Four direct measurements of the fine-structure constant 13 billion years ago

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Dimensionless Constants

Quantity	Algebraic ratio	Numerical value	Related to
α_{EM}	$\dfrac{e^2}{4\pi\epsilon_0\hbar c}$	$1/137.03599976$	Strength of the electromagnetic force
α_{W}	$\dfrac{G_{\mathrm{F}} m_p^2 c}{\hbar^3}$	1.03×10^{-5}	Strength of the weak force
$\alpha_{\mathrm{S}}(E)$	$\dfrac{g_s^2(E)}{\hbar c}$		Strength of the strong force
α_{G}	$\dfrac{G m_p^2}{\hbar c}$	5×10^{-39}	Strength of the gravitational force
μ	$\dfrac{m_e}{m_p}$	5.44617×10^{-4}	
x	$g_p \alpha_{\mathrm{EM}}^2 \mu$	1.62×10^{-7}	
y	$g_p \alpha_{\mathrm{EM}}^2$	2.977×10^{-4}	

Varying Fine Structure Constant

- Fine-structure effect (Hydrogen-like atom):

$$\Delta E = \alpha_{EM}^2 Z_a^2 Z^2 \frac{E_0}{n_*^4}\left[\frac{n_*}{J+1/2} - \frac{Z_a}{Z}\left(1 - \frac{Z_a}{4Z}\right)\right],$$

  where Z, Z_a and n_* are the charge of the atoms, the effective charge and the effective principal quantum number, respectively.

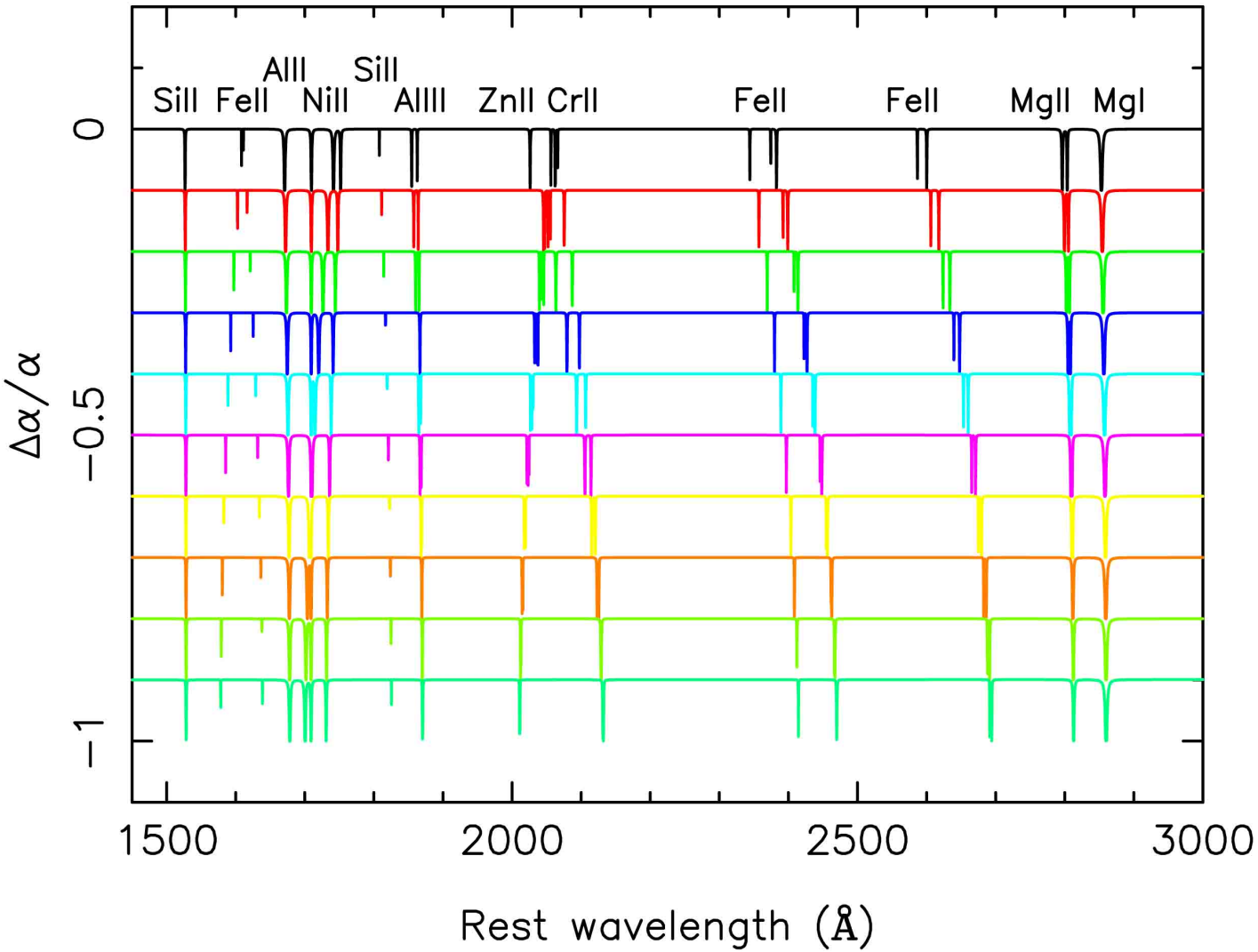
- General case[1]:

$$E - E_0 = Q_1\left[\left(\frac{\alpha}{\alpha_{EM}}\right)^2 - 1\right] + Q_2\left[\left(\frac{\alpha}{\alpha_{EM}}\right)^4 - 1\right]$$
$$+K_1\mathbf{L}\cdot\mathbf{S}\left(\frac{\alpha}{\alpha_{EM}}\right)^2 + K_2\mathbf{L}\cdot\mathbf{S}\left(\frac{\alpha}{\alpha_{EM}}\right)^4.$$

$$\Rightarrow \text{Frequency} : \omega = \omega_0 + q_1\left[\left(\frac{\alpha}{\alpha_{EM}}\right)^2 - 1\right] + q_2\left[\left(\frac{\alpha}{\alpha_{EM}}\right)^4 - 1\right].$$

[1] V.A. Dzuba, V.V. Flambaum, and J.K. Webb, PRL 82, 888 (1999)

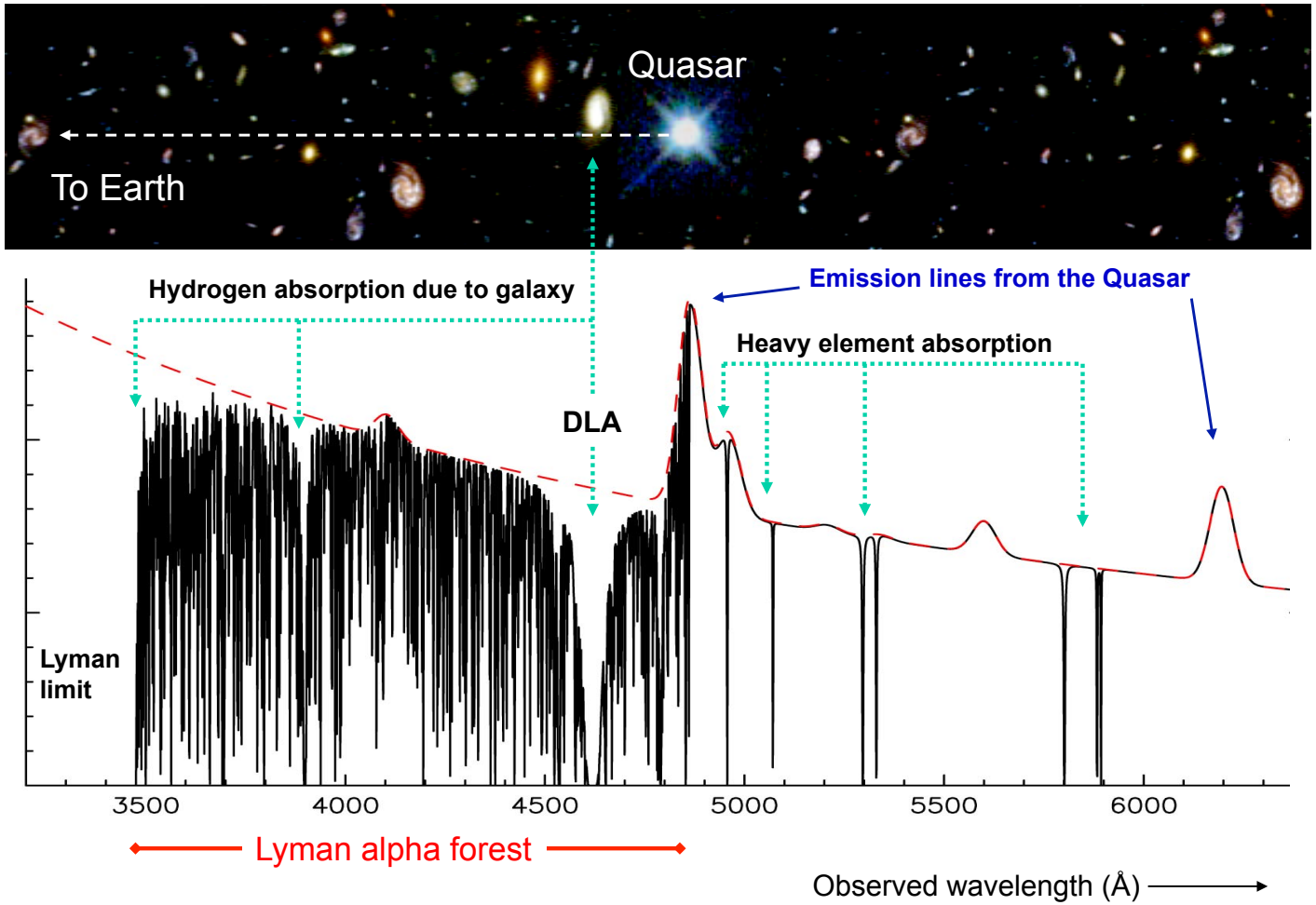
Varying Fine Structure Constant



Quasar

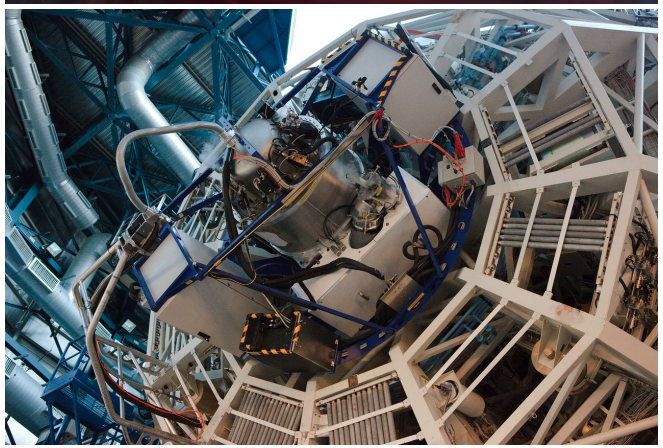
www.sciencenews.org

Absorption Profile



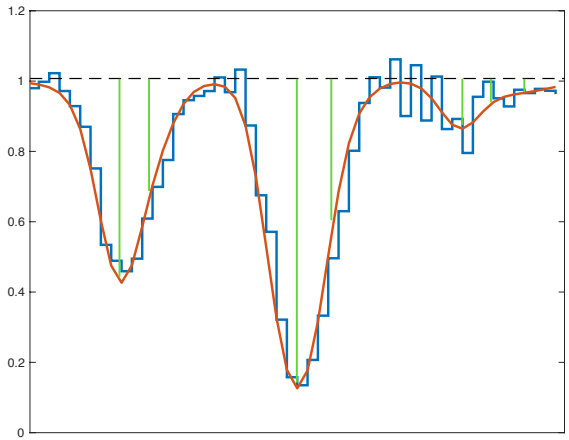
Observations

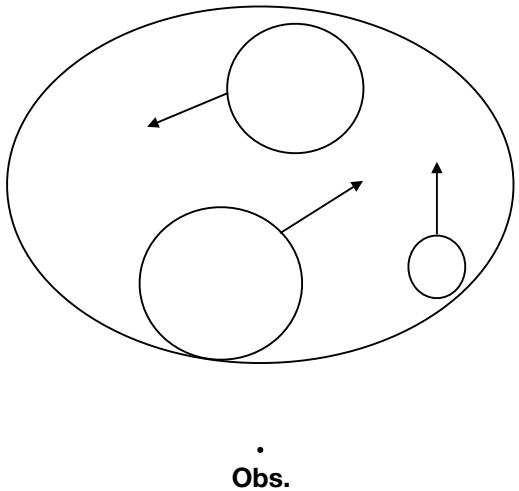
- Quasar: J1120+0641
  - Second most distant quasar: z = 7.085 (12.96 billion years ago).
  - Bright: 6.3×10^{13} solar luminosities.
- Very Large Telescope (VLT): X-SHOOTER
  - Broad spectral wavelength coverage.
  - High resolution: $R = \lambda/\Delta\lambda = 7,000 - 10,000$.



AI algorithm

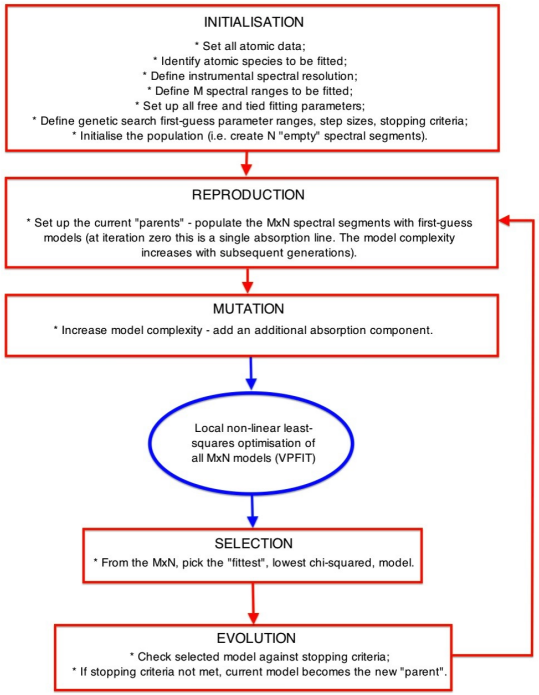
- VPFIT: Voigt profile fitting program[2]
- No unique model.

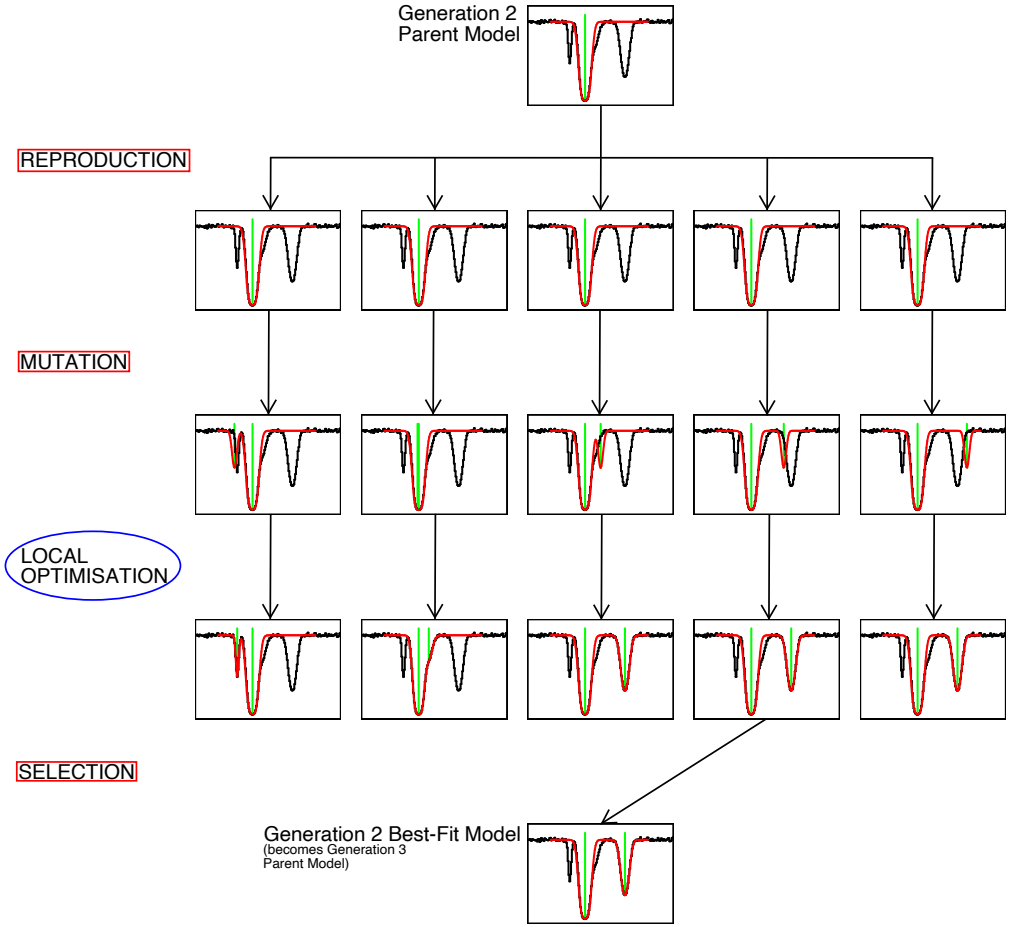




[2] https://www.ast.cam.ac.uk/ rfc/

AI algorithm: GVPFIT[3]

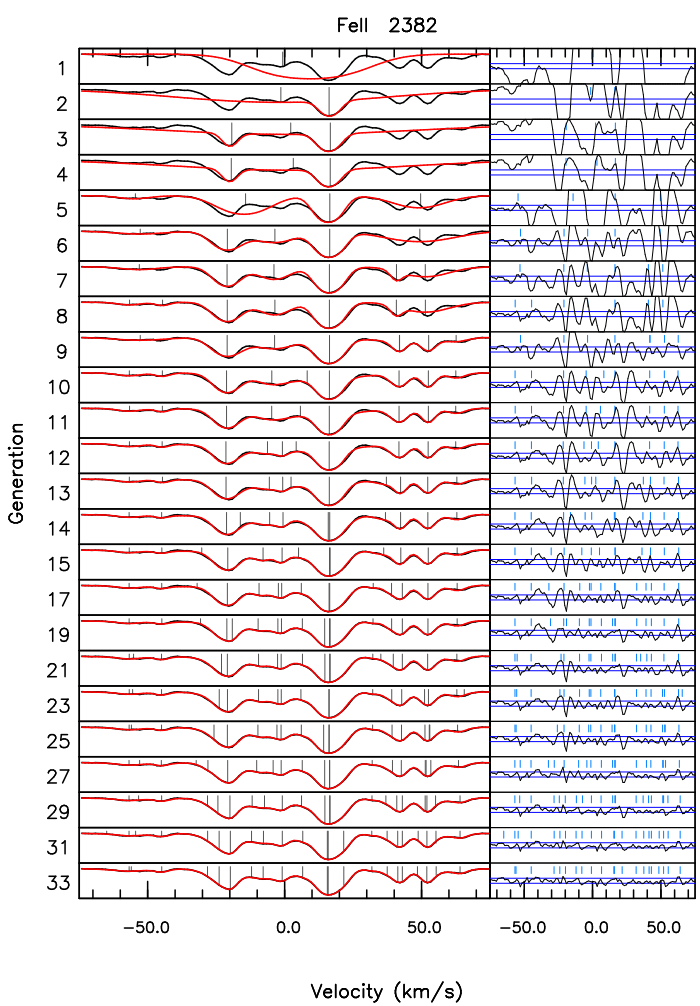


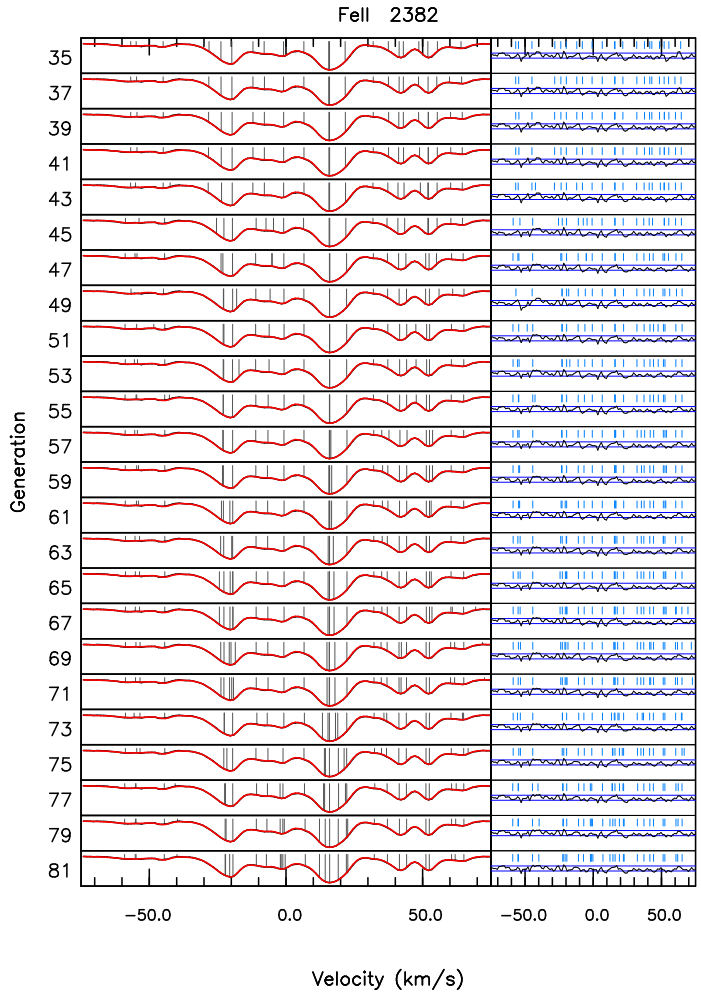


M.B. Bainbridge and J.K. Webb, MNRAS 468, 1639

[3] M.B. Bainbridge and J.K. Webb, MNRAS 468, 1639 (2017)

AI algorithm: GVPFIT





AI algorithm

- Akaike Information Criterion statistic:

$$AICc = \chi^2 + 2k + \frac{2k(k+1)}{(n-k-1)},$$

  where k is the number of free parameters, and n is the number of data points.
- Eliminates most of the human decision-making processes.
- Minimises or removes any possible bias.

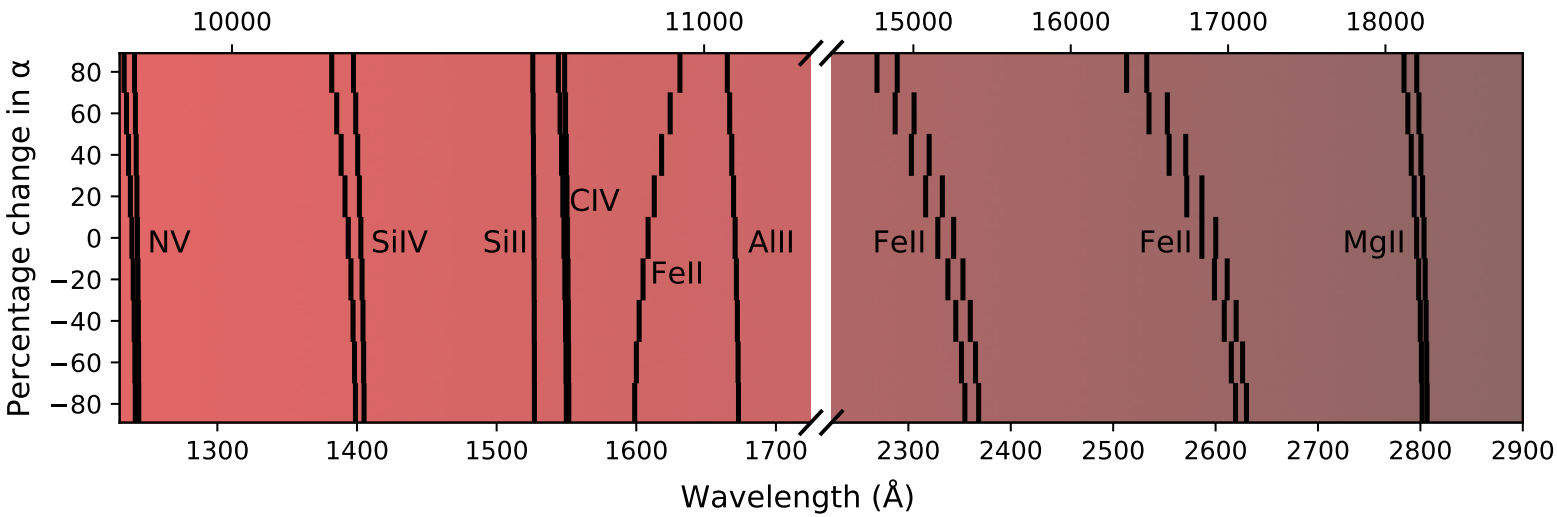
Identified Systems

z_{abs}	Transitions (Å)
7.05852	**C IV 1548/1550, Si IV 1393/1402, N V 1242/1238**
7.01652	C IV 1548/1550
6.51511	C IV 1548/1402
6.40671	Mg II 2796/2803
6.21845	C IV 1548/1550, Mg II 2796/2803
6.17097	**Al II 1670**, C IV 1548/1550, **Si II 1526**, **Fe II 2383**, **Mg II 2796/2803**, Si IV 1393[1]/1402
5.95074	**Fe II 2344/2383/2587/2600, Mg II 2796[2]/2803[2], Si II 1526**
5.79539	CIV 1548/1550
5.50726	Al II 1670, **Fe II 2344/2383**/2587[3]**/2600**[4]**/1608, Mg II** 2796[3]**/2803, Si II 1526**
4.47260	Mg II 2796/2803
2.80961	Mg II 2796/2803

[1] Line is contaminated by N V 1238 from intervening absorption system at $z_{abs} = 7.05852$.
[2] Mildly affected by cosmic rays.
[3] Line is blended with incompletely removed telluric line.
[4] Broad interloper at -100 km s^{-1}.

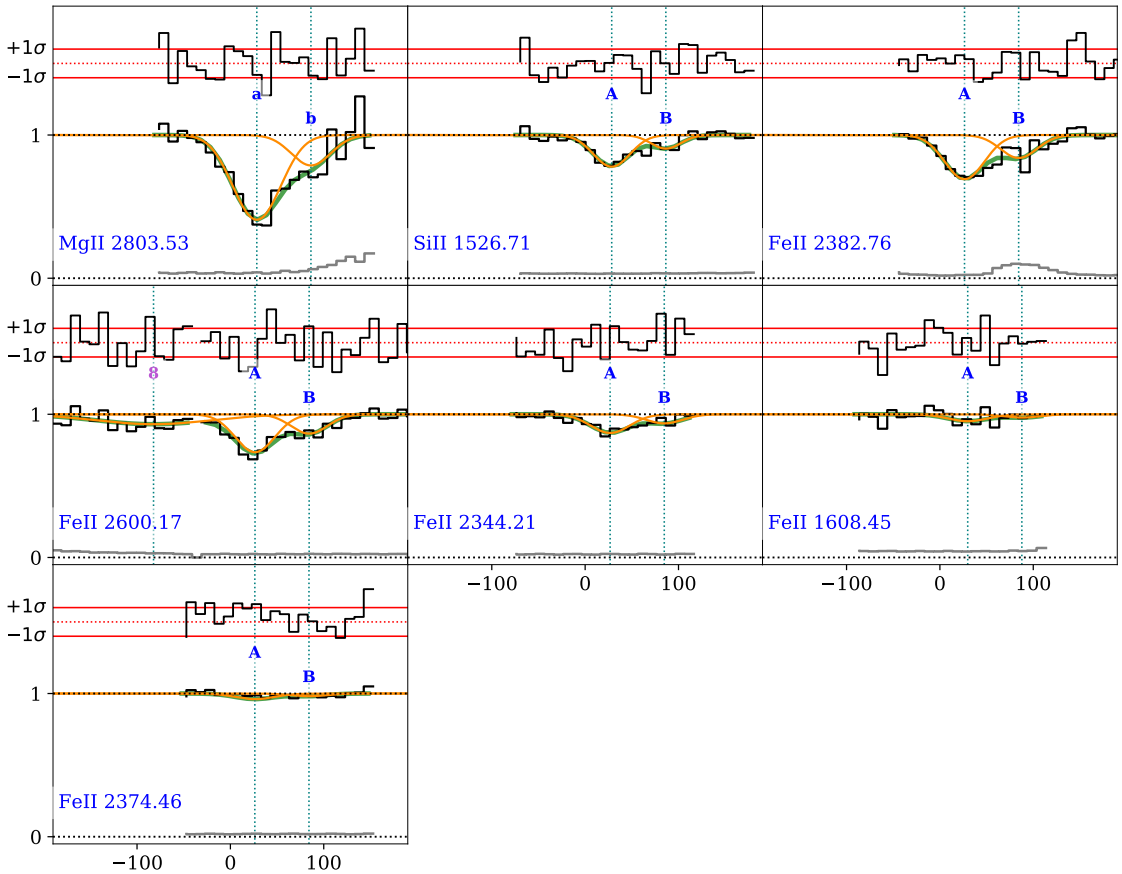
Identified Systems

- α dependence of the transitions observed in these systems.
- Observed frequency: $\omega_z = \omega_0 + q(\alpha_z^2/\alpha_{EM}^2 - 1)$.



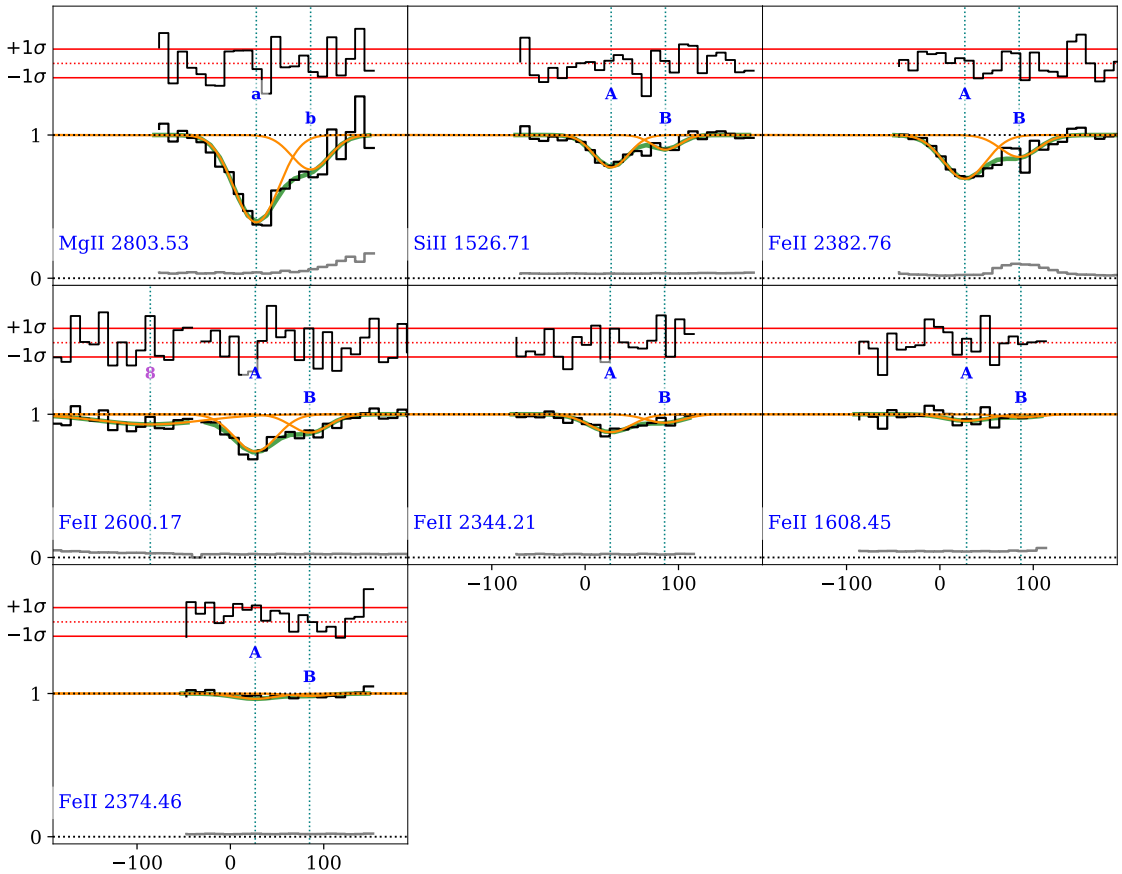
System-I

- Thermal fit at $z_{abs} = 5.507$



System-I

- Turbulent fit at $z_{abs} = 5.507$

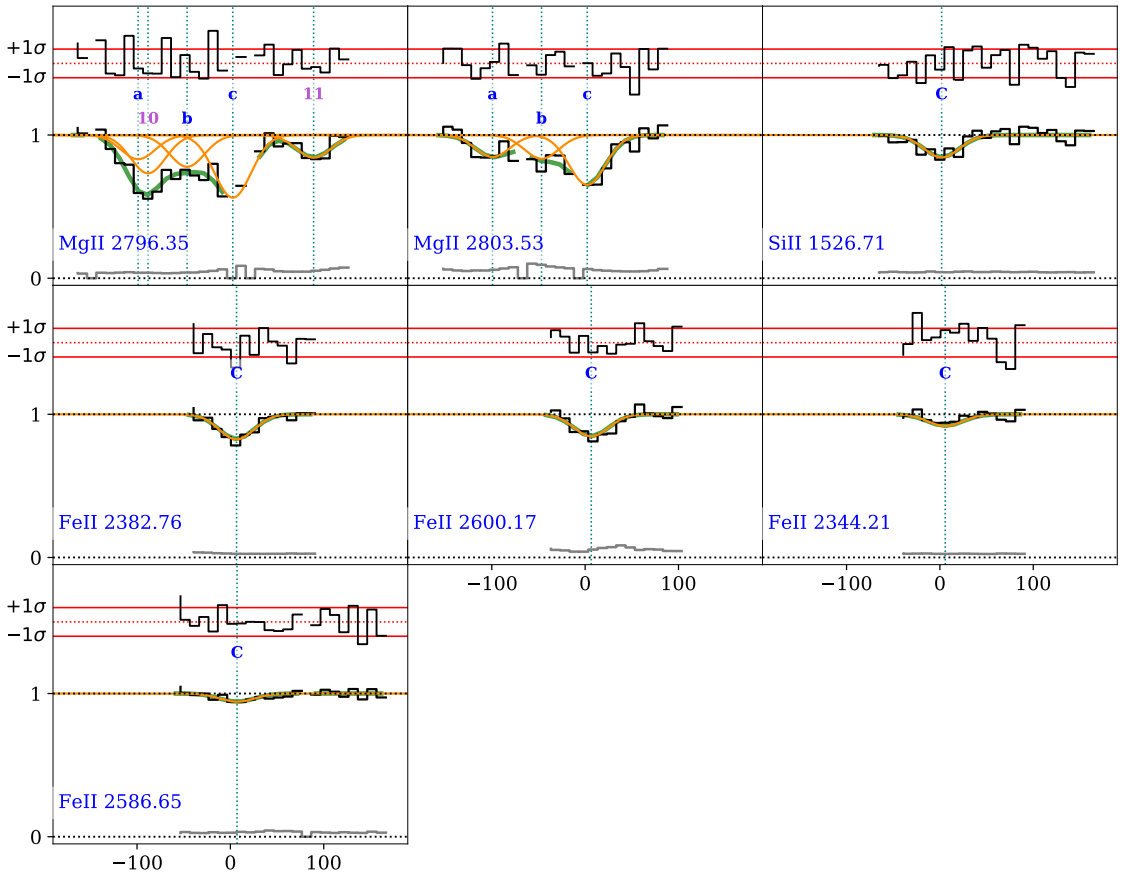


System-I

- Doppler / b-parameter: $b_i = \sqrt{\frac{2kT}{m_i} + b_{turb}^2}$
  - Thermal: $b_i = \sqrt{\frac{2kT}{m_i}}$ or $v_i = \sqrt{\frac{3kT}{m_i}}$
  - Turbulent: $b_i = b_{turb}$ or $v_i = v_{turb}$

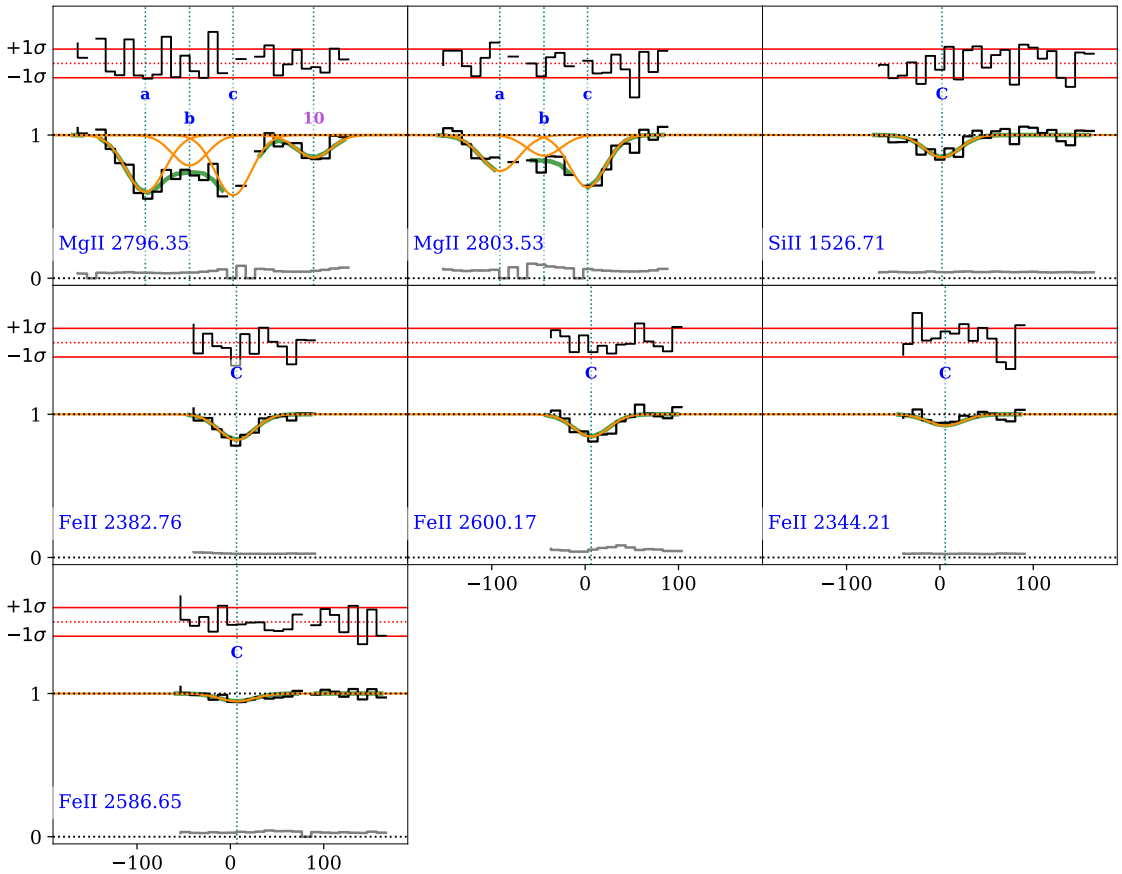
System-II

- Thermal fit at $z_{abs} = 5.591$



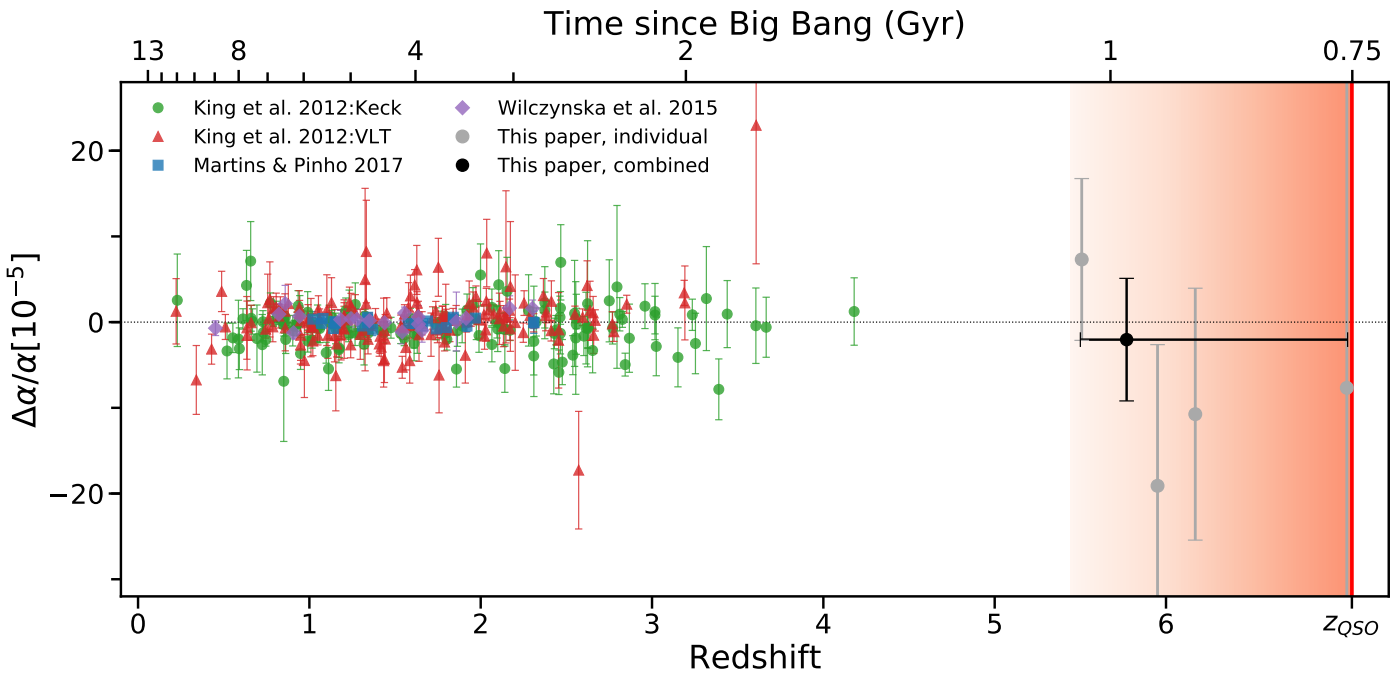
System-II

- Turbulent fit at $z_{abs} = 5.591$



Results

- 323 measurements: $0.2 < z_{abs} < 7.1$.



Results

- Final column combines the thermal and turbulent values.

Absorption redshift	Thermal $\Delta\alpha/\alpha\,[10^{-5}]$	Turbulent $\Delta\alpha/\alpha\,[10^{-5}]$	Method of moments $\Delta\alpha/\alpha\,[10^{-5}]$
7.05852	16.18±48.99	-9.38±48.71	12.79±48.66±19.74
6.17097	-10.14±14.79	-10.43±14.91	-10.16±14.80±0.42
5.95074	-23.00±17.10	-20.61±16.90	-22.85±17.11±0.32
5.50726	7.60±9.58	4.83±8.92	7.42±9.60±1.52
Weighted means:	1.84±7.20	-2.97±6.90	-2.18±7.27