ^2\text{P}^o_{1/2}$	$3s^24s\ ^2\text{S}_{1/2}$	g	8.2	0.116^h	24	22
	1808.01301(1)	55309.3365(4)^c		$3s3p^2\ ^2\text{D}_{3/2}$	h		0.00218^f	525	3
Cr II	2056.25693(8)	48632.055(2)^d	$3d^5\ ^6\text{S}_{5/2}$	$3d^44p\ ^6\text{P}_{7/2}$	i	6.8	0.105^i	-1030	-13
	2062.23610(8)	48491.053(2)^d		$3d^44p\ ^6\text{P}_{5/2}$	j		0.078^i	-1168	-16
	2066.16403(8)	48398.868(2)^d		$3d^44p\ ^6\text{P}_{3/2}$	k		0.0515^i	-1267	-9
Fe II	1608.45085(8)	62171.625(3)^e	$3d^64s\ z^6\text{D}_{9/2}$	$3d^64p\ y^6\text{P}_{7/2}$	l	7.9	0.0619^j	1002	141
	1611.20034(8)	62065.528(3)^e		$3d^64p\ y^4\text{F}_{7/2}$	m		0.00102^j	1110	48
	2344.2130(1)	42658.2404(2)^e		$3d^64p\ z^6\text{P}_{7/2}$	n		0.110^j	1325	47
	2374.4603(1)	42114.8329(2)^e		$3d^64p\ z^4\text{F}_{9/2}$	o		0.0326^j	1730	26
	2382.7642(1)	41968.0642(2)^e		$3d^64p\ z^6\text{F}_{11/2}$	p		0.300^j	1580	29
	2586.6496(1)	38660.0494(2)^e		$3d^64p\ z^6\text{D}^o_{7/2}$	q		0.0684^j	1687	-36
	2600.1725(1)	38458.9871(2)^e		$3d^64p\ ^4\text{D}_{9/2}$	r		0.213^j	1449	2
Ni II	1709.6042(1)	58493.071(4)^d	$3d^9\ ^2\text{D}_{5/2}$	$3d^84p\ z^2\text{F}_{5/2}$	s	7.6	0.0348^k	800	0
	1741.5531(1)	57420.013(4)^d		$3d^84p\ z^2\text{D}_{5/2}$	t		0.0419^k	-700	0
	1751.9157(1)	57080.373(4)^d		$3d^84p\ z^2\text{F}_{7/2}$	u		0.0264^k	-300	0
Zn II	2026.13709(8)	49355.002(2)^d	$3d^{10}4s\ ^2\text{S}_{1/2}$	$3d^{10}4p\ ^2\text{P}_{3/2}$	v	9.4	0.489^i	2291	94
	2062.66045(9)	48481.077(2)^d		$3d^{10}4p\ ^2\text{P}_{3/2}$	w		0.256^i	1445	66

Highly exaggerated illustration of how transitions shift in different directions by different amounts – unique pattern



Numerical procedure:

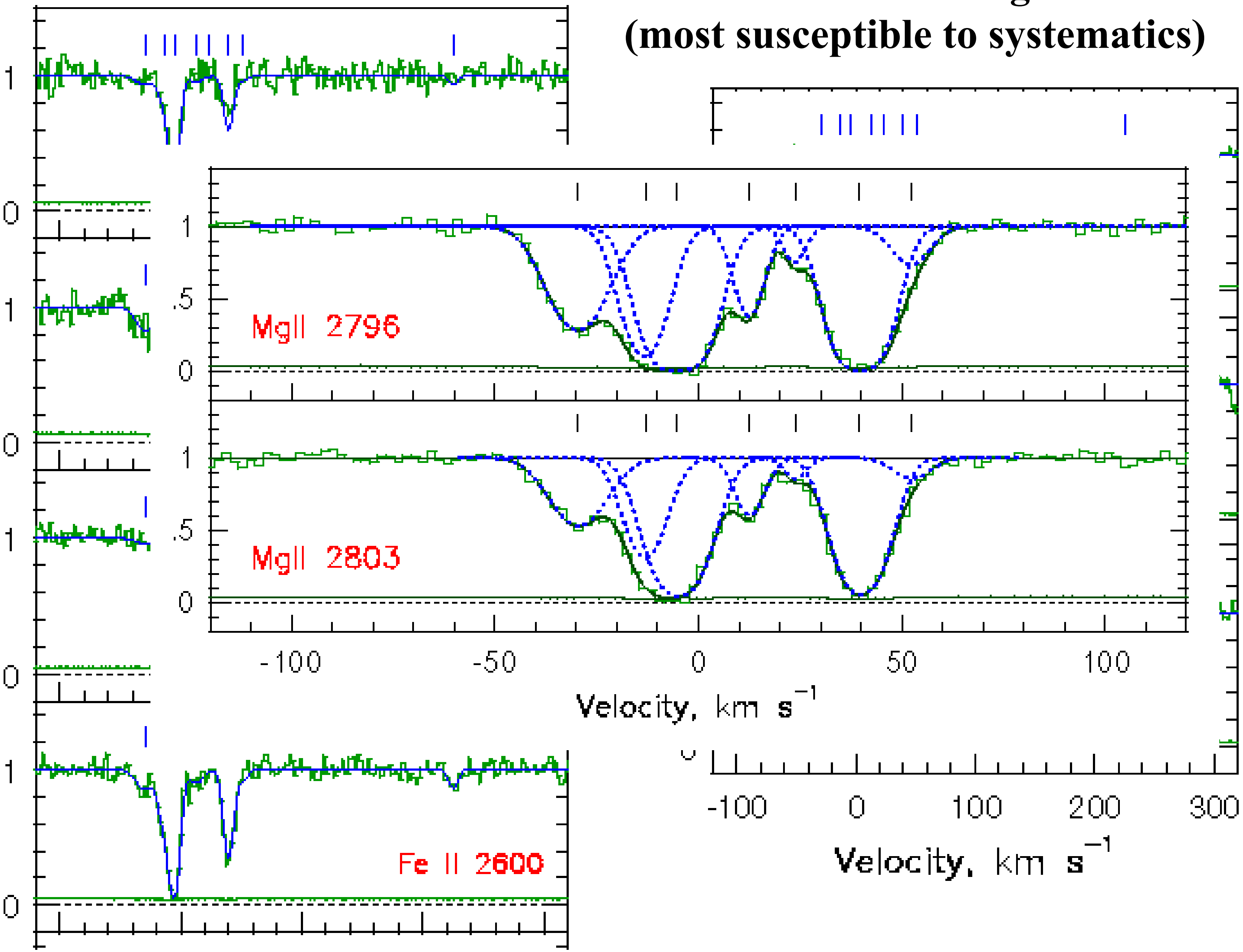
- *Use minimum no. of free parameters to fit the data*

- *Unconstrained optimisation (Gauss-Newton) non-linear least-squares method (modified version of VPFIT, $\Delta\alpha/\alpha$ explicitly included as a free parameter);*

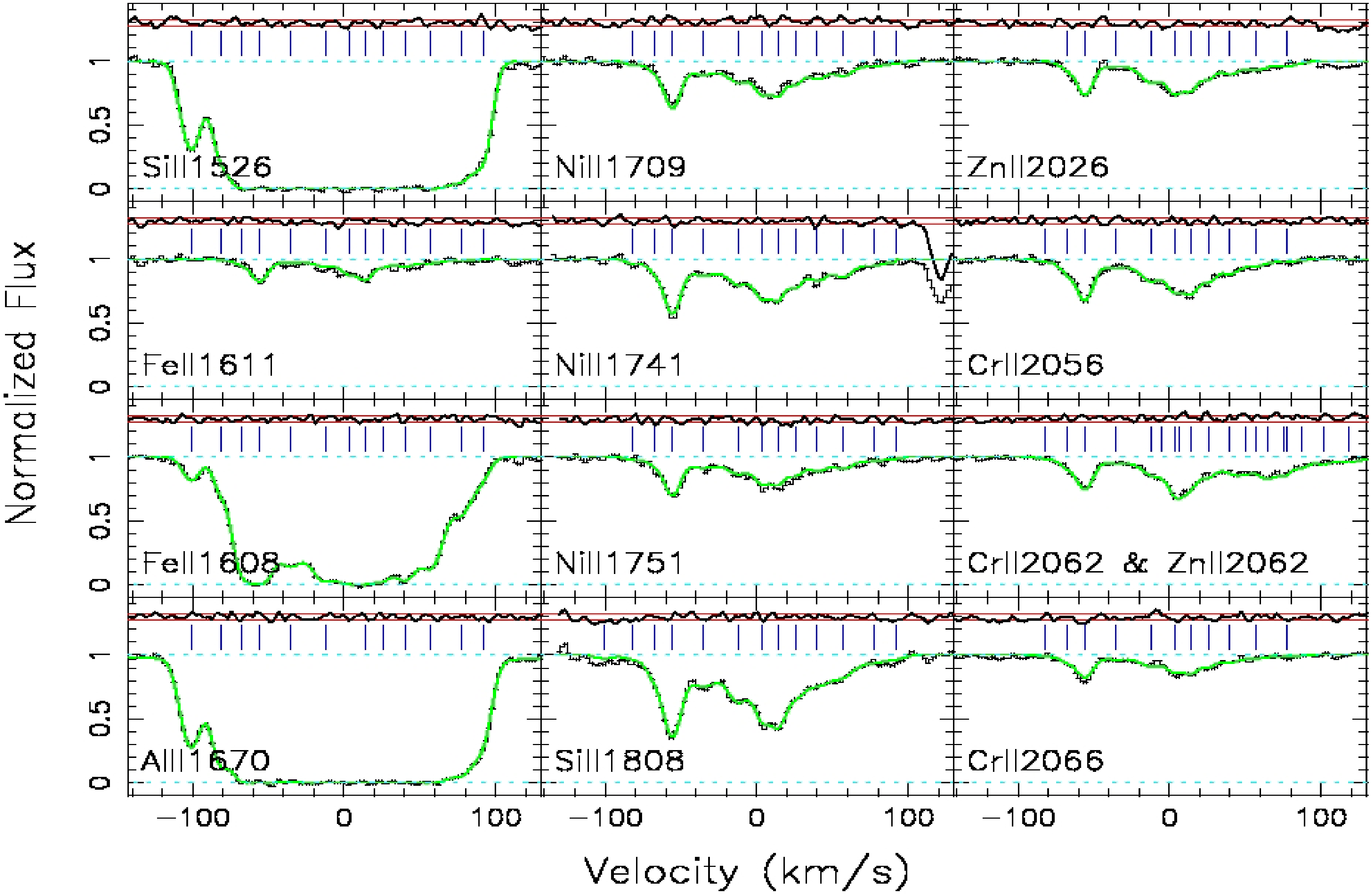
- *Uses 1st and 2nd derivates of χ^2 with respect to each free parameter (→ natural weighting for estimating $\Delta\alpha/\alpha$);*

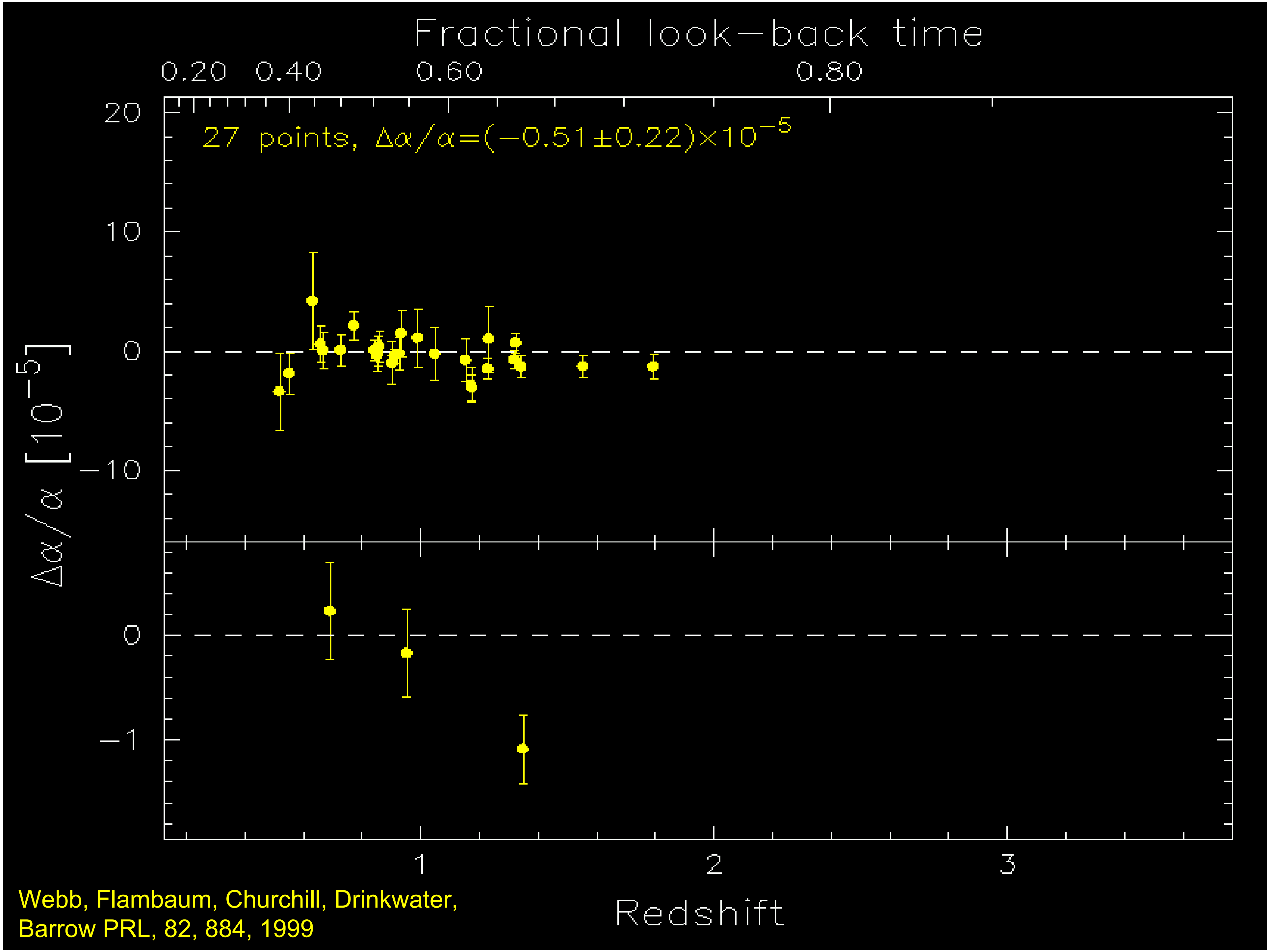
- *All parameter errors (including those for $\Delta\alpha/\alpha$ derived from diagonal terms of covariance matrix (assumes uncorrelated variables but Monte Carlo verifies this works well)*

Low redshift data: **MgII and FeII**
(most susceptible to systematics)

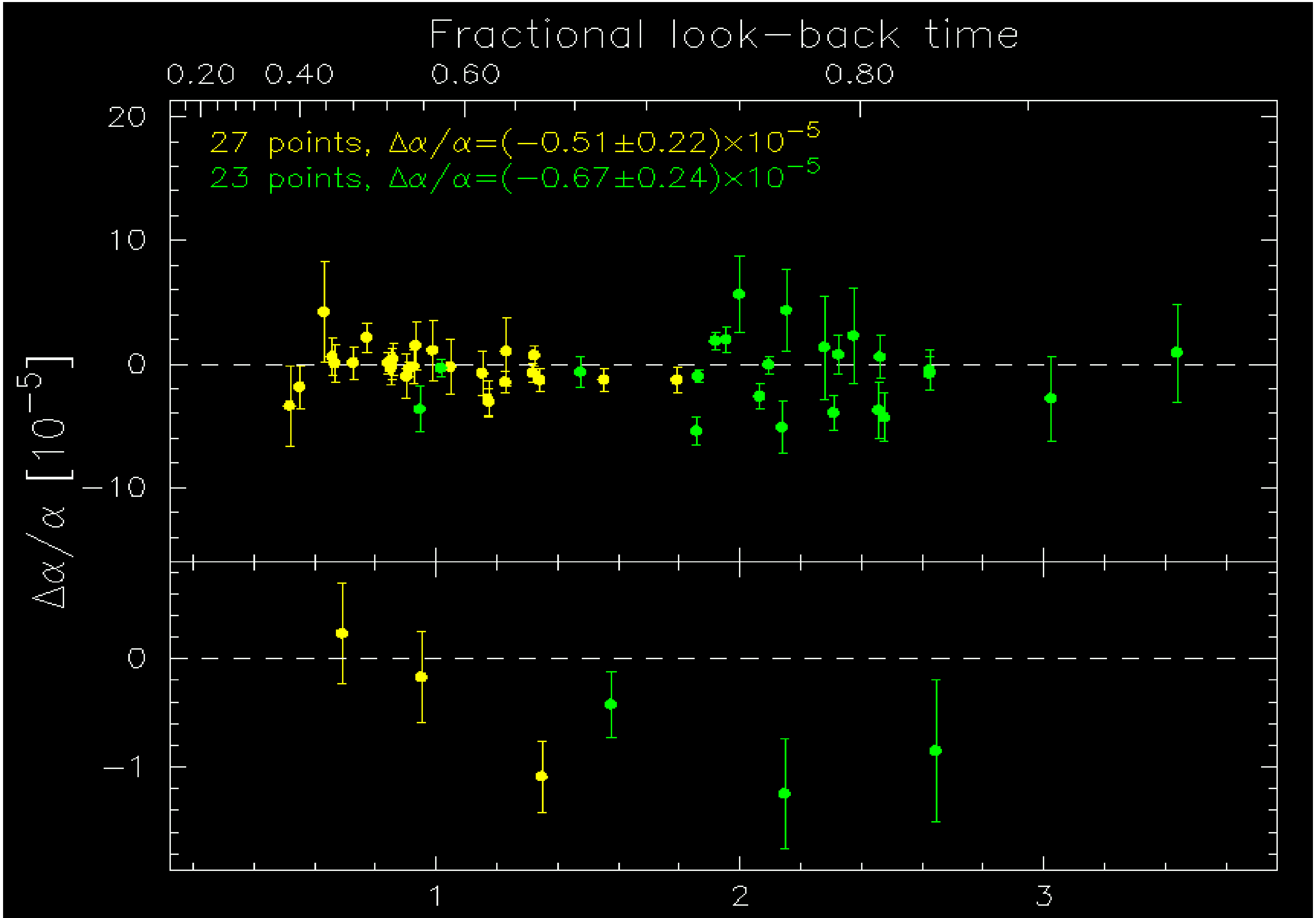


High-z damped Lyman-α systems:

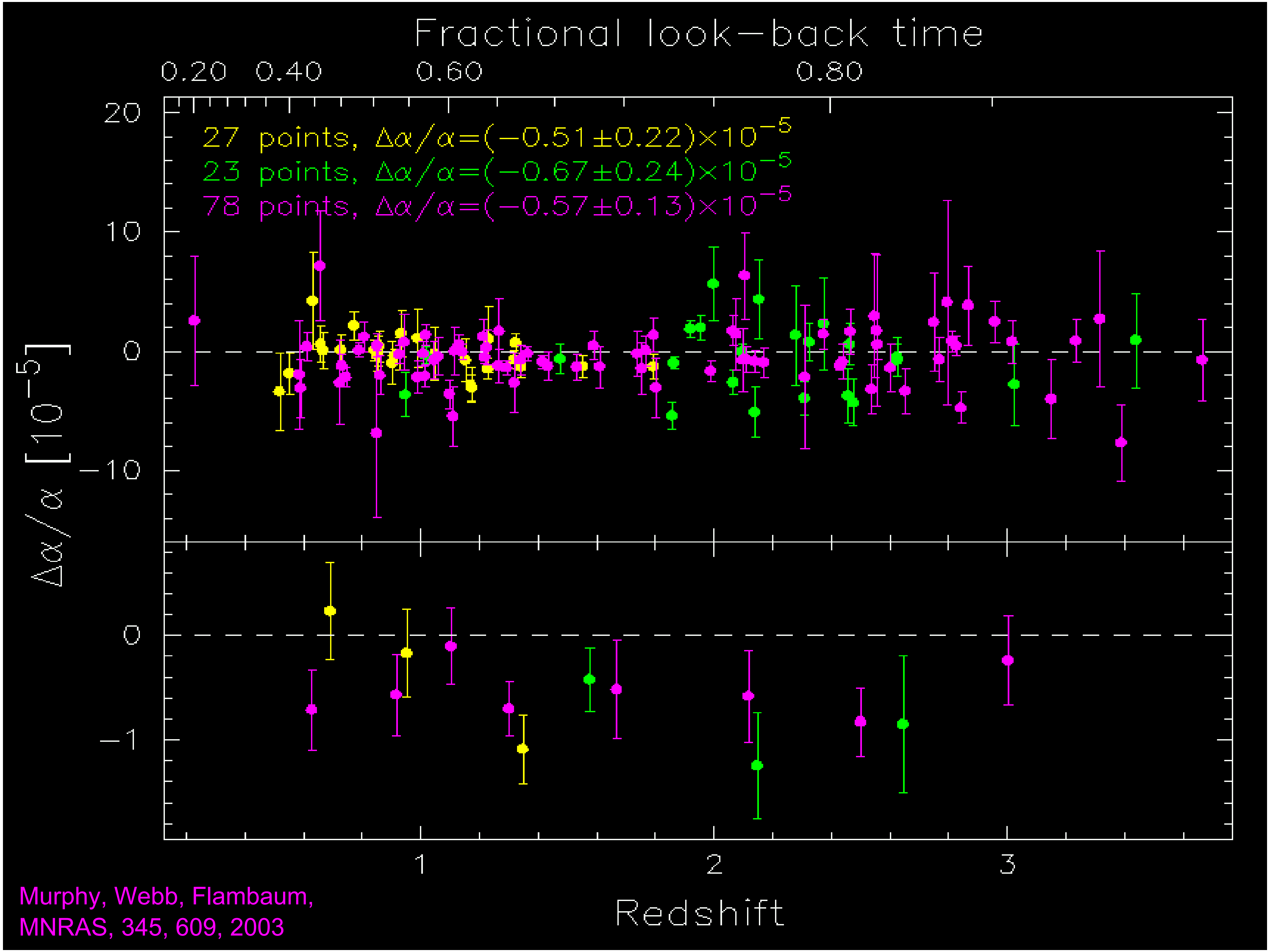




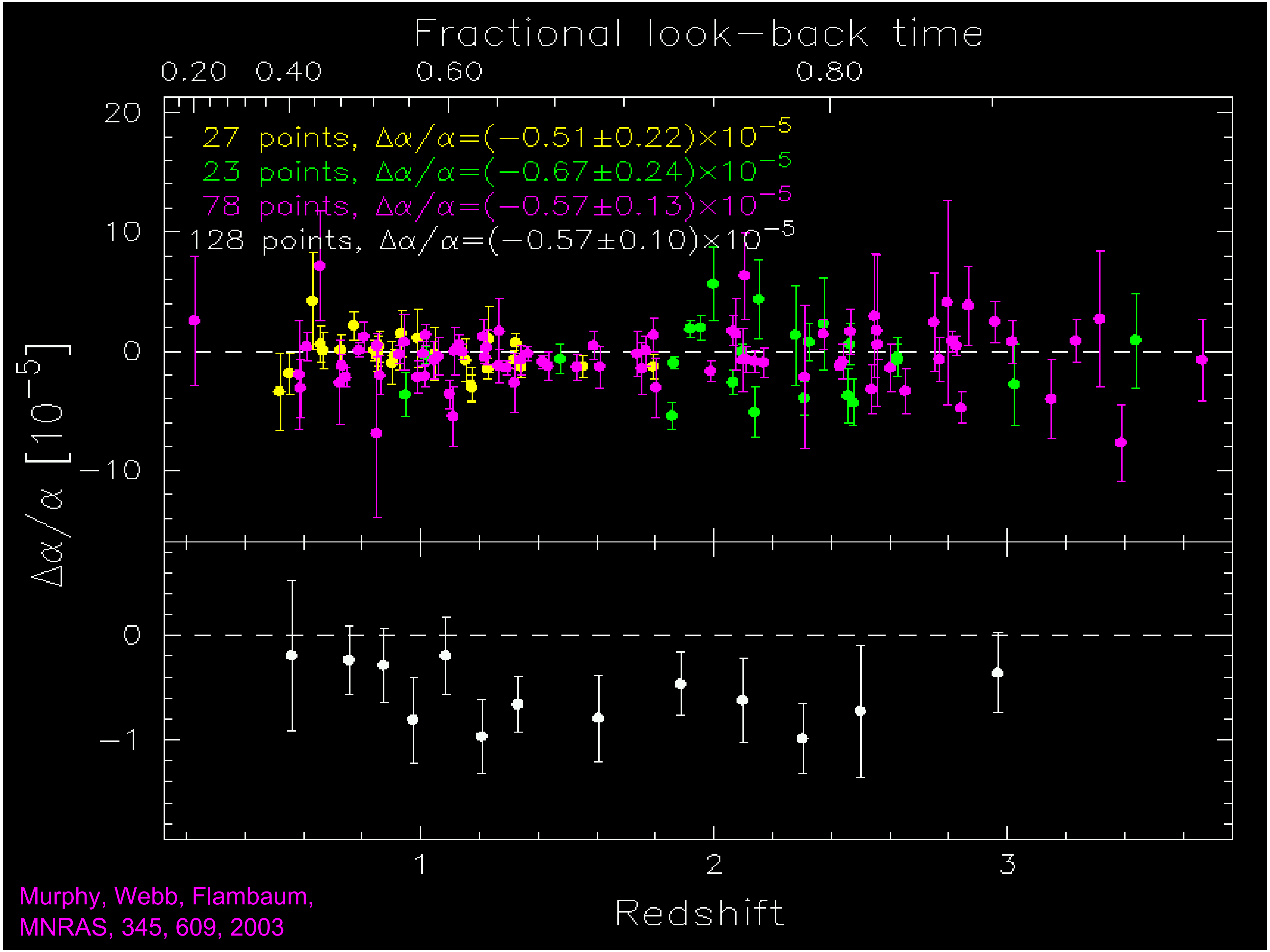
Webb, Flambaum, Churchill, Drinkwater,
Barrow PRL, 82, 884, 1999



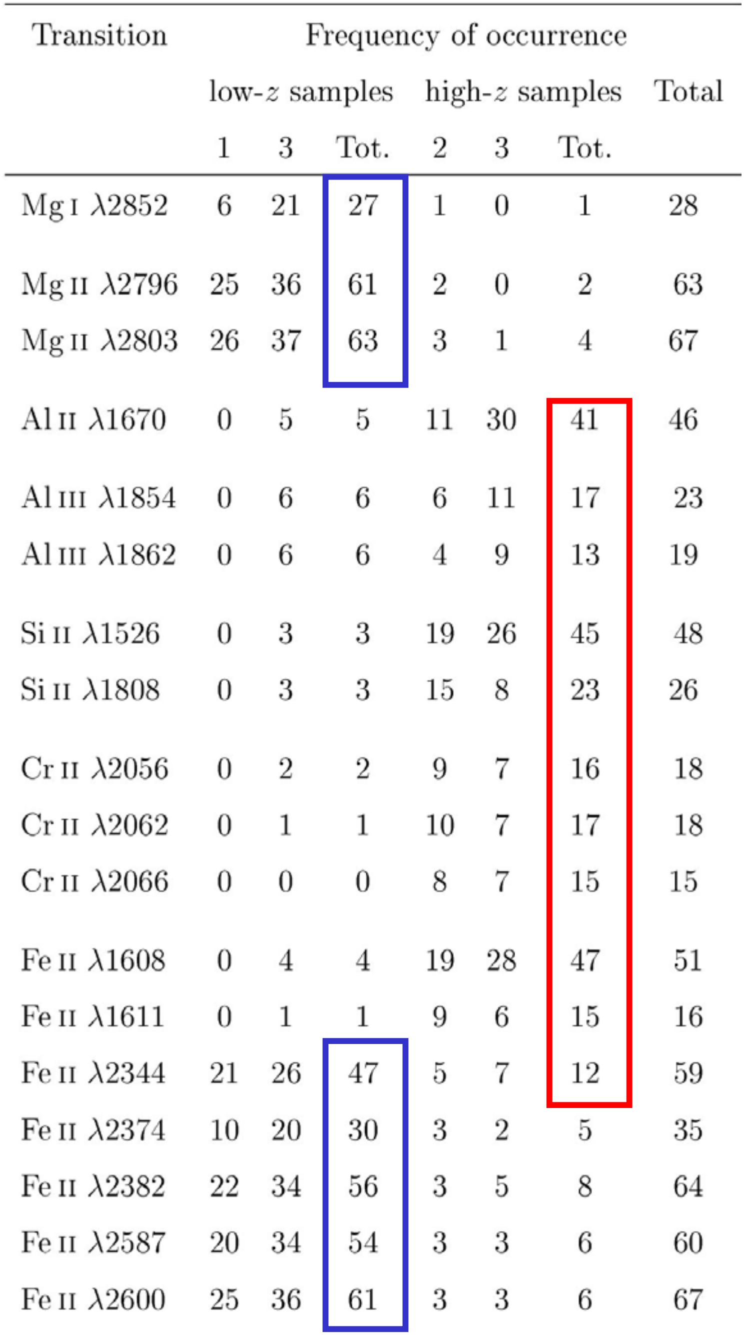
Webb, Murphy, Flambaum, Dzuba, Barrow, Churchill, Prochaska, Wolfe. PRL, 87, 091301-1, 2001



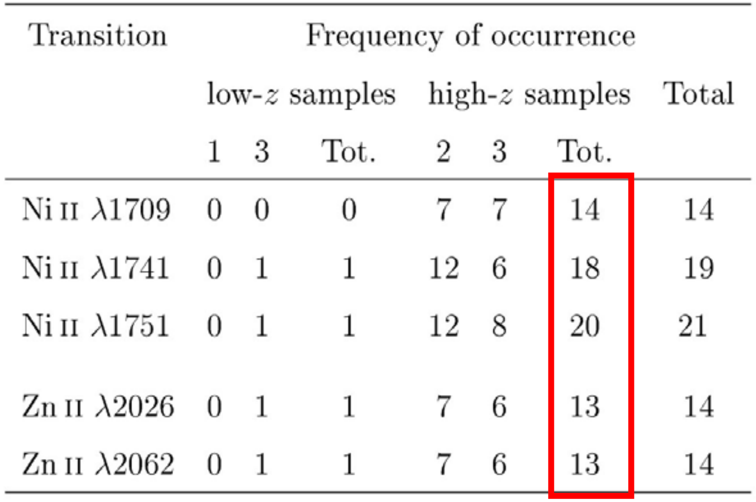
Murphy, Webb, Flambaum,
MNRAS, 345, 609, 2003



Murphy, Webb, Flambaum,
MNRAS, 345, 609, 2003



Transition	Frequency of occurrence						
	low-z samples			high-z samples			Total
	1	3	Tot.	2	3	Tot.	
Mg I $\lambda2852$	6	21	27	1	0	1	28
Mg II $\lambda2796$	25	36	61	2	0	2	63
Mg II $\lambda2803$	26	37	63	3	1	4	67
Al II $\lambda1670$	0	5	5	11	30	41	46
Al III $\lambda1854$	0	6	6	6	11	17	23
Al III $\lambda1862$	0	6	6	4	9	13	19
Si II $\lambda1526$	0	3	3	19	26	45	48
Si II $\lambda1808$	0	3	3	15	8	23	26
Cr II $\lambda2056$	0	2	2	9	7	16	18
Cr II $\lambda2062$	0	1	1	10	7	17	18
Cr II $\lambda2066$	0	0	0	8	7	15	15
Fe II $\lambda1608$	0	4	4	19	28	47	51
Fe II $\lambda1611$	0	1	1	9	6	15	16
Fe II $\lambda2344$	21	26	47	5	7	12	59
Fe II $\lambda2374$	10	20	30	3	2	5	35
Fe II $\lambda2382$	22	34	56	3	5	8	64
Fe II $\lambda2587$	20	34	54	3	3	6	60
Fe II $\lambda2600$	25	36	61	3	3	6	67



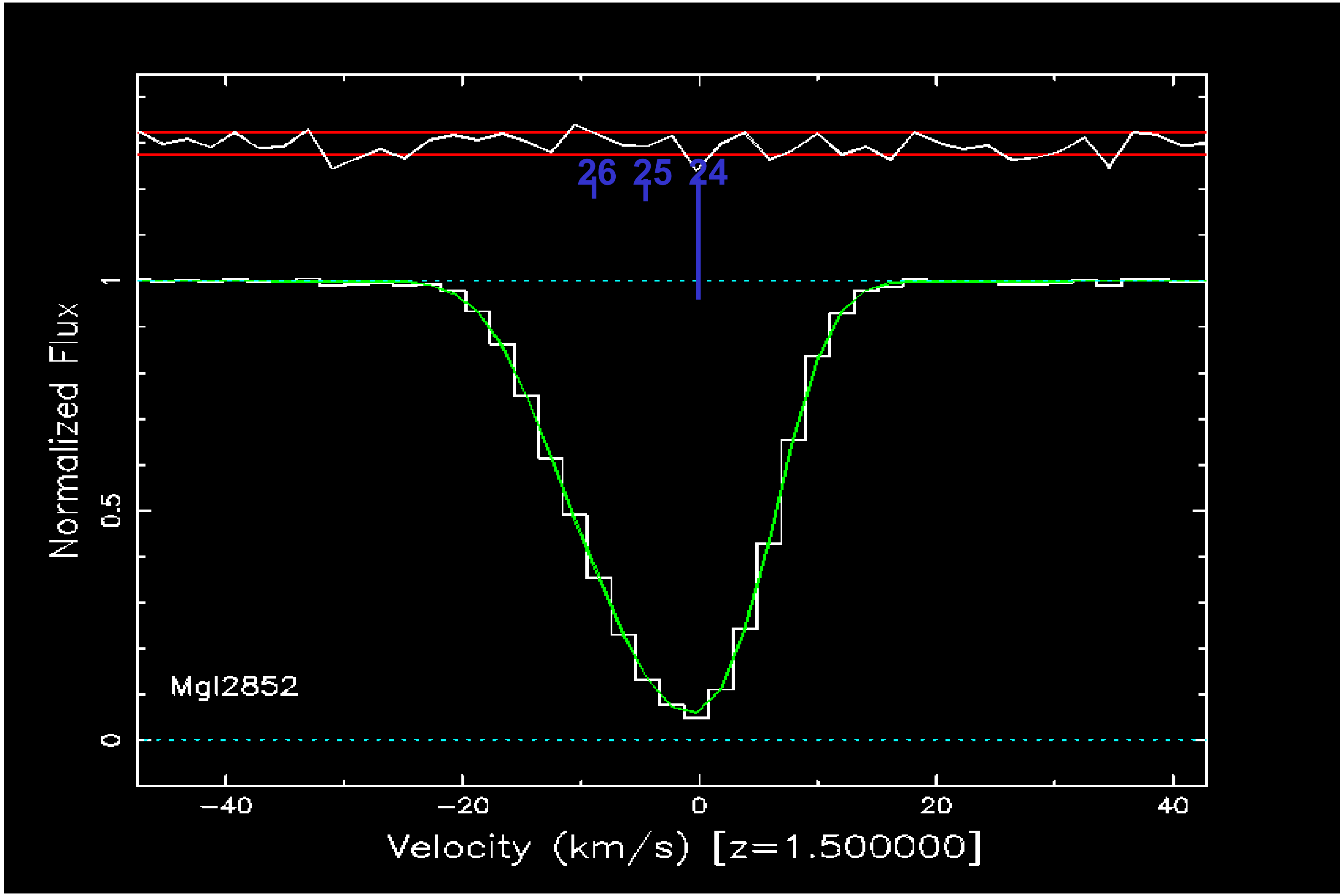
Transition	Frequency of occurrence						
	low-z samples			high-z samples			Total
	1	3	Tot.	2	3	Tot.	
Ni II $\lambda1709$	0	0	0	7	7	14	14
Ni II $\lambda1741$	0	1	1	12	6	18	19
Ni II $\lambda1751$	0	1	1	12	8	20	21
Zn II $\lambda2026$	0	1	1	7	6	13	14
Zn II $\lambda2062$	0	1	1	7	6	13	14

High and low redshift samples are more or less independent

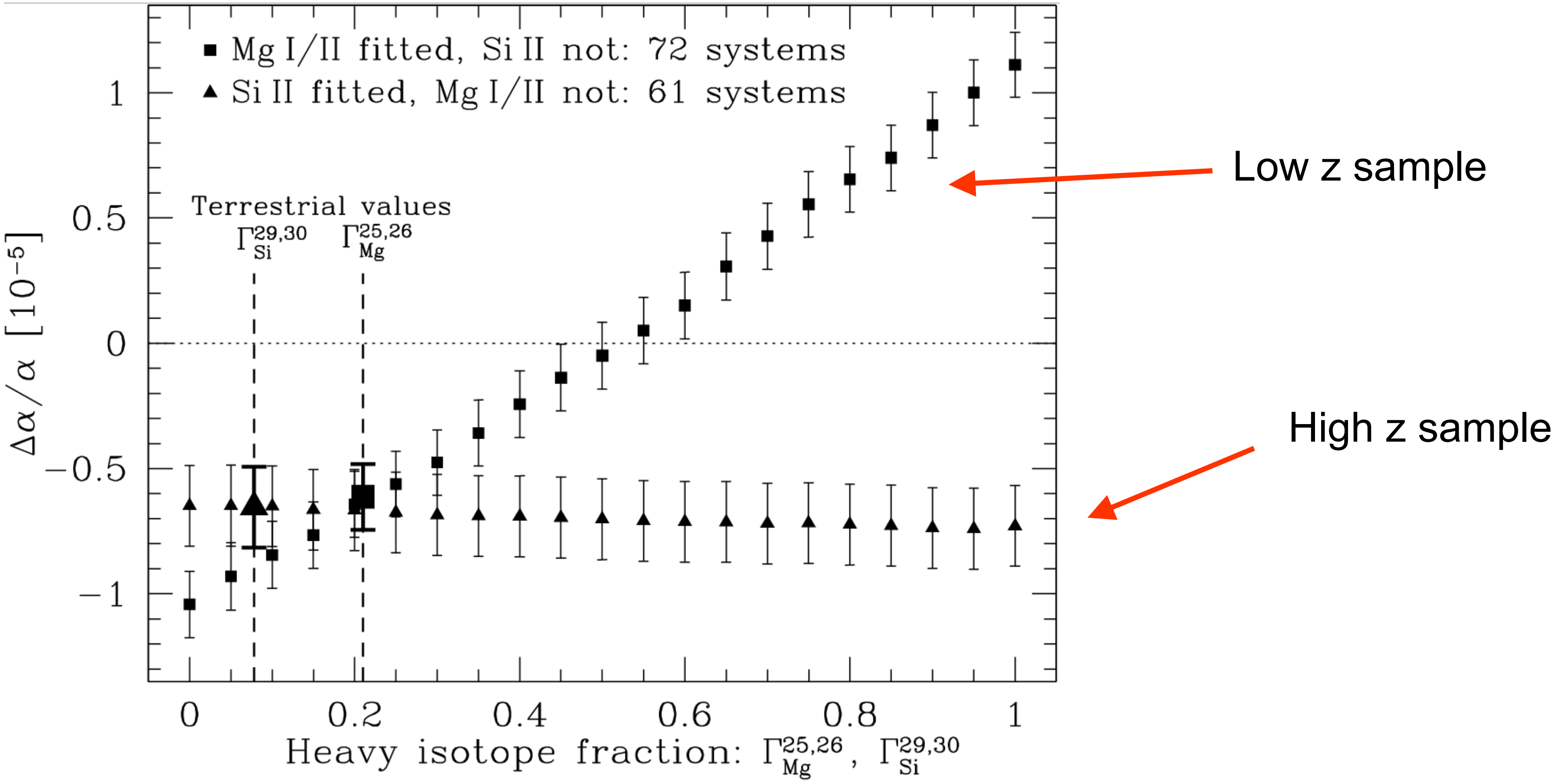
Potential systematic effects (Murphy et al. MNRAS, 2003)

- ☺ **Laboratory wavelength errors:** New mutually consistent laboratory spectra from Imperial College, Lund University and NIST
- ☺ **Data quality variations:** Can only produce systematic shifts if combined with laboratory wavelength errors
- ☺ **Heliocentric velocity variation:** Smearing in velocity space is degenerate with fitted redshift parameters
- ☺ **Hyperfine structure shifts:** same as for isotopic shifts
- ☺ **Magnetic fields:** Large scale fields could introduce correlations in $\Delta\alpha/\alpha$ for neighbouring QSO site lines (if QSO light is polarised) - extremely unlikely and huge fields required
- ☺ **Wavelength miscalibration:** mis-identification of ThAr lines or poor polynomial fits could lead to systematic miscalibration of wavelength scale
- ☺ **Pressure/temperature changes during observations:** Refractive index changes between ThAr and QSO exposures – random error
- ☺ **Line blending:** Are there ionic species in the clouds with transitions close to those we used to find $\Delta\alpha/\alpha$?
- ☺ **Instrumental profile variations:** Intrinsic IP variations along spectral direction of CCD?
- ☺ **“Isotope-saturation effect”** (for low mass species)
- ☹ **Isotopic ratio shifts:** Effect possible at low z if evolution of isotopic ratios allowed
- ☹ **Atmospheric dispersion effects:** Different angles through optics for blue and red light – can only produce positive $\Delta\alpha/\alpha$ at low redshift

Variation in isotopic abundances rather than variation of α_{EM}?



Simulations – vary $\Gamma=(^{25}\mathrm{Mg}+^{26}\mathrm{Mg})/^{24}\mathrm{Mg}$ and refit all the data:



Results:

If $\Gamma_z<\Gamma_T$ (consistent with Galactic chemical evolution, Timmes et al '95), $\Delta\alpha/\alpha$ would be more –ve. However, $\Gamma_z>\Gamma_T$ can emulate $\Delta\alpha/\alpha < 0$ (explained by an enhanced AGB star population, see Ashentfelter et al '04 for a detailed treatment). This remains a possible explanation (for the low redshift end only).

Consistency checks:

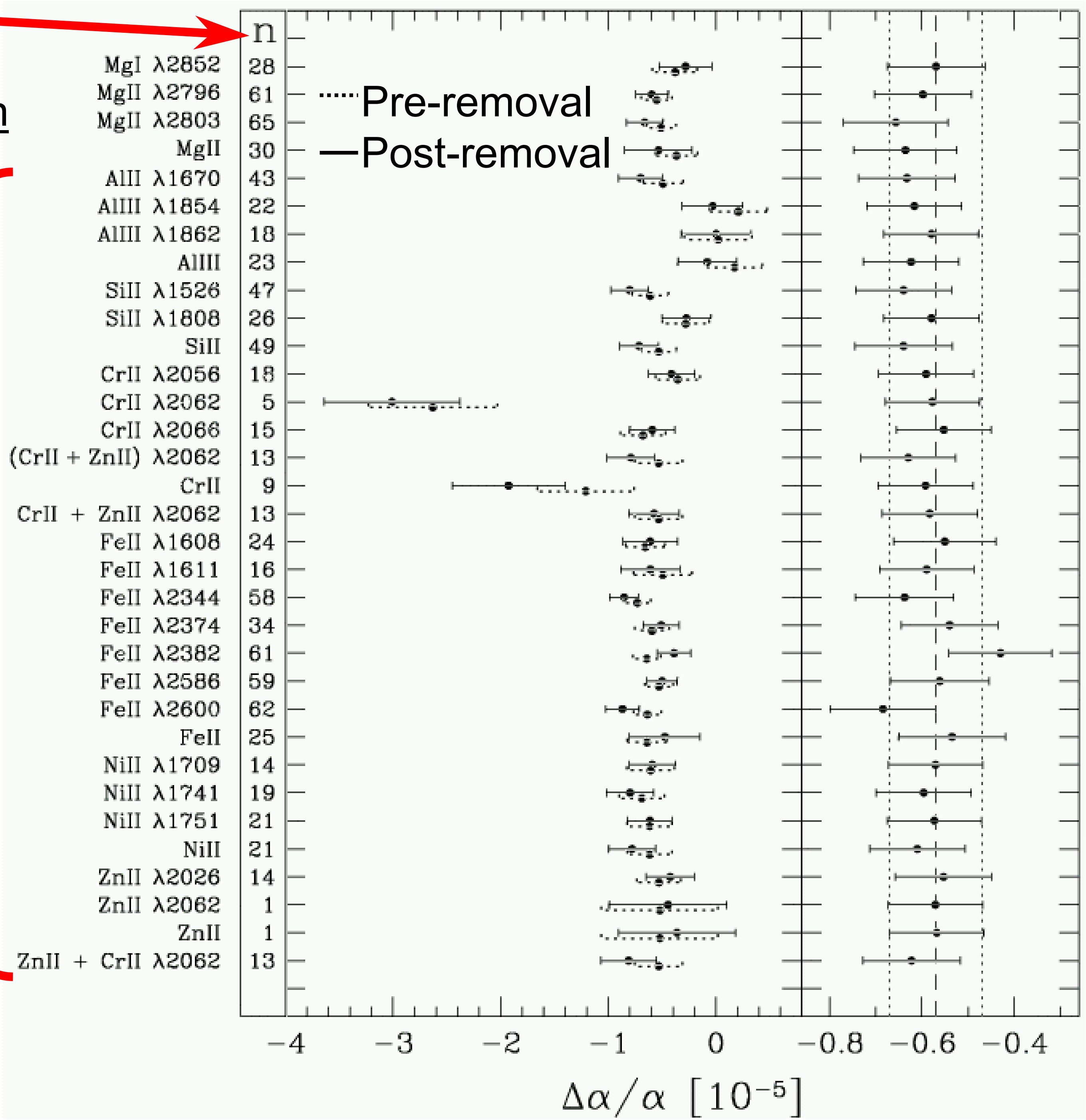
- **Line removal test:** remove each transition and fit for $\Delta\alpha/\alpha$ again. Compare the $\Delta\alpha/\alpha$'s before and after line removal. We have done this for all species and see no inconsistencies. **Tests for:** Lab wavelength errors, isotopic ratio and hyperfine structure variation.

- **"Shifter test":** For a given $\Delta\alpha/\alpha$, a species can shift (a) very little (*an anchor*), (b) to lower wavelengths (*a negative-shifter*), (c) to higher wavelengths (*a positive-shifter*).

- Procedure: remove each *type* of line collectively and recalculate $\Delta\alpha/\alpha$.

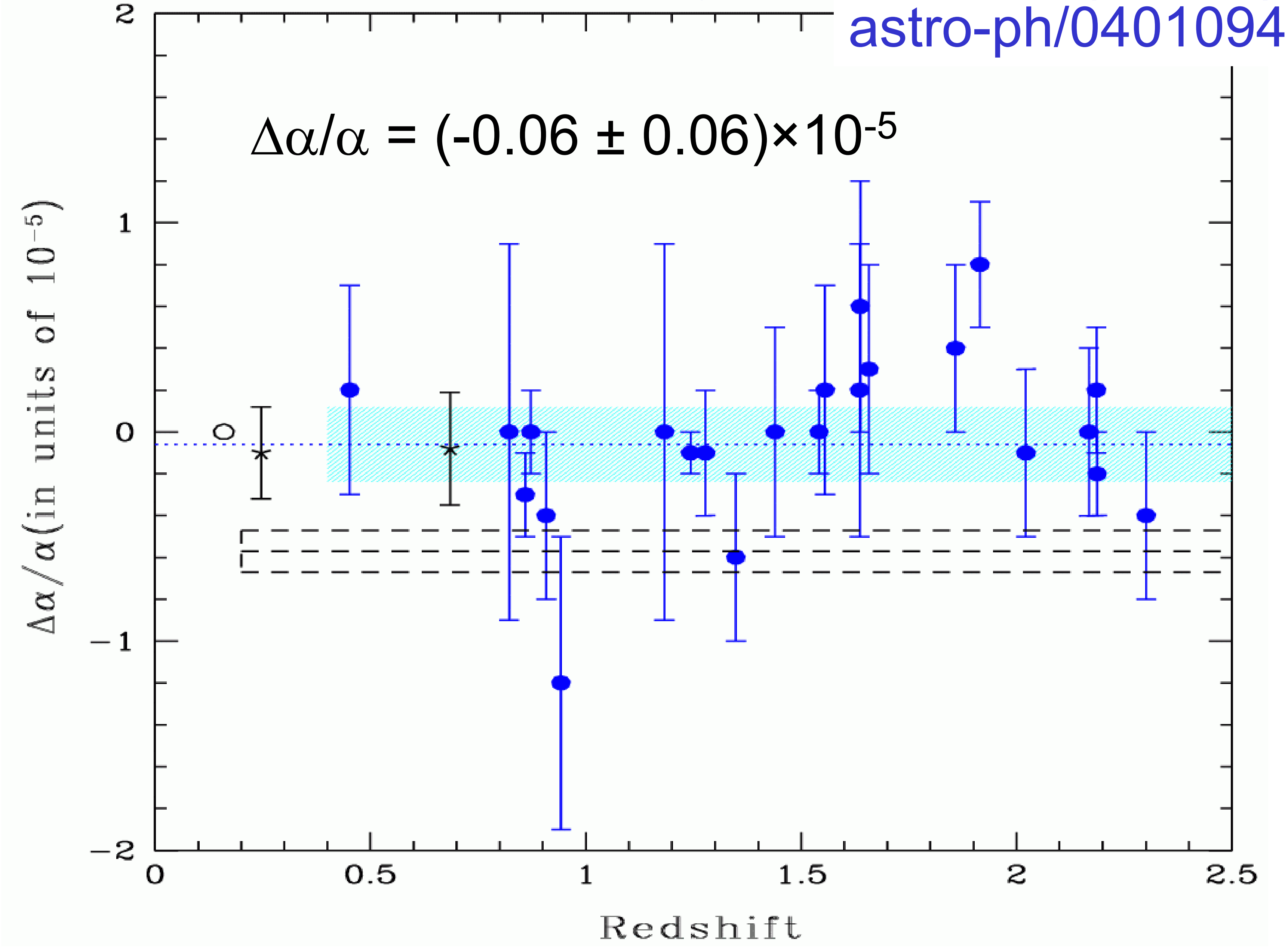
Number of systems where transition(s) <u>can</u> be removed

Transition(s) removed



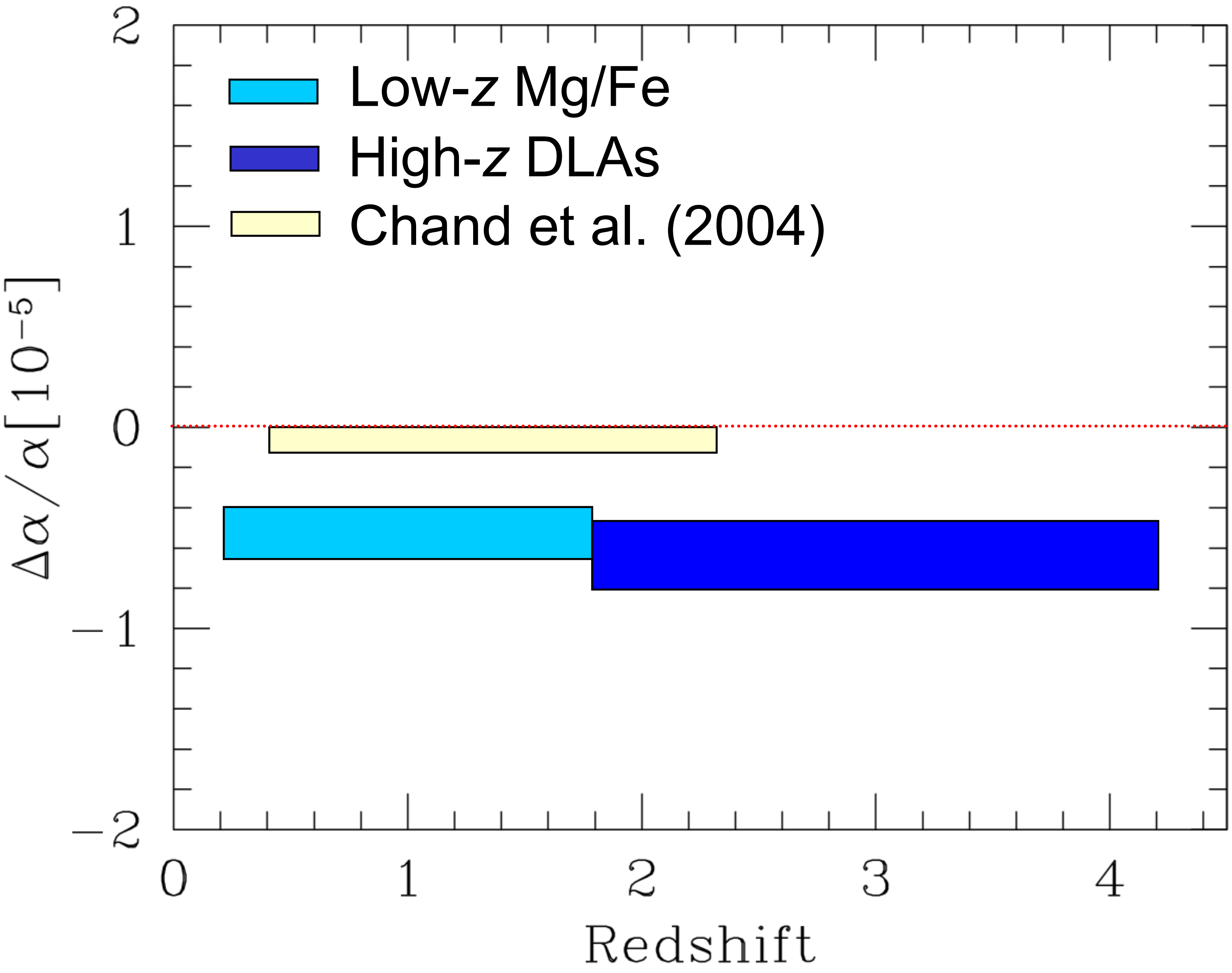
Chand, Srianand, Petitjean, Aracil (2004):

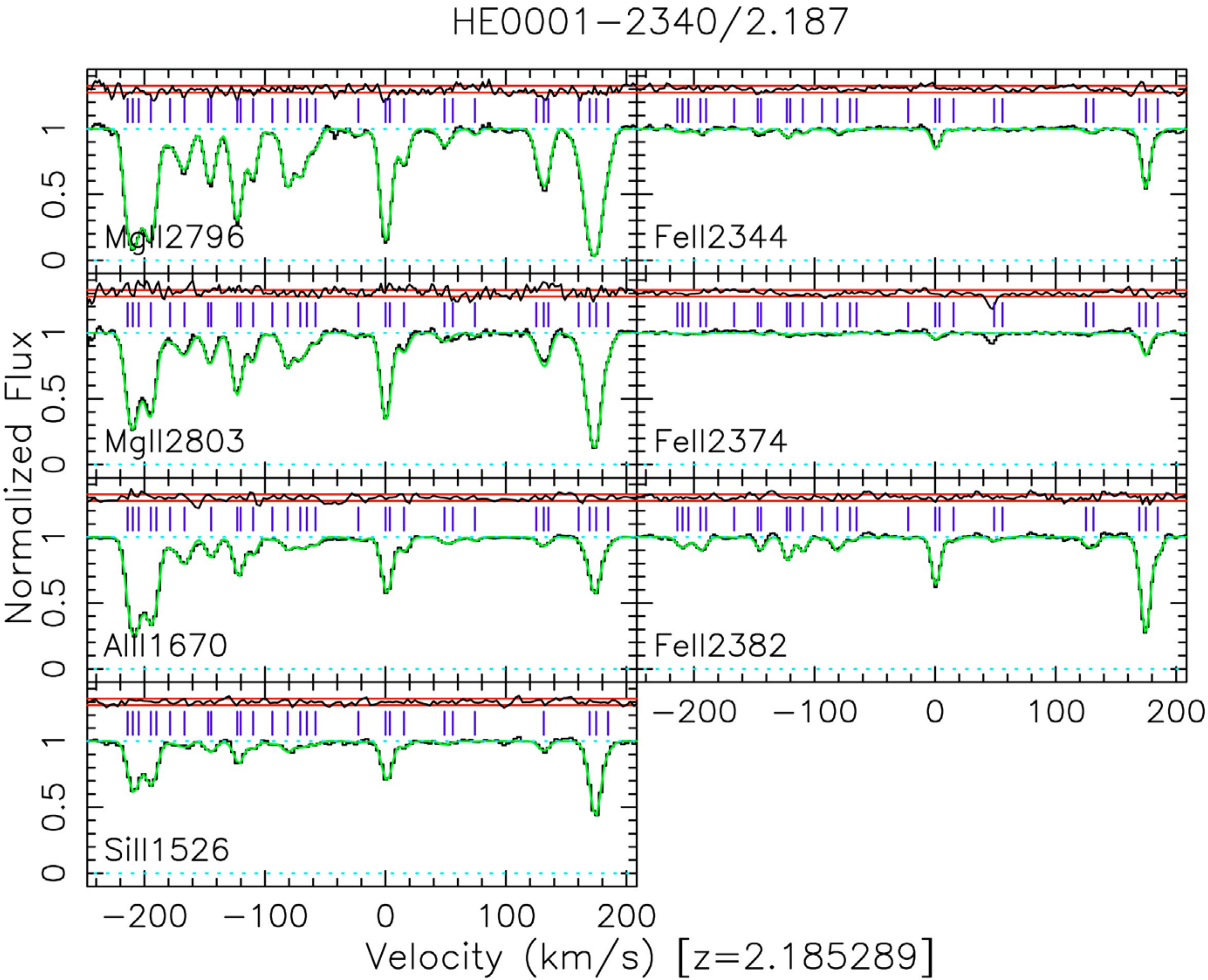
astro-ph/0401094



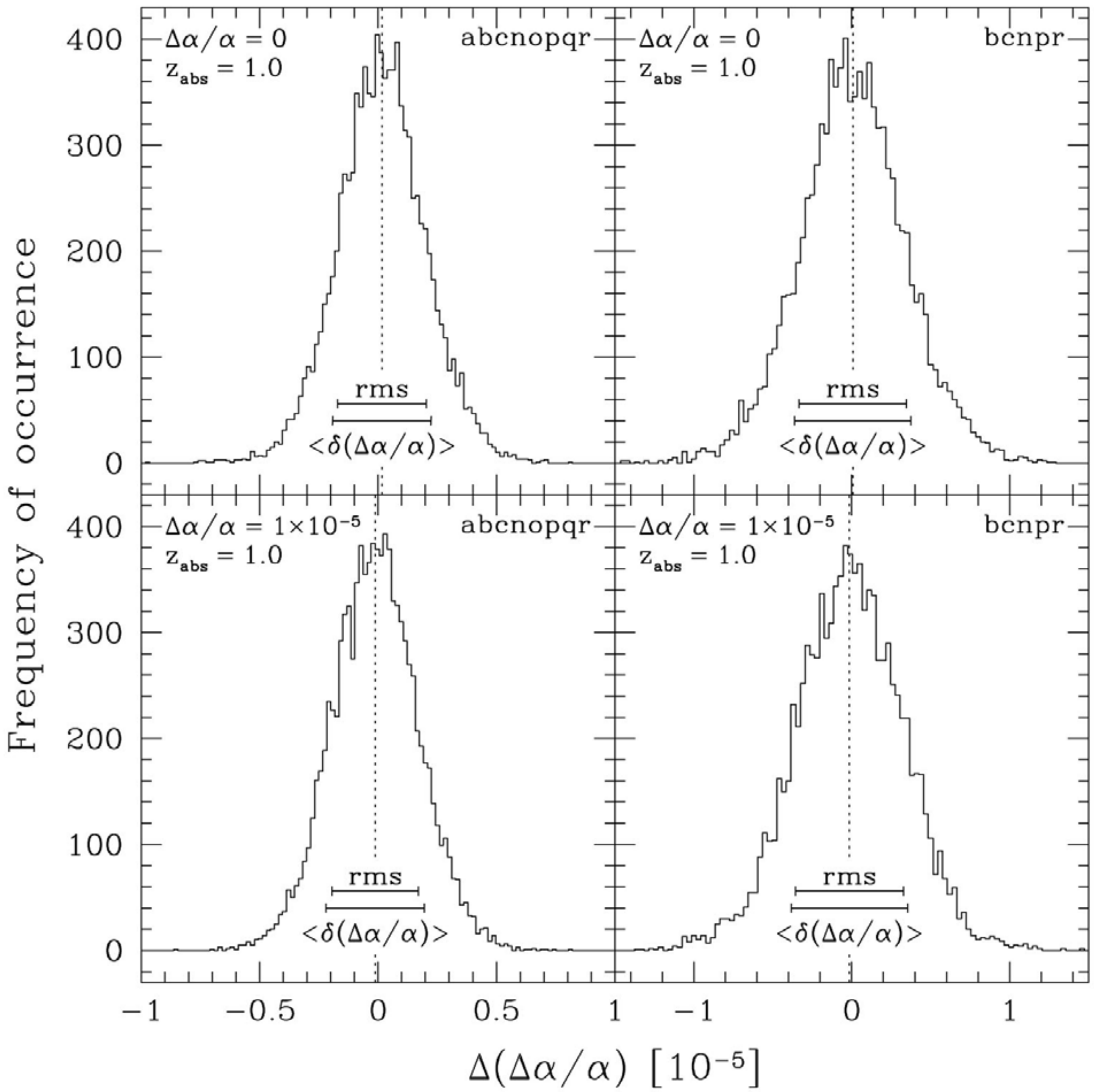
$\Delta\alpha/\alpha = (-0.06 \pm 0.06)\times 10^{-5}$

Comparison of two MM QSO results:



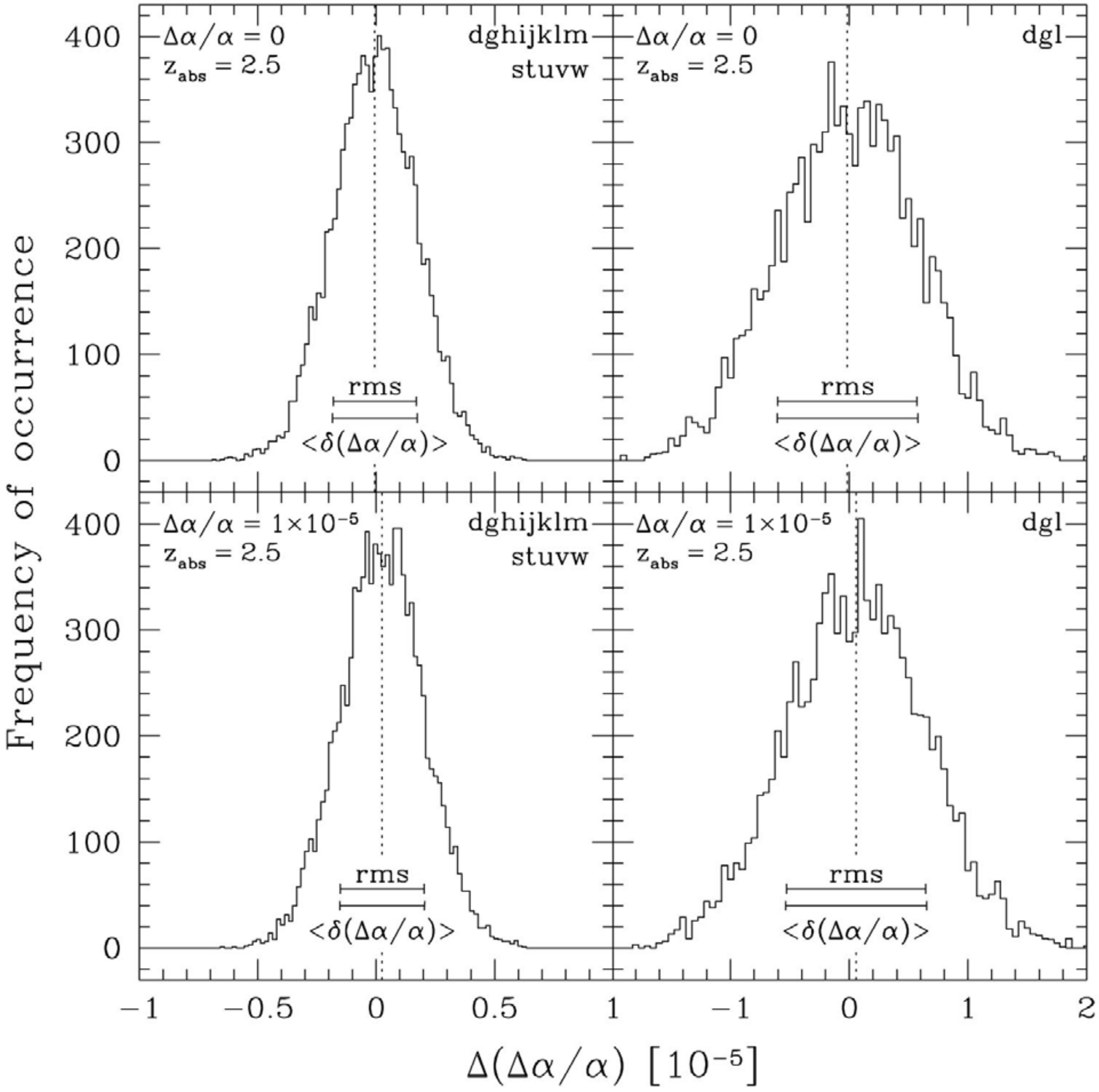

HE0001−2340/2.187
Normalized Flux
MgII2796
MgII2803
AlII1670
SiII1526
FeII2344
FeII2374
FeII2382
0
0.5
1
−200
−100
0
100
200
Velocity (km/s) [z=2.185289]

Example Monte Carlo simulations at z=1.0



- *10,000 absorption systems*
- *Multiple species fitted*
- *S/N per pixel =100*
- *Single and complex velocity structures explored*
- *Voigt profile generator for simulated spectra is independent of that used for analysis*

Example Monte Carlo simulations at z=2.5



Two conclusions:

1) ***Correct $\Delta\alpha/\alpha$ is recovered in all cases***

2) ***Error estimates from inverting Hessian at solution are very good (ie. observed scatter and mean error agree).***

Summary

1. We find significant non-zero result in 3 Keck samples. Varying α or isotopic changes? Need independent check on AGB populations at high z.

2. Chand et al disagree. Very small scatter hard to understand. Different redshift range? Spatial variations? Just systematics?

3. Isotopic abundance evolution may explain results at lower redshift, but not high redshift.

4. If $\Delta\alpha/\alpha=0$, we may get sensitive constraints on high z isotopic ratios and hence stellar population. Also, future tighter null result means no violation of EEP hence Λ=const may be preferred, providing tight constraint on equation of state. Note precision on “consistency of physics” is comparable to CMB.

5. Prospects for better constraints are excellent – Subaru, Gemini, other large telescopes. More Keck and VLT data. 21cm+optical. Future 30m telescopes.