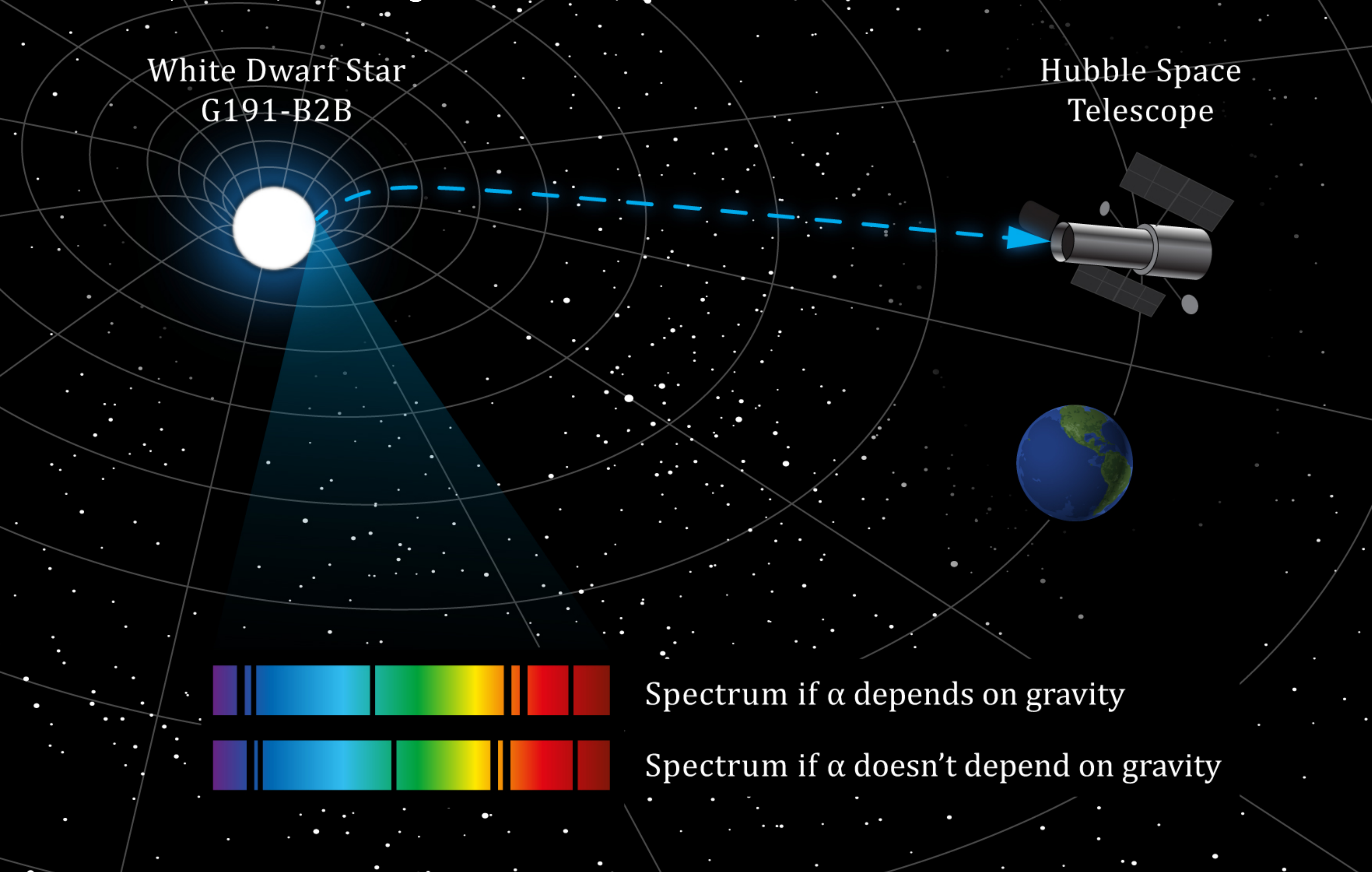
Searching for variations in fundamental constants using Hubble Space Telescope observations of White Dwarfs

John Webb, UNSW/Cambridge



Matthew. Bainbridge (Leicester)
Martin Barstow (Leicester)
Nicole Reindl (Leicester)
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Simon Preval (Strathclyde)
Jay Holberg (Arizona)
Gillian Nave (NIST)
Lydia Tchang-Brillet (Paris)
Tom Ayres (Colorado)

Summary of this talk:

- Preliminary analysis described in Berengut et al 2013 (B13):
- New analyses of several WD spectra using FeV absorption
- FeV sample stringently filtered from max. of 750 transitions
- Each absorption profile Voigt profile fitted
- Six tests made for potential systematics (including isotopic variations, long-range spectral distortions, Zeeman and Stark shifts.
- None so far emulate the apparently non-zero result.

Results so far:

1. Eckberg 1975 wavelengths: $\Delta\alpha/\alpha$(G191-B2B) = 4.07 ± 0.47 x 10^{-5}
Kramida 2014 wavelengths: $\Delta\alpha/\alpha$(G191-B2B) = 2.95 ± 0.53 x 10^{-5}

2. Bd+28 gives similar results, consistent with the G191-B2B

3. Several other preliminary measurements also give non-zero

4. Systematics have not yet been fully quantified so treat the results with skepticism! Dominant error is lab wavelength uncertainties (about 1 x 10^{-5}).

Changing physics near massive bodies:

- Gravity is so important on large scales because it is additive (more particles = more gravity).
- Scalar fields couple to gravity.
- Therefore massive bodies should also impact on scalar fields.
- Variation in any standard model parameters are expressed in terms of variations in a scalar field (e.g. the dilaton, a hypothetical particle in the scalar field in string models and models with extra dimensions).
- Thus it would seem natural that fundamental constants vary near massive bodies.

1. Damour & Polyakov, Nucl. Phys. B 423, 532 (1994) (arXiv:hep-th/9401069)
2. Flambaum & Shuryak, 2008, Nuclei and Mesoscopic Physic - WNMP 2007, 995, 1 (arXiv:physics/0701220v2)
3. Magueijo, Barrow, Sandvik, Physics Letters B, Volume 549, Issue 3-4, p. 284-289 (arXiv:astro-ph/0202374)

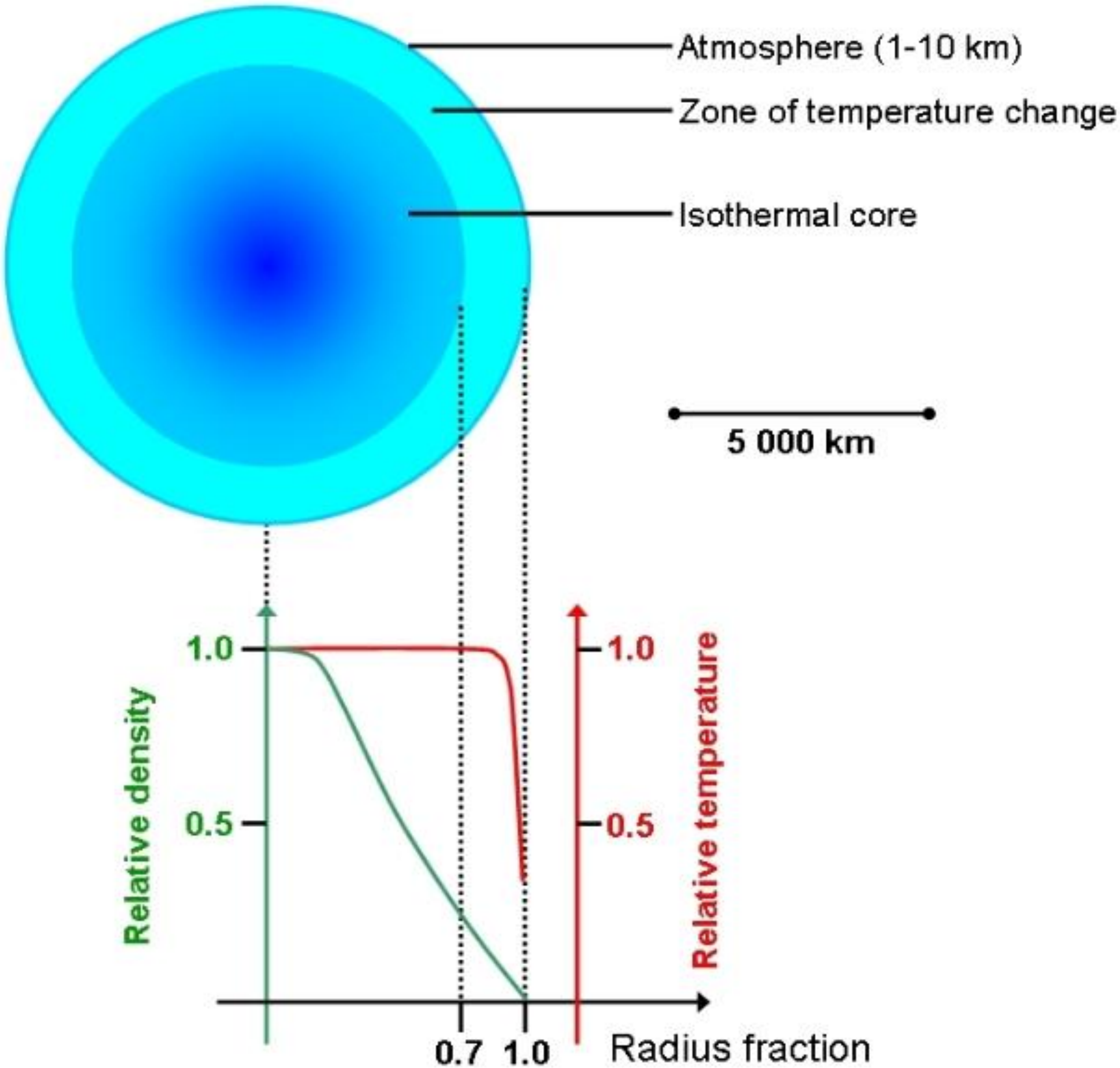
Why white dwarfs?

1. GM/r at the photosphere is ~10,000 times greater than on Earth

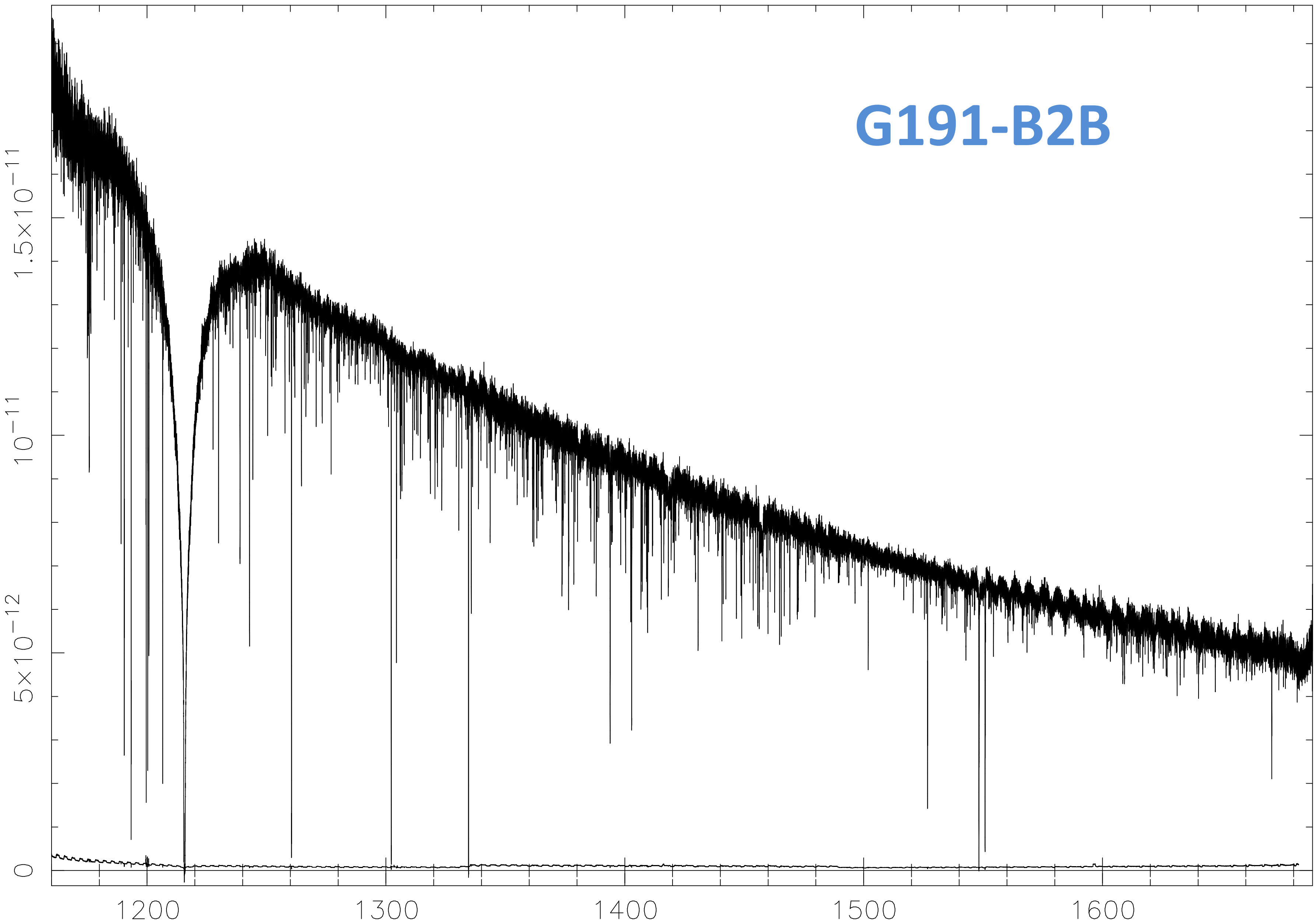
2. They are relatively bright objects so we can get high quality spectra (although only in the UV and therefore from space)

3. There are many narrow spectral lines from species that are sensitive to a change in the electromagnetic coupling constant

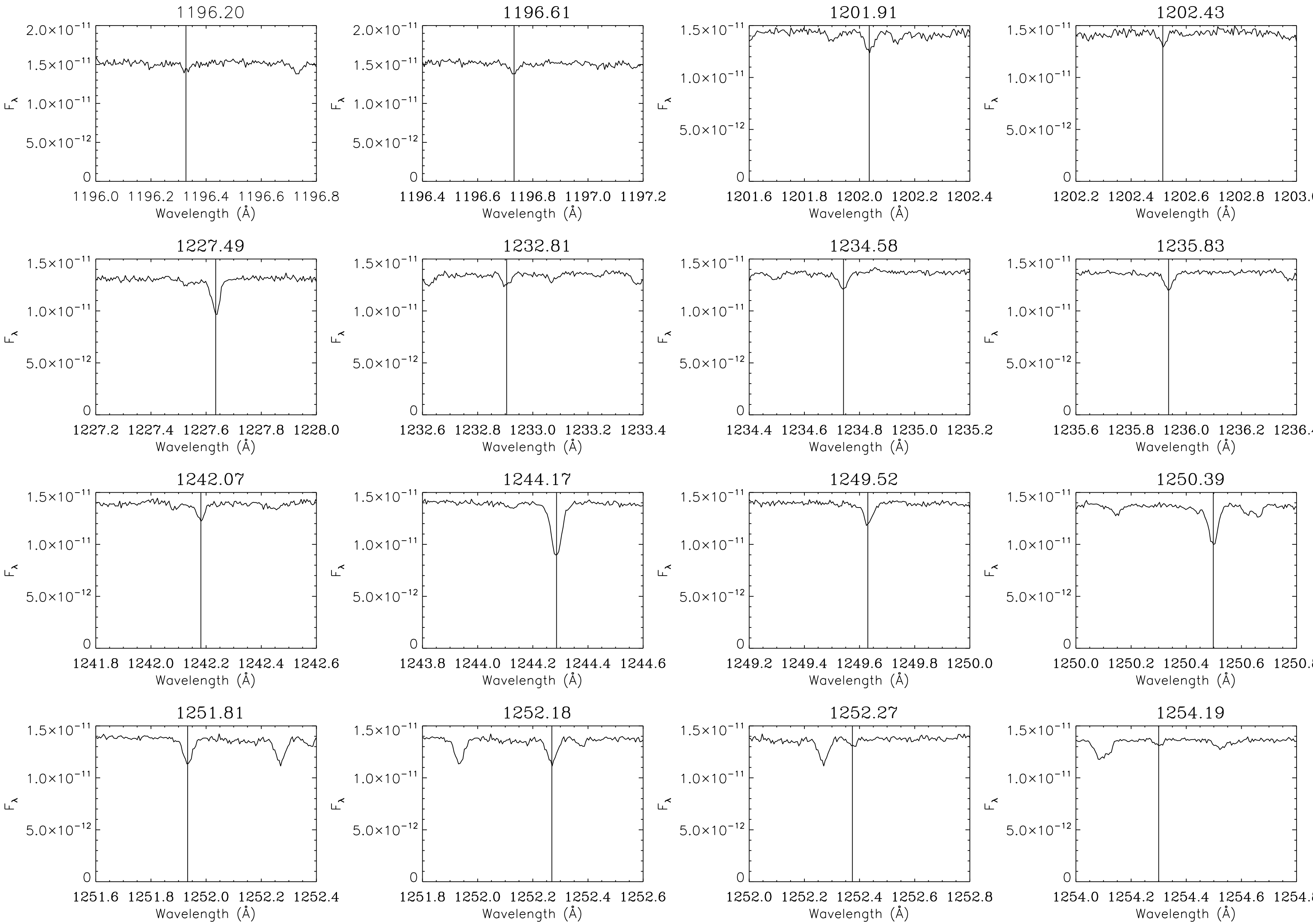
Structure of a White Dwarf



http://cronodon.com/

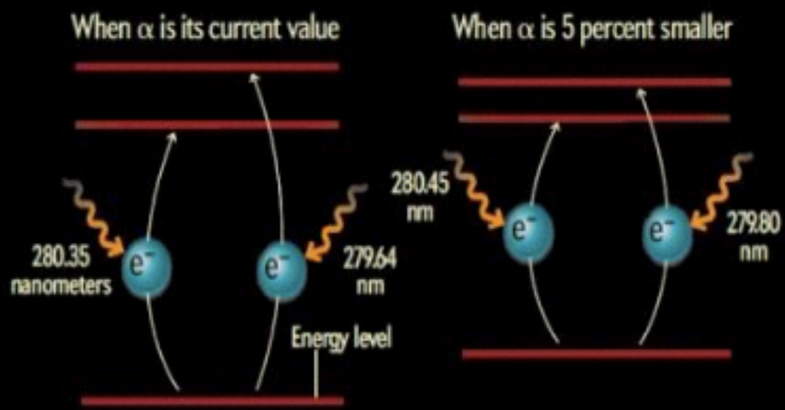

G191-B2B
0
5×10⁻¹²
10⁻¹¹
1.5×10⁻¹¹
1200
1300
1400
1500
1600

HST STIS spectra of G191-B2B. Line widths ~4 km/s. Spectral resolution ~120,000



Many-multiplet Method

If a changes…



(Credit: Alison Kendall)

**The transition energy will change, thus
the transition line will be shifted.**

Sensitivity to variation in a ?

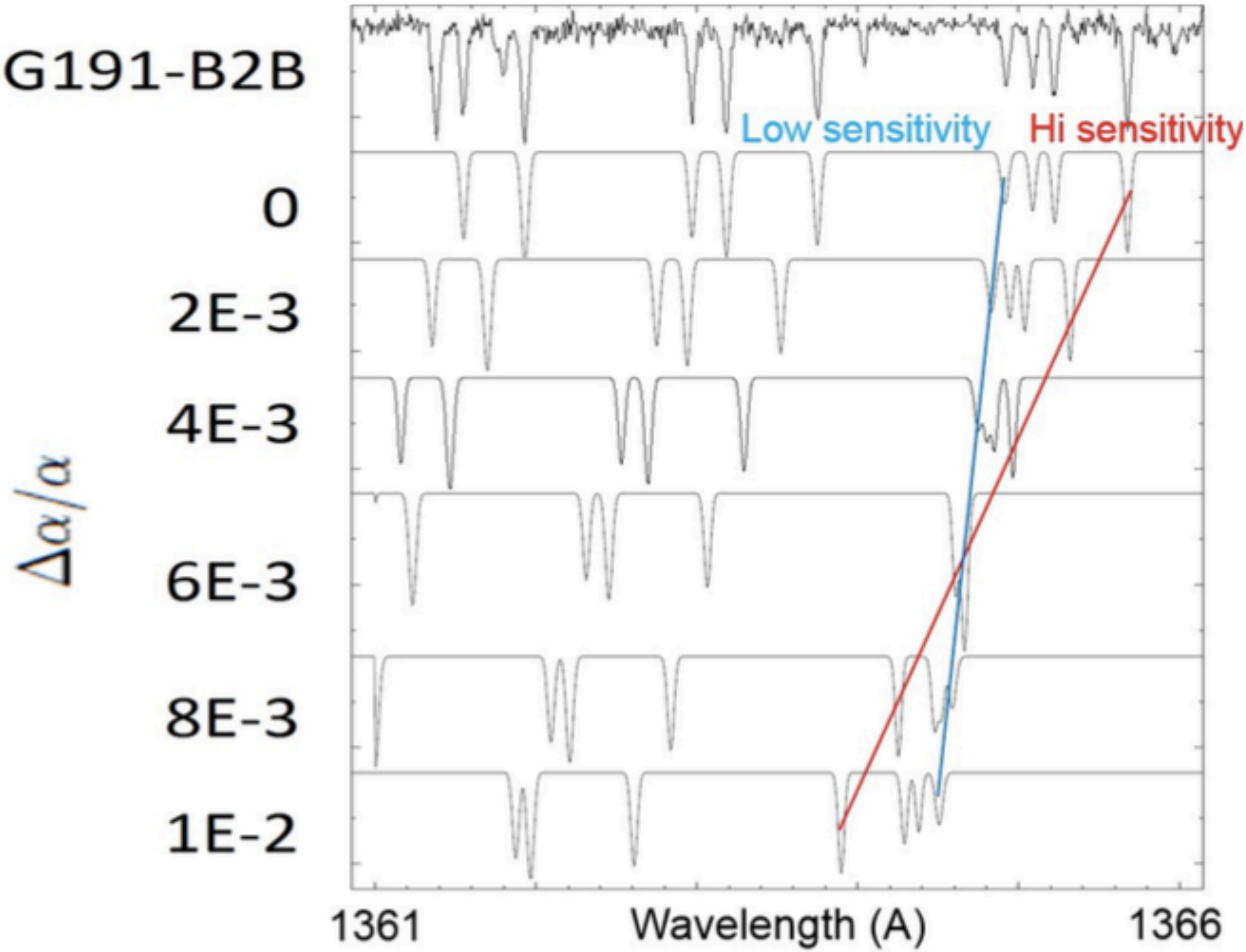
q-coefficient

Characterize sensitivity of transition frequency ω to the change in α [4]:

$$q = \frac{d\omega}{dx}\Big|_{x=0},$$

where $x = (\alpha/\alpha0)^2 - 1 \approx 2\Delta\alpha/\alpha$

- ***q is different for different transitions***
- ***Atoms* with higher Z and higher ionization state generally have larger $|q|$**


G191-B2B
Low sensitivity
Hi sensitivity
0
2E-3
4E-3
6E-3
8E-3
1E-2
Δα/α
1361
Wavelength (A)
1366

First WD varying constant measurement

Phys. Rev. Lett. 111, 010801, 2013, arXiv:1305.1337

Limits on the dependence of the fine-structure constant on gravitational potential from white-dwarf spectra

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(Dated: 9 July 2013)

We propose a new probe of the dependence of the fine structure constant, α, on a strong gravitational field using metal lines in the spectra of white dwarf stars. Comparison of laboratory spectra with far-UV astronomical spectra from the white dwarf star G191-B2B recorded by the Hubble Space Telescope Imaging Spectrograph gives limits of $\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ and $(-6.1 \pm 5.8) \times 10^{-5}$ from Fe V and Ni V spectra, respectively, at a dimensionless gravitational potential relative to Earth of $\Delta\phi \approx 5 \times 10^{-5}$. With better determinations of the laboratory wavelengths of the lines employed these results could be improved by up to two orders of magnitude.

Limits on variations of the fine-structure constant with gravitational potential from white-dwarf spectra

Berengut et al, arXiv:1305.1337

- White dwarf G191-B2B, ≈ 45 pc
- $M = 0.51 M_\odot$, $R = 0.022 R_\odot$
- $\Delta\phi \sim 10^5$ larger than terrestrial, “medium strength ϕ”
- HST/STIS spectra, R ≈ 144, 000
- Lab wavelength precision ~7mA (from residuals)
- Many FeV and NiV lines (~100) – helpful for some systematics cf. quasar data
- Higher ionization lines => sensitivity coefficients higher

$$\Delta\alpha/\alpha \equiv \frac{\alpha(r)-\alpha_0}{\alpha_0} \equiv k_\alpha \, \Delta\phi = k_\alpha \, \Delta\left(\frac{GM}{rc^2}\right)$$

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda-\lambda_0}{\lambda_0} = z - Q_\alpha \frac{\Delta\alpha}{\alpha}(1+z)$$

Parameterize sensitivity of each transition frequency to a change:

$$q = \left.\frac{d\omega}{dx}\right|_{x=0}$$

where a small change in α is described by

$$x \equiv (\alpha/\alpha_0)^2 - 1 \approx 2\Delta\alpha/\alpha$$

Observed spectral lines are shifted due to

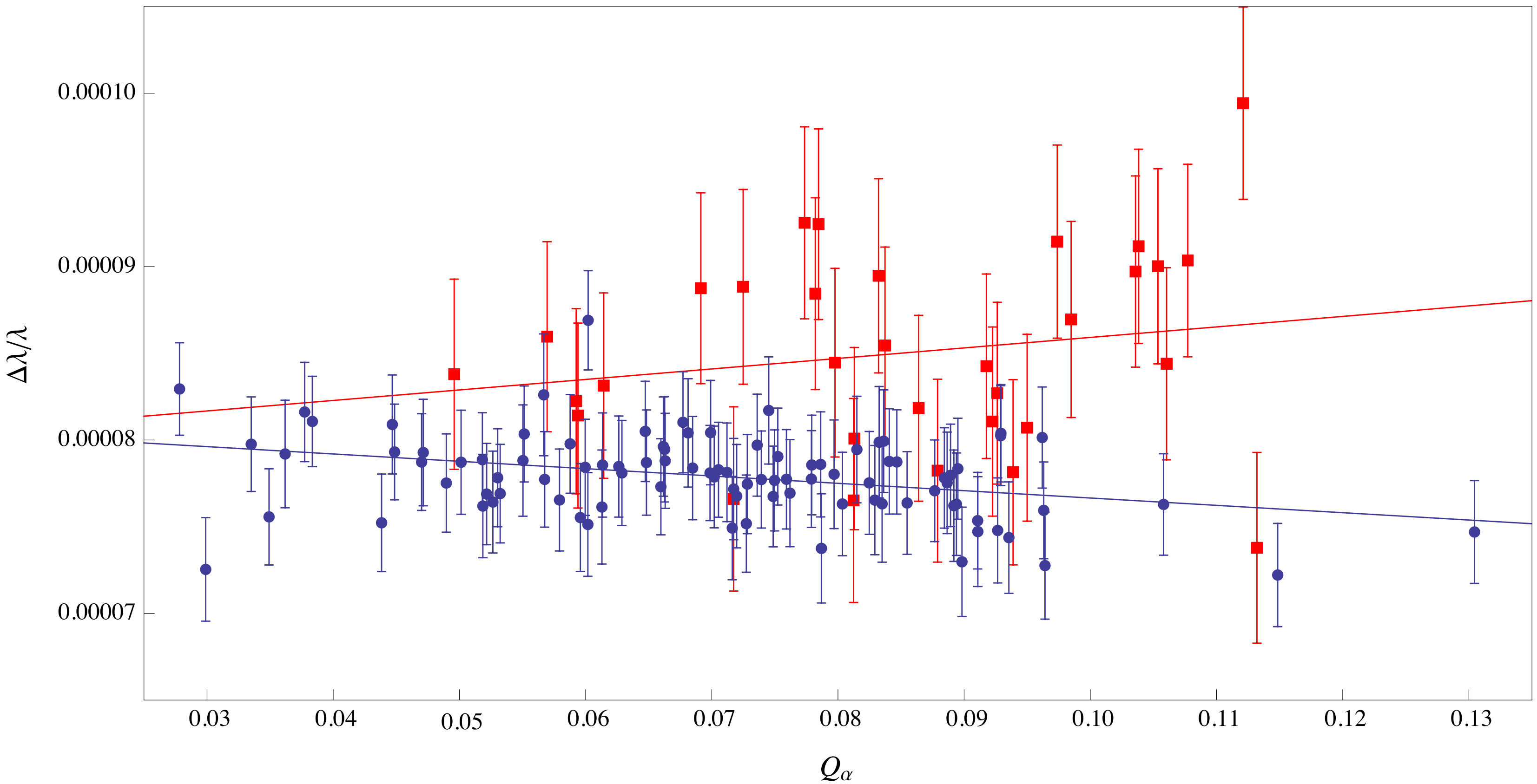
1. Doppler motion of star
2. Gravitational redshift
3. Any possible dependence of α on Φ

$$1 + z = \frac{\omega_0 + qx}{\omega}$$

Relating the laboratory wavelength to the observed wavelength in the WD photosphere:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0} = z - Q_\alpha \frac{\Delta\alpha}{\alpha}(1 + z)$$

Where $Q_\alpha = 2q/\omega_0$ is the relative sensitivity of the transition frequency to a change in α



FeV (blue circles) and NiV (red squares). Slopes of the lines give:

$\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ for FeV ;

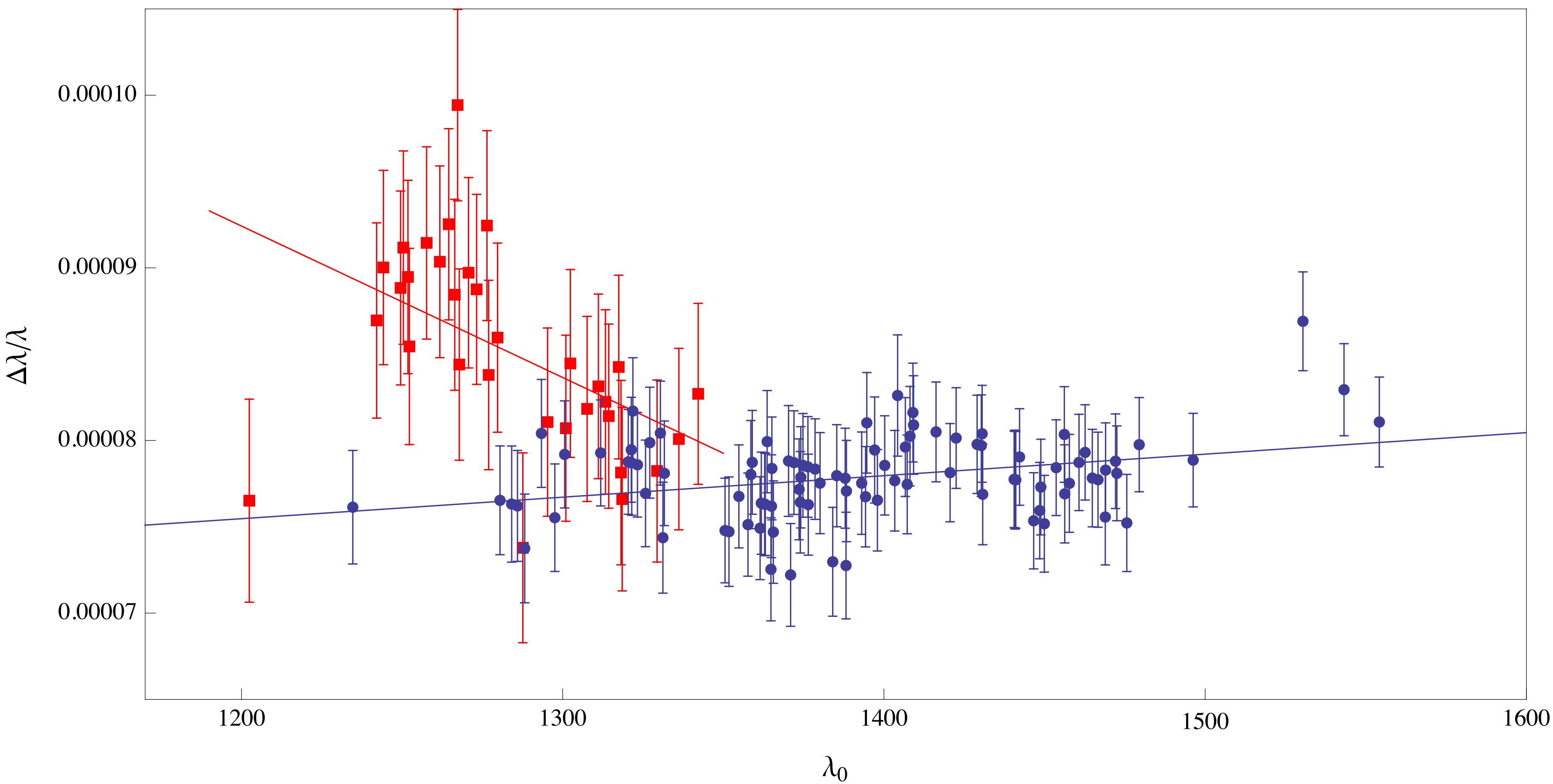
$\Delta\alpha/\alpha = (-6.1 \pm 5.8) \times 10^{-5}$ for Ni V

The above plot does not make much sense!

Clearly there is something wrong in previous figure.
The two sets of points should coincide.
Yet
$\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ for FeV ;
$\Delta\alpha/\alpha = (-6.1 \pm 5.8) \times 10^{-5}$ for Ni V
Where's the mistake?

- Laboratory wavelengths wrong?
  Maybe. But observed mean residuals are 0.03mA compared to published wavelength errors of 0.04mA, suggesting not.

- Nonlinear wavelength distortions (i.e. incorrect calibration between real and observed wavelength)?
  Maybe. To be determined.



FeV (blue circles) and NiV (red squares).

Note the different wavelength coverage for the 2 species. A "double"-linear wavelength distortion, with a change in slope around 1350A could emulate varying alpha (but ruled out – later)

New analysis - Instead of using line centroids, model each individual absorption line with a Voigt profile

$$F(\mathbf{x}) = \frac{1}{2}\sum_{i=1}^{n}(I(\mathbf{x})_i - d_i)^2/\sigma_i^2$$
$$= \frac{1}{2}\sum_{i=1}^{n}(f_i(\mathbf{x}))^2 = \frac{1}{2}\mathbf{f}(\mathbf{x})^T\mathbf{f}(\mathbf{x}) \qquad (1)$$

Define chi-squared

We then make the approximation that the objective function $F(\mathbf{x})$ can be modelled by a second order Taylor series expansion about $\mathbf{x}$

$$\mathbf{f}(\mathbf{x}+\mathbf{p}) = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})^T\mathbf{p} + \frac{1}{2}\mathbf{p}^T\mathbf{H}(\mathbf{x})\mathbf{p} \qquad (2)$$

Taylor series expand it

where the gradient vector of $F(\mathbf{x})$ is

$$\mathbf{g}(\mathbf{x}) = [\partial F(\mathbf{x})/\partial \mathrm{x}_1, \partial F(\mathbf{x})/\partial \mathrm{x}_2, ..., \partial F(\mathbf{x})/\partial \mathrm{x}_m]$$
$$= \mathbf{J}(\mathbf{x})^T\mathbf{f}(\mathbf{x}) \qquad (3)$$

The Hessian matrix of $F(\mathbf{x})$ is

$$\mathbf{H}(\mathbf{x}) = \begin{bmatrix} \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_1^2} & \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_1 \partial \mathrm{X}_2} & \cdots & \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_1 \partial \mathrm{X}_m} \\ \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_2 \partial \mathrm{X}_1} & \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_2^2} & \cdots & \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_2 \partial \mathrm{X}_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_m \partial \mathrm{X}_1} & \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_m \partial \mathrm{X}_2} & \cdots & \frac{\partial^2 F(\mathbf{X})}{\partial \mathrm{X}_m^2} \end{bmatrix} \qquad (5)$$

Therefore have to calculate derivatives

$$H(\mathbf{x})_{qr} = \left(\sum_{i=1}^{n} \frac{\partial^2 I(\mathbf{x})_i}{\partial x_q \partial x_r} \frac{(I(\mathbf{x})_i - d_i)}{\sigma_i^2}\right) + \left(\sum_{i=1}^{n} \frac{\partial I(\mathbf{x})_i}{\partial x_q} \frac{\partial I(\mathbf{x})_i}{\partial x_r} \frac{1}{\sigma_i^2}\right)$$

Discard first term

Keep this one

But the first term averages to zero so we can ignore it and get a simple equation to solve!

$$\mathbf{H}(\mathbf{x}) = -\mathbf{g}(\mathbf{x})$$

Which in practice is modified slightly by introducing another free parameter p that enables more efficient minimisation

$$\mathbf{H}(\mathbf{x})\mathbf{p}_{min} = -\mathbf{g}(\mathbf{x})$$

Second derivatives of chi-squared

First derivatives of chi-squared

Astronomical and laboratory data used:

Conservative approach: Stringent absorption line sample selection:

- The Kentucky atomic database lists #12,364 electric dipole (E1) transitions (all species) in the range $1160<\lambda<1680$Å (range corresponding to HST STIS E140H)
- Of these 750 are FeV
- We minimise blends by selecting FeV lines without any other E1 transitions nearby

We therefore:

1. Detect all lines in the WD spectrum above 3σ limit
2. Identify all electric dipole E1 transitions in the Kentucky atomic database satisfying

$$\frac{|\lambda_{obs} - \lambda_K|}{\sqrt{\sigma(\lambda_{obs})^2 + \sigma(\lambda_K)^2}} \leq 3$$

3. Accept line if there is only one identification satisfying the condition above, otherwise exclude (typical blend criterion is 3 km/s).

Laboratory wavelength data:

Eckberg 1975 and re-calibrations of Eckberg's data by Kramida 2014

Nominally 4mÅ wavelength uncertainties (although not a random error – see later slide)

Plus new laboratory measurements (2 independent laboratories)

Why FeV?

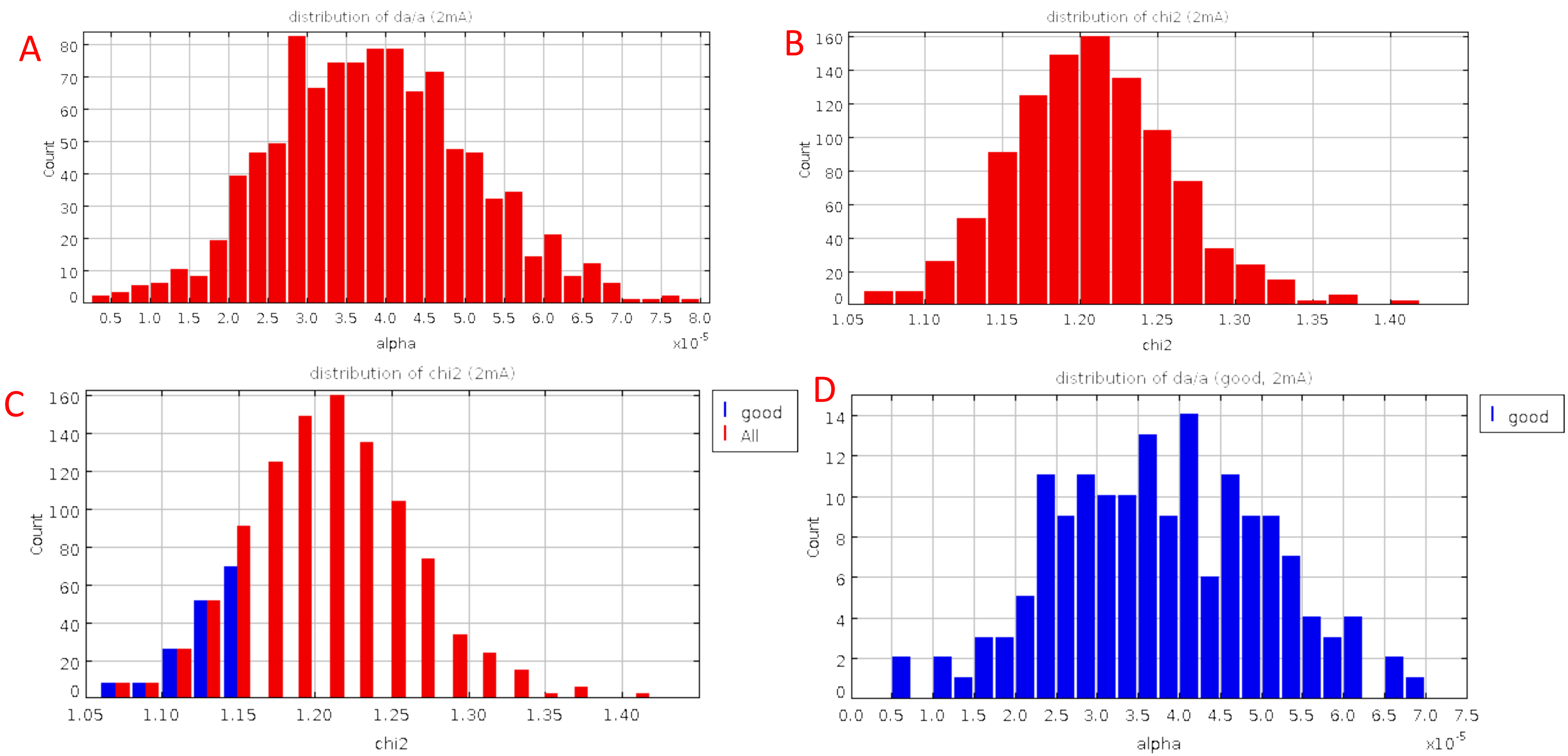
There are lots of lines with a broad q-range

Why not NiV or other species?

Fewer NiV lines. Lab wavelength uncertainties considerably worse

Test 1. The effect of random laboratory wavelength errors

- Simulate spectrum using {lab λs; the observed FeV line strengths; $\Delta\alpha/\alpha = 4.1 \times 10^{-5}$ (the observed value)}
- Add noise matching the real spectrum (and convolve to match STIS E140H)
- Add random uncertainties to the lab λs (in atom.dat)
- Measure $\Delta\alpha/\alpha$ in the simulated spectrum (VPFIT)
- Repeat 1000 times.



Test 1. The effect of random laboratory wavelength errors

TEST	$<\Delta\alpha/\alpha>$ $(\times 10^{-5})$	$\sigma(<\Delta\alpha/\alpha>)$ $(\times 10^{-5})$	$<\chi_n^2>$	$\sigma(<\chi_n^2>)$	# of trials with $\chi_n^2<1.15$
4mÅ (1000)			1.66	0.17	0
2mÅ (1000)	3.84	1.24	1.21	0.05	159
2mÅ (159)	3.78	1.27	1.13	0.02	159

Interpretation of 1.27 for 159 trials: distribution is comparable to the full 1000 trials. This supports an error of about 2mÅ and shows the approach is plausible.

Conclusions are:

(i) The data rule out random lab uncertainties of 4mÅ

(ii) The data marginally permit random lab uncertainties of up to 2mÅ

(iii) Assuming 2mÅ random uncertainties, we could accommodate a systematic uncertainty on $\Delta\alpha/\alpha$ of about 1.3×10^{-5}

(iv) This strongly motivates improving the lab wavelengths.

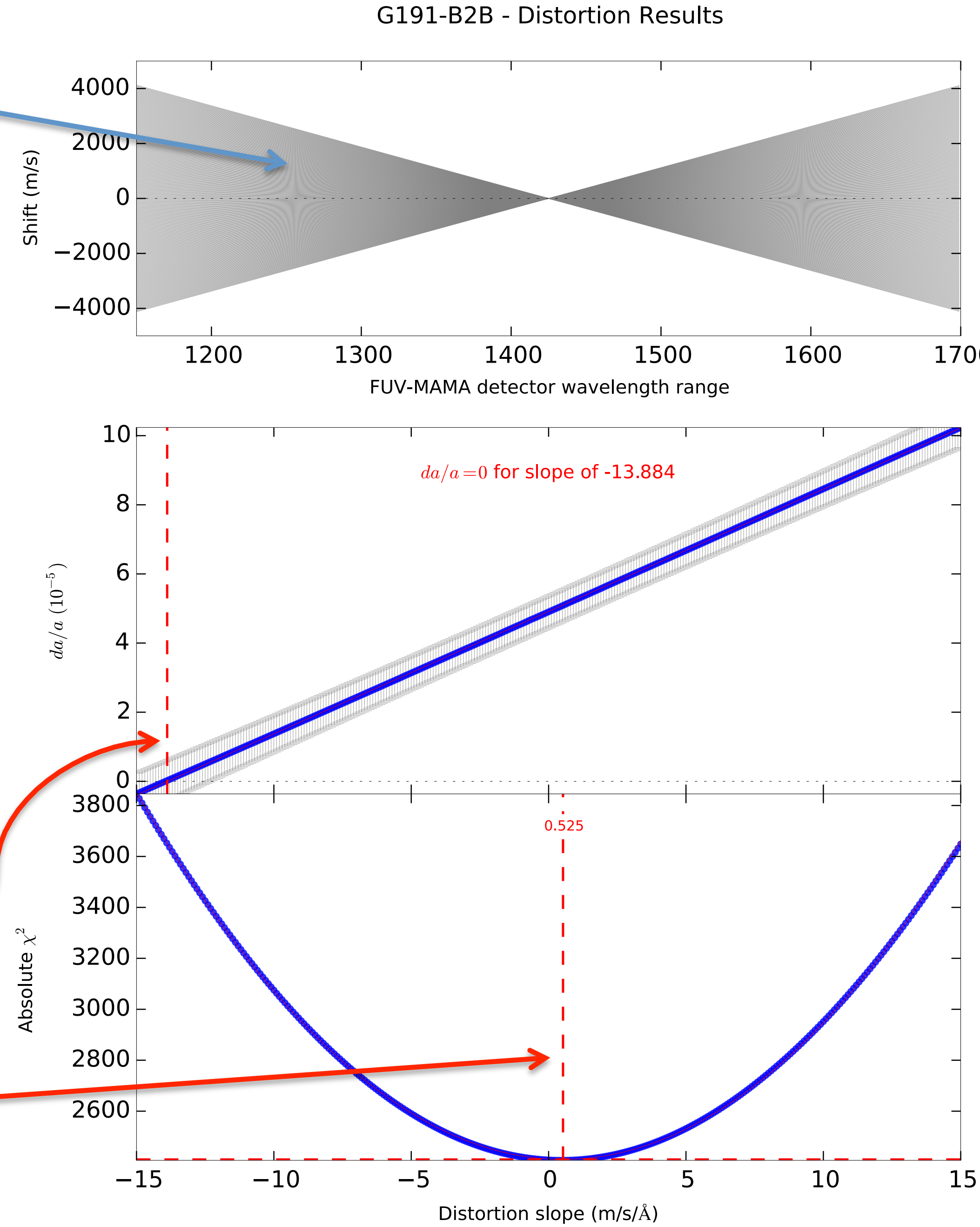
Test 2. Simple linear wavelength distortion

Range of models tried

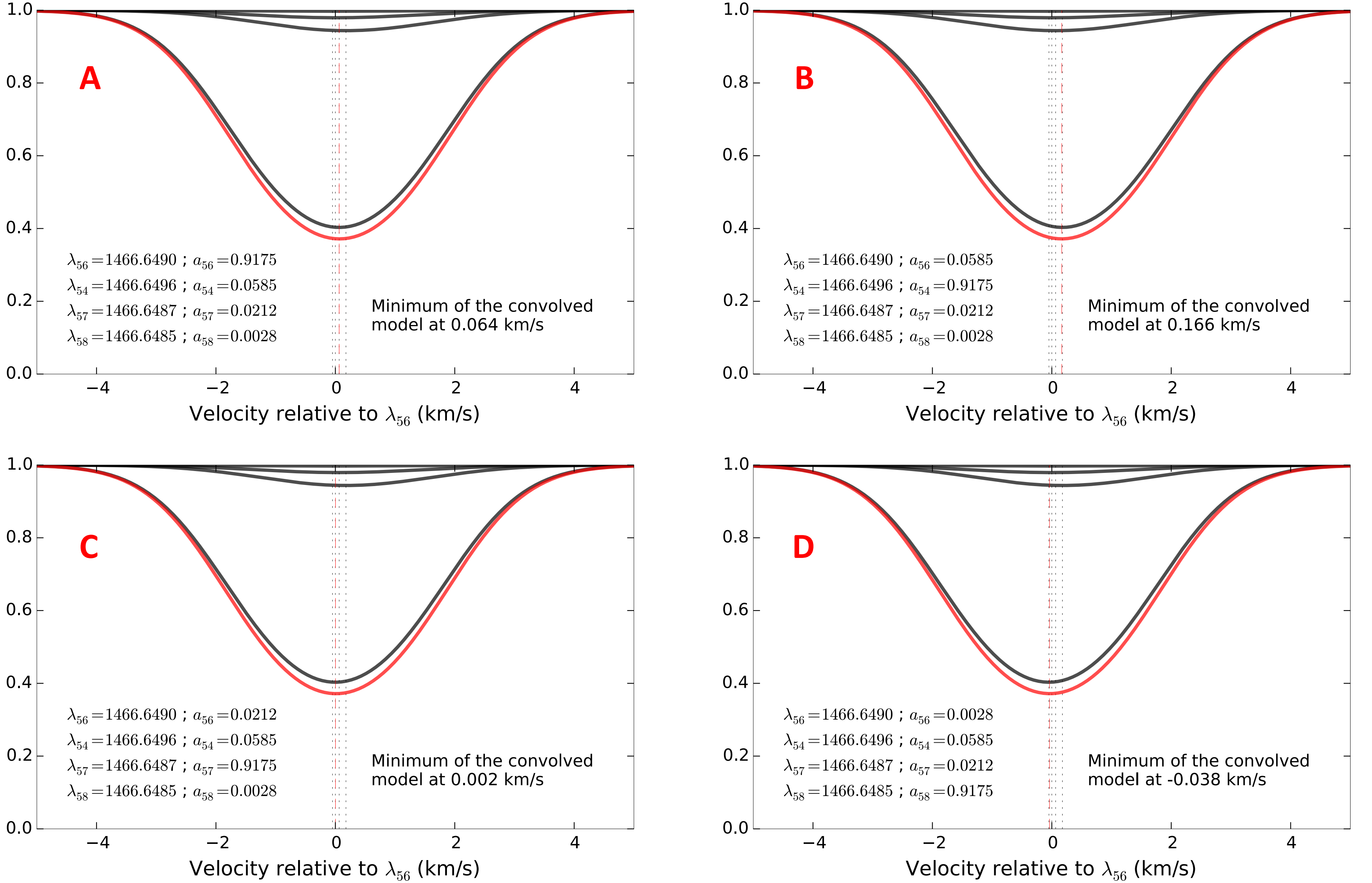
Applying this distortion makes α deviate further from terrestrial:
$\Delta\alpha/\alpha$ goes from $4.1 \pm 0.47 \times 10^{-5}$ (no distortion correction), to $\Delta\alpha/\alpha = 5.4 \pm 0.46 \times 10^{-5}$ (applying linear distortion of 0.5 m/s/Å

Forcing α to the terrestrial value requires a massive distortion, -14 m/s/Å, ruled out by the data itself

Best fit distortion model, 0.5 m/s/Å



Test 3. Varying the Fe isotopic relative abundances

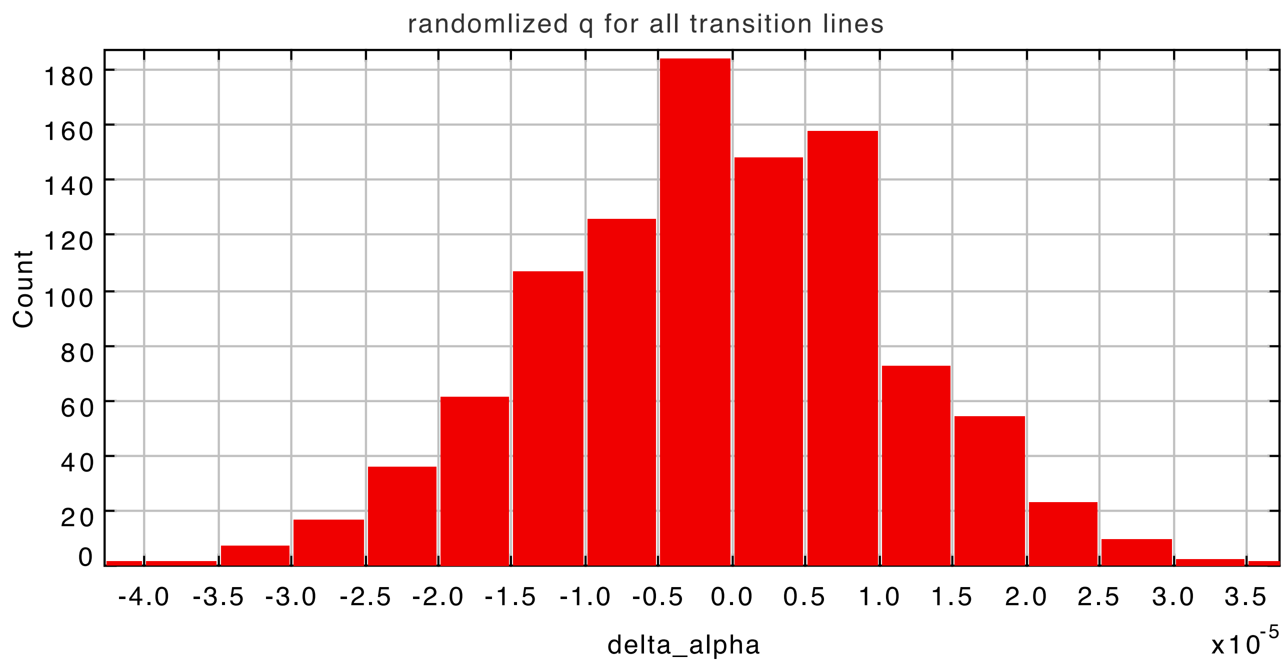


Simulation parameters: 10^{-4} Å/pixel, b=2 km/s

Test 4. Randomly re-assign α-sensitivity coefficients (q)

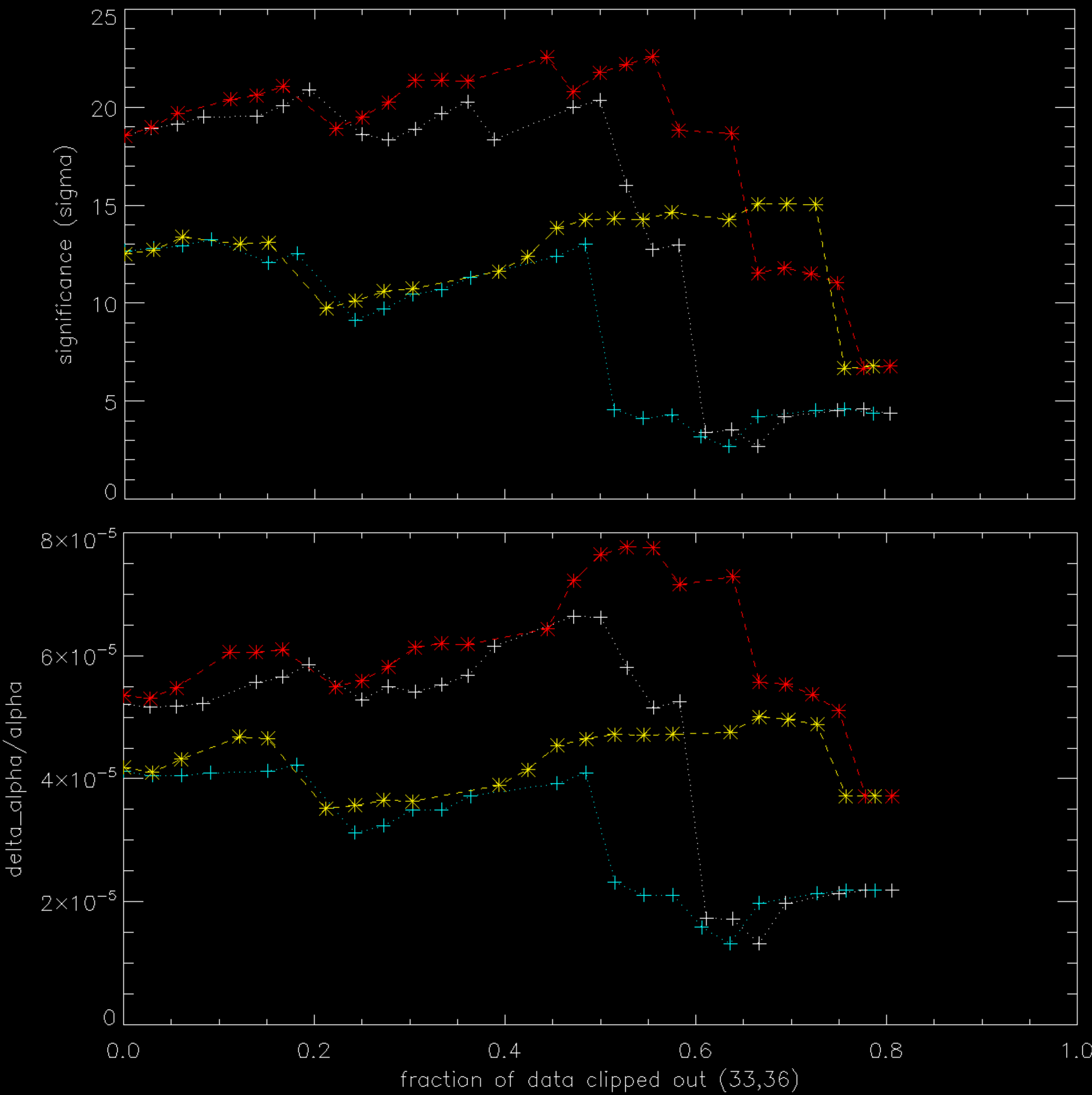
Randomise q's over the whole sample
1000 trials
$\Delta\alpha/\alpha = -1.02 \pm 11.87 \times 10^{-6}$
Or, error on mean (rather than dispersion): $-1.02e\text{-}6 \pm 0.38 \times 10^{-6}$

Global randomisation suggests things are working as expected



A refinement of this: Perhaps more informatively: Randomise q's within limited wavelength range about each line, i.e. allow for misidentifications (if present at all) to be local, rather than global). Not yet done.

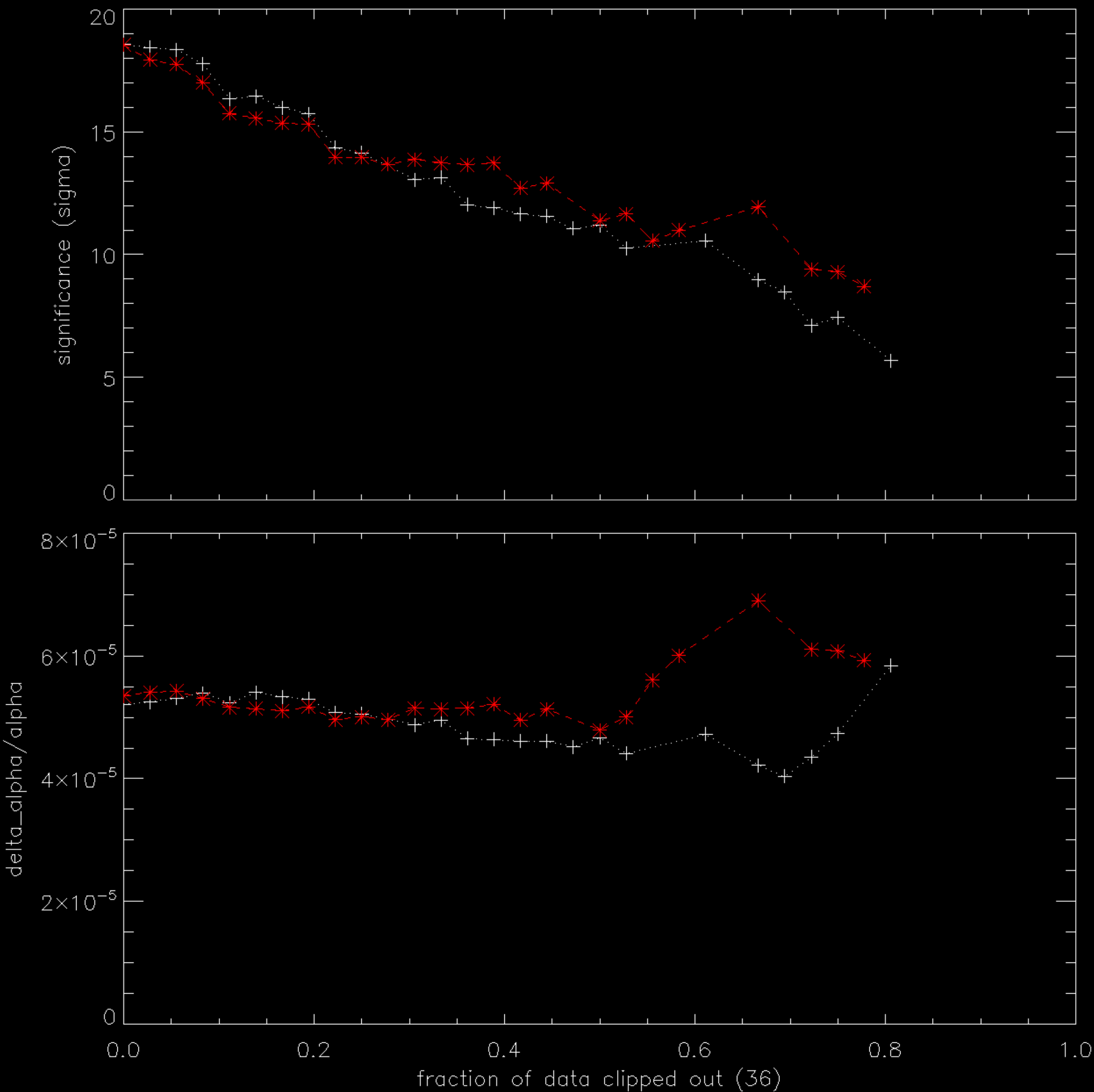
Test 5. Iteratively remove *most* discrepant FeV line



White: G191-B2B (36 lines)
Red: Synthetic (36 lines)
Blue: G191-B2B (33 lines)
Yellow: Synthetic (33 lines)

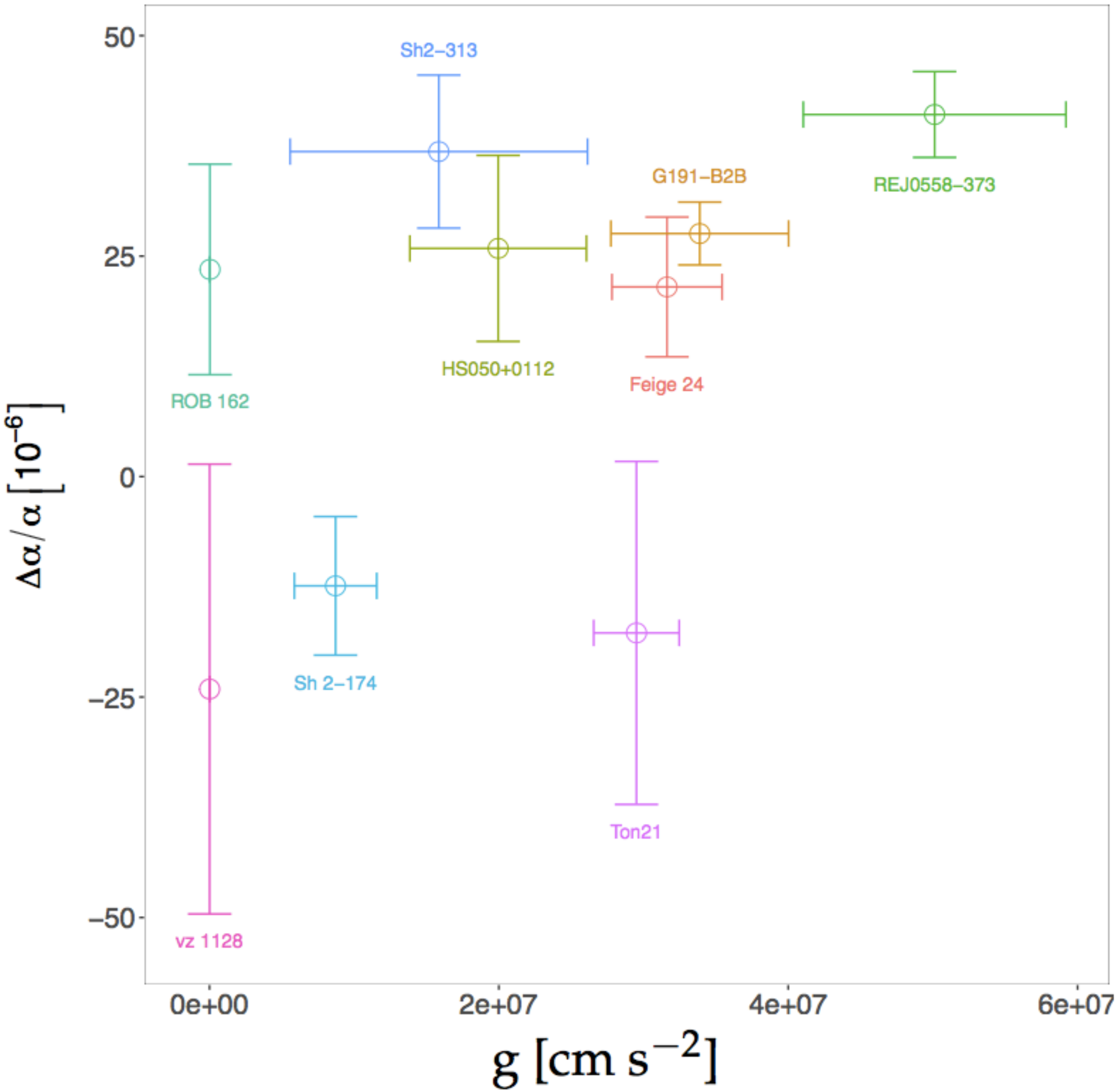
Why 36 ⟶ 33?
3 points appear to cause a sharp drop around f=0.6 and thus may be "spurious"

Test 6. Iteratively remove *least* discrepant FeV line



White: G191-B2B (36 lines)

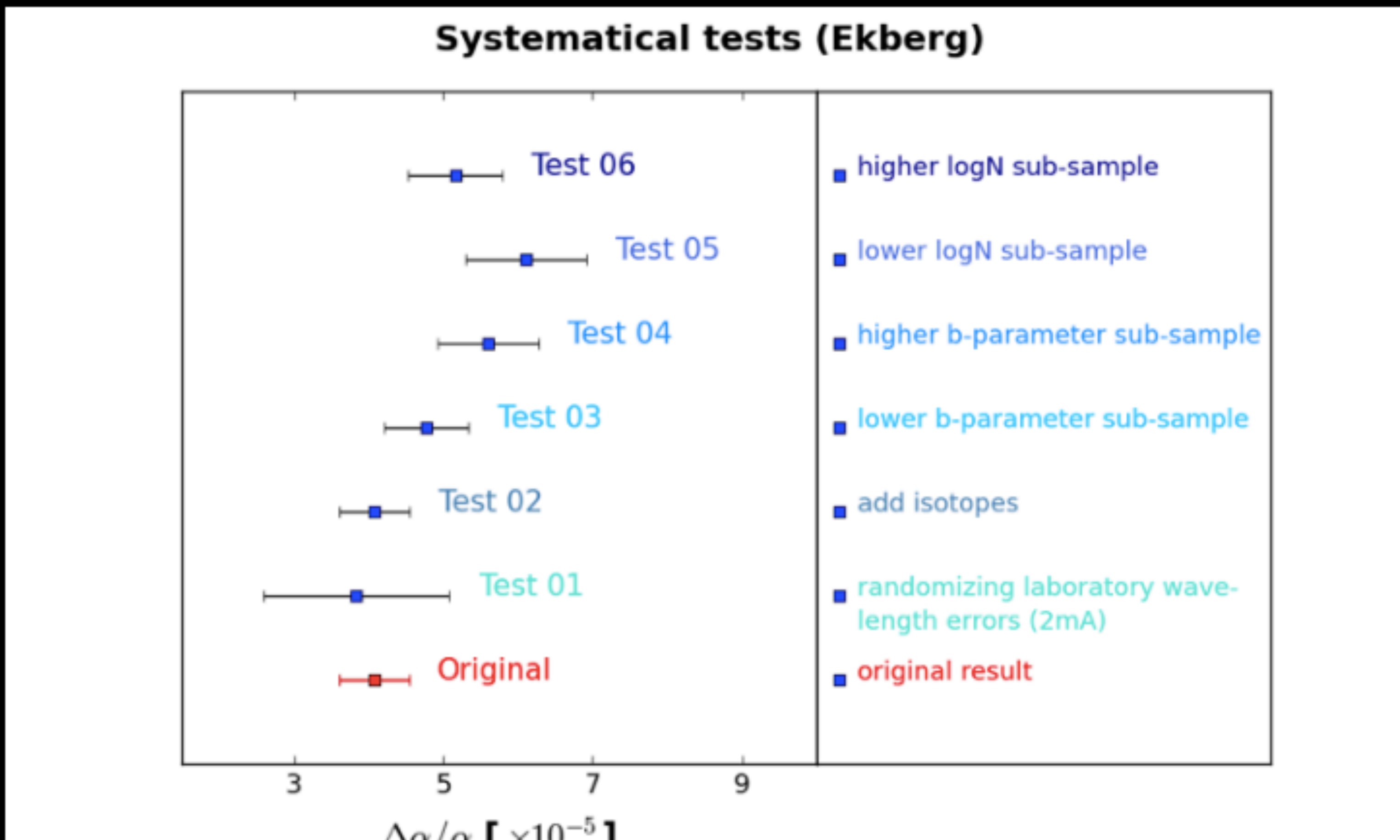
Red: Synthetic (36 lines)



Sh2−313
REJ0558−373
G191−B2B
ROB 162
HS050+0112
Feige 24
vz 1128
Sh 2−174
Ton21
50
25
0
−25
−50
0e+00
2e+07
4e+07
6e+07
Δα/α [10^−6]
g [cm s^−2]

Systematics Analysis

Using Fe V: $\Delta\alpha/\alpha = (4.1 +/- 0.47) \times 10^{-5}$



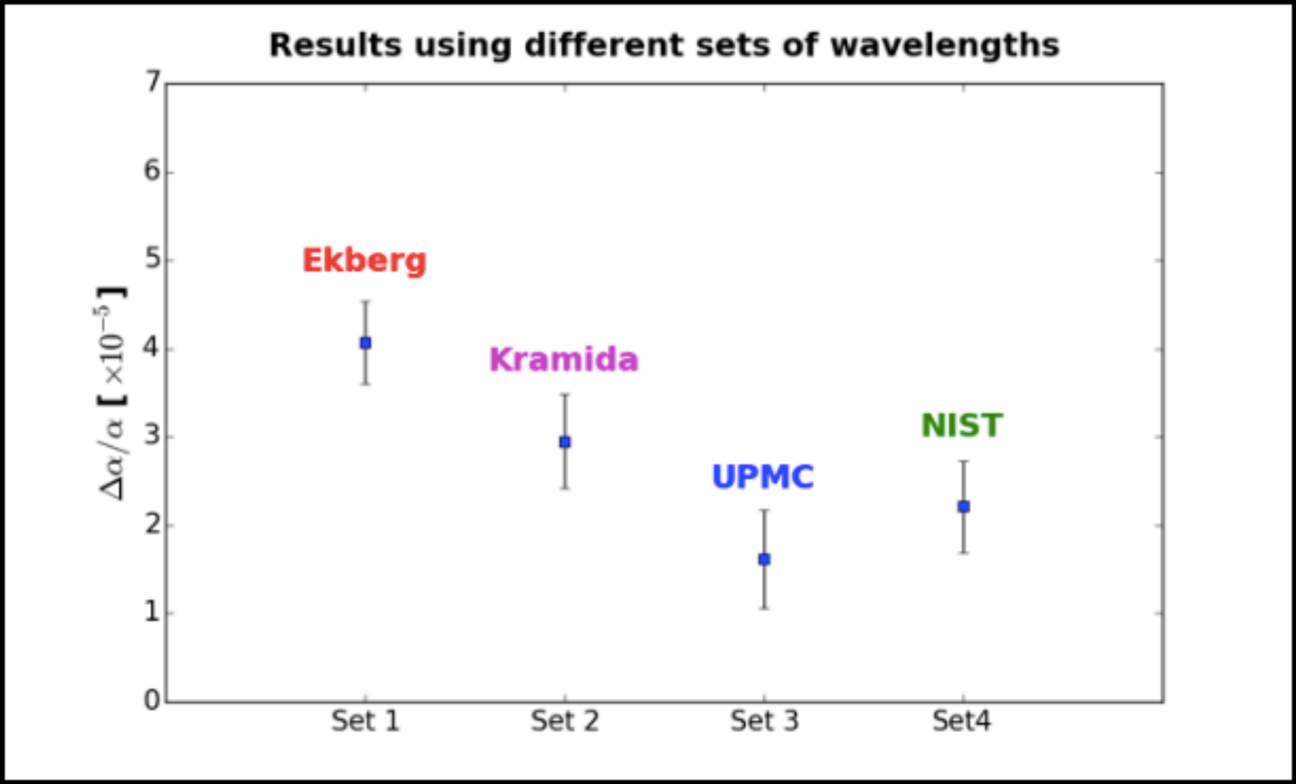
Systematics Analysis

Systematics Test	Constrain	Estimation
Zeeman quadratic shift	$B < 4$ T	$\sim 3 \times 10^{-6}$
Stark shift	$E = 7$ esu	$\sim 3 \times 10^{-12}$
Long-range distortion	linear distortion model	small effect

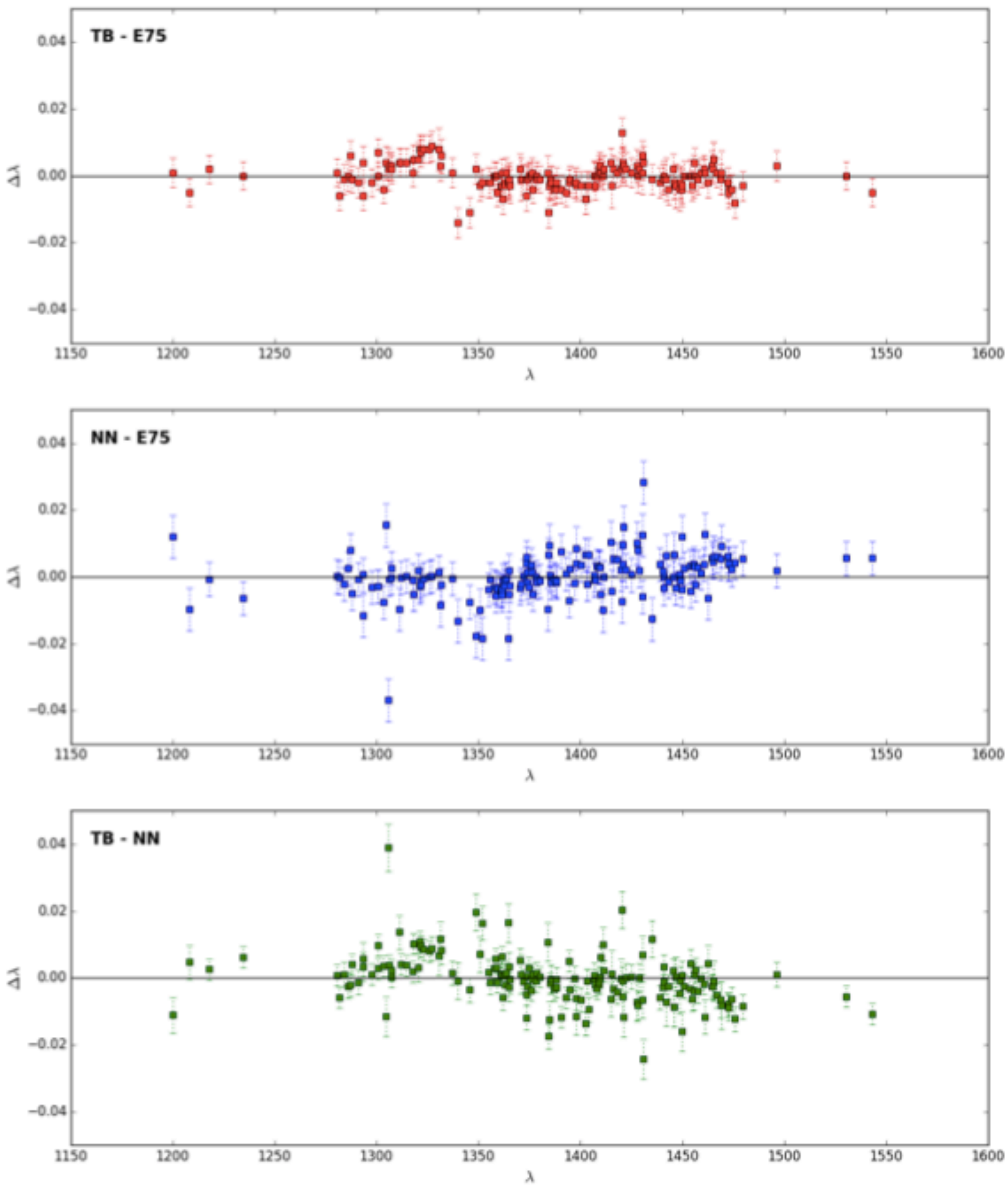
New results

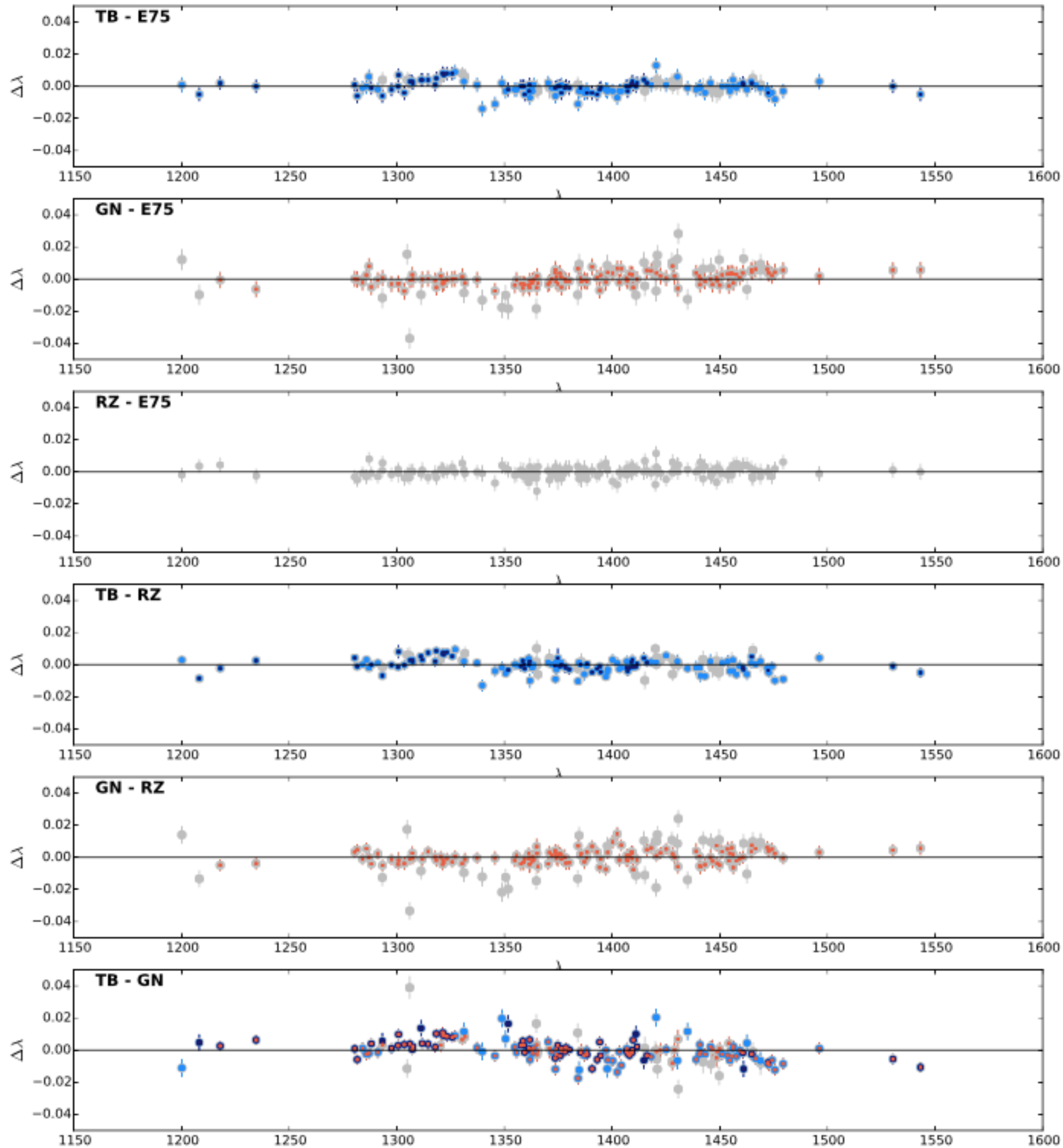
New laboratory wavelength measurements

Measurement	Uncertainties
Ekberg	4mA
UPMC	1 - 5 mA
NIST	3 - 5 mA



Comparison among 3 sets of laboratory wavelengths: Fe V (161 lines)





TB - E75
GN - E75
RZ - E75
TB - RZ
GN - RZ
TB - GN
Δλ
λ
0.04
0.02
0.00
−0.02
−0.04
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600

Closing remarks:

We have apparent non-zero results from several white dwarf photospheres.

Proper accounting for systematics is incomplete, so non-zero results should be considered as upper limits at present.

Laboratory wavelengths are particularly troublesome. But we now have 2 new independent experiments (NIST and Paris) AND in any case can look at *changes* in alpha from one WD to another

Nevertheless we are closing in on a very good understanding of all systematics

New Hubble Space Telescope STIS data is being collected this observing cycle. 10-12 independent measurements on a timescale of about a year