

Title: Variation of fundamental constants from Big Bang to atomic clocks: theory and observations

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Abstract: Theories unifying gravity with other interactions suggest temporal and spatial variation of the fundamental 'constants' in expanding Universe. The spatial variation can explain fine tuning of the fundamental constants which allows humans (and any life) to appear. We appeared in the area of the Universe where the values of the fundamental constants are consistent with our existence. I present a review of works devoted to the variation of the fine structure constant α , strong interaction and fundamental masses (Higgs vacuum). There are some hints for the variation in quasar absorption spectra and Big Bang nucleosynthesis data. A very promising method to search for the variation consists in comparison of different atomic clocks. Huge enhancement of the variation effects happens in transitions between very close atomic, nuclear and molecular energy levels. Large enhancement also happens in nuclear, atomic and molecular collisions near resonances. How changing physical constants may occur? Light scalar fields very naturally appear in modern cosmological models, affecting parameters of the Standard Model (e.g. α). Cosmological variations of these scalar fields should occur because of drastic changes of matter composition in Universe: the latest such event is rather recent (about 5 billion years ago), from matter to dark energy domination. Massive bodies can also affect physical constants. The strongest limits are obtained from the measurements of dependence of atomic frequencies on the distance from Sun (the distance varies due to the ellipticity of the Earth's orbit).

Motivation

- **Extra space dimensions** (Kaluza-Klein, Superstring and M-theories). Extra space dimensions is a common feature of theories unifying **gravity** with other interactions. Any change in size of these dimensions would manifest itself in the 3D world as variation of fundamental constants.
- **Scalar fields** . Fundamental constants depend on scalar fields which vary in space and time (variable vacuum dielectric constant ϵ_0). May be related to “dark energy” and accelerated expansion of the Universe..
- **“Fine tuning”** of fundamental constants is needed for humans to exist. Example: low-energy resonance in production of carbon from helium in stars ($\text{He}+\text{He}+\text{He}=\text{C}$). Slightly different coupling constants — no resonance — no life.

Variation of coupling constants in space provide natural explanation of the “fine tuning”: we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

Search for variation of fundamental constants

- Big Bang Nucleosynthesis
- Quasar Absorption Spectra ¹
- Oklo natural nuclear reactor
- Atomic clocks ¹
- Enhanced effects in atoms ¹, molecules¹ and nuclei
- Dependence on gravity

Search for variation of fundamental constants

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evidence?

evidences¹

Dimensionless Constants

Since variation of dimensional constants cannot be distinguished from variation of units, it only makes sense to consider variation of dimensionless constants.

- **Fine structure constant** $\alpha = e^2 / \hbar c = 1/137.036$
- **Electron or quark mass/QCD strong interaction scale**, $m_{e,q} / \Lambda_{\text{QCD}}$

$$\alpha_{\text{strong}}(r) = \text{const} / \ln(r \cdot \Lambda_{\text{QCD}} / \hbar c)$$

$m_{e,q}$ are proportional to Higgs vacuum (weak scale)

Relation between variations of different coupling constants Grand unification models

$$\alpha_i^{-1}(\nu) = \alpha_{GUT}^{-1} + b_i \ln(\nu / \nu_0)$$

Variation of GUT const α_{GUT}

$$d\alpha_1^{-1} = d\alpha_2^{-1} = d\alpha_3^{-1} = d\alpha_{GUT}^{-1}$$

$$d\alpha_3 / \alpha_3 = (\alpha_3 / \alpha_1) d\alpha_1 / \alpha_1$$

$$\alpha_3^{-1}(m) = \alpha_{\text{strong}}^{-1}(m) = b_3 \ln(m / \Lambda_{\text{QCD}})$$

$$\alpha^{-1}(m) = 5/3 \alpha_1^{-1}(m) + \alpha_2^{-1}(m)$$

$$\frac{\Delta(m / \Lambda_{\text{QCD}})}{m / \Lambda_{\text{QCD}}} = \frac{1}{b_3 \alpha_3} \frac{\Delta \alpha_3}{\alpha_3} = \frac{\text{const}}{\alpha} \frac{\Delta \alpha}{\alpha} \approx 35 \frac{\Delta \alpha}{\alpha}$$

1. Proton mass $M_p \approx 3 \Lambda_{\text{QCD}}$, measure m_e / M_p

2. Nuclear magnetic moments

$$\mu = g e \hbar / 4 M_p c, \quad g = g(m_q / \Lambda_{\text{QCD}})$$

3. Nuclear energy levels and resonances

Nucleon magnetic moment

$$\mu = \mu_0 (1 + am_\pi + \dots) = \mu_0 (1 + b\sqrt{m_q} + \dots)$$

Nucleon and meson masses

$$M = M_0 + am_q$$

QCD calculations: lattice, chiral perturbation theory, cloudy bag model, Dyson-Schwinger and Faddeev equations, semiempirical.

Nuclear calculations: meson exchange theory of strong interaction. Nucleon mass in kinetic

Big Bang Nucleosynthesis:

Dependence on $m_q / \Lambda_{\text{QCD}}$

- ^2H $1+7.7x=1.07(15)$ $x=0.009(19)$
- ^4He $1-0.95x=1.005(36)$ $x=-0.005(38)$
- ^7Li $1-50x=0.33(11)$ $x=0.013(02)$

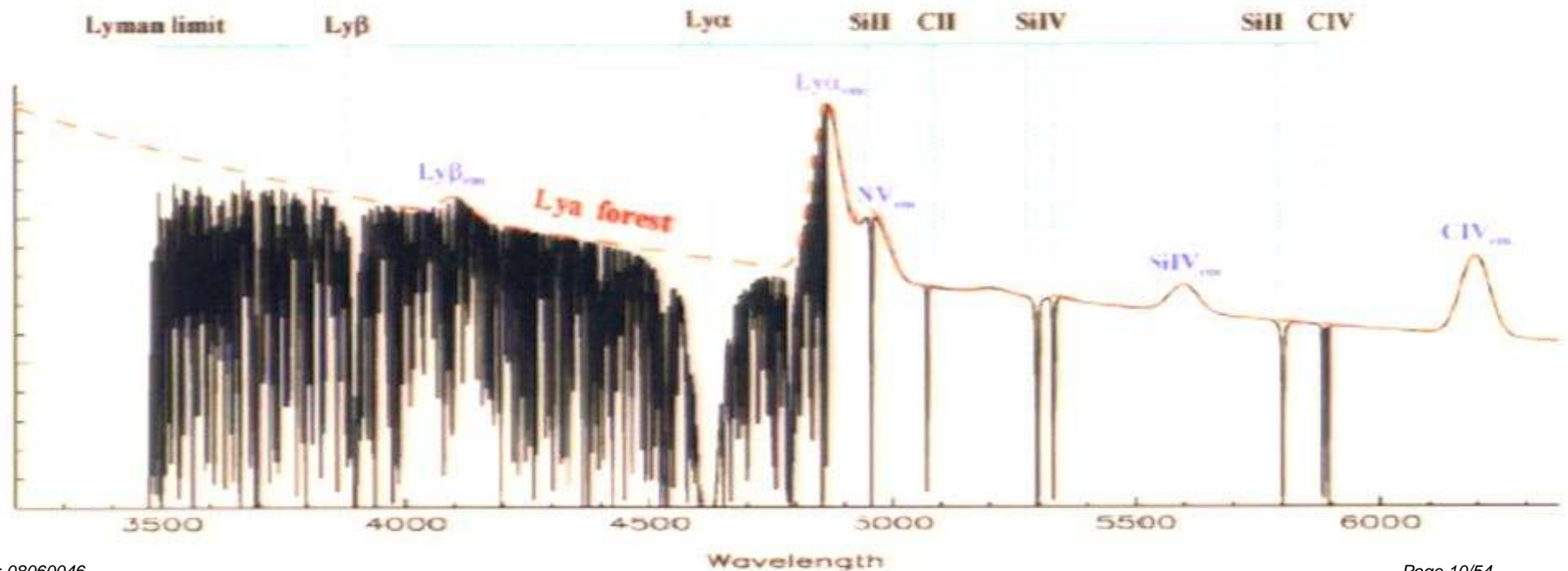
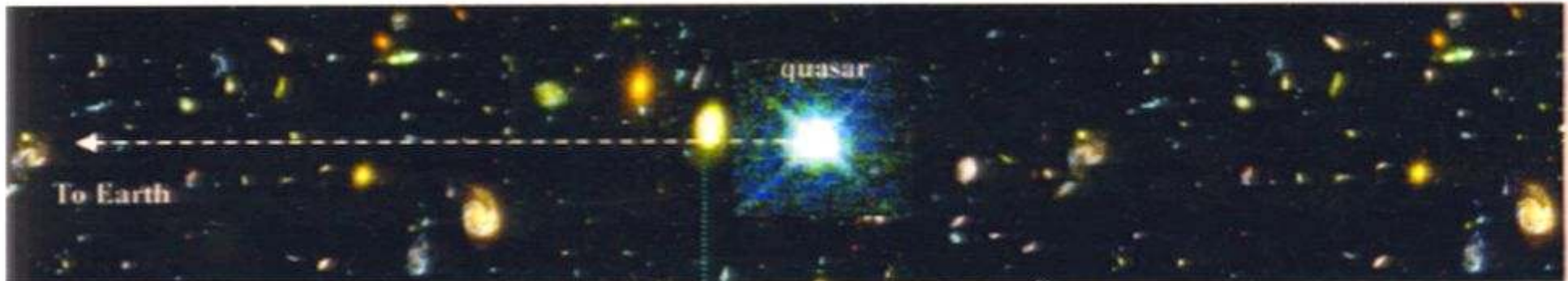
Final result

$$x = \Delta X_q / X_q = 0.013(02), \quad X_q = m_q / \Lambda_{\text{QCD}}$$

Dominated by ^7Li abundance (3 times difference), consistent with $^2\text{H}, ^4\text{He}$

$$\text{Nonlinear effects: } x = \Delta X_q / X_q = 0.015(02)$$

4.2 Astrophysical constraints: Quasars - probing the universe back to much earlier times



Variation of fine structure constant α

Many-Multiplet Method

Relativistic correction to electron energy E_n :

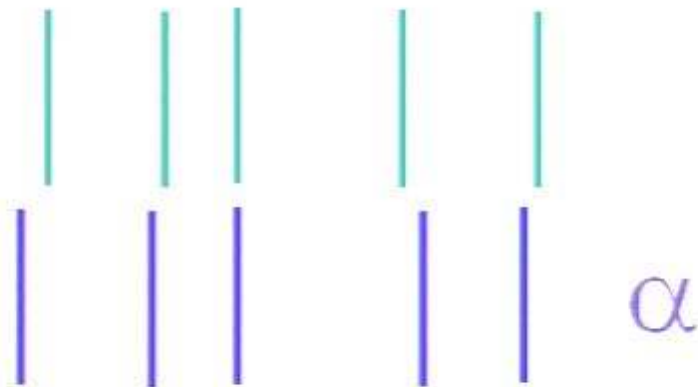
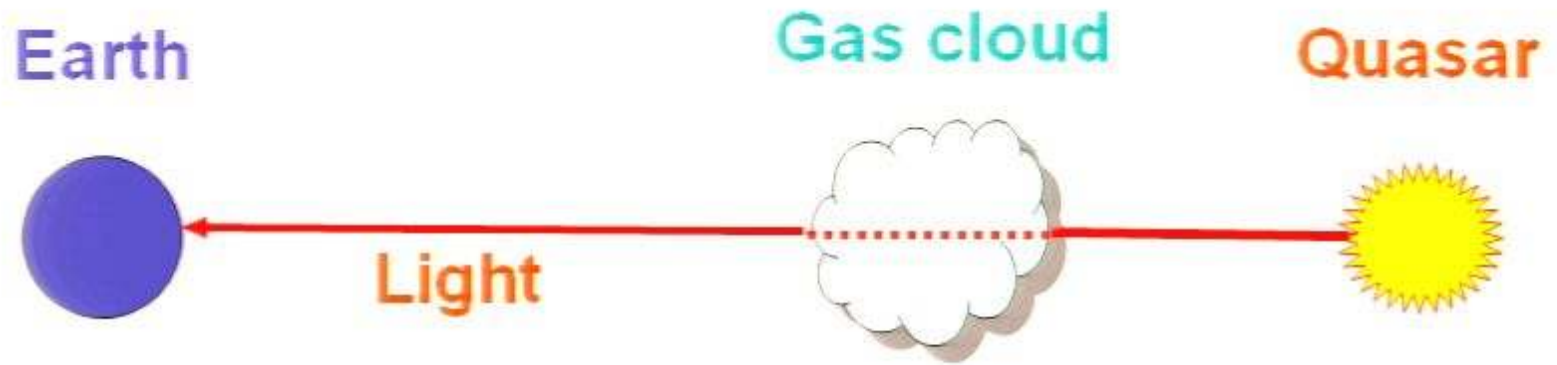
$$\Delta_n = \frac{E_n}{\nu} (Z\alpha)^2 \left[\frac{1}{j + 1/2} - C(Z, j, l) \right] \quad C \approx 0.6$$

1. Increases with nuclear charge Z .
2. Changes sign for higher angular momentum j .

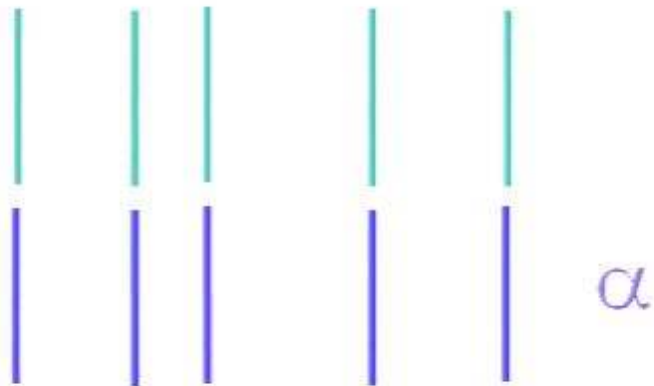
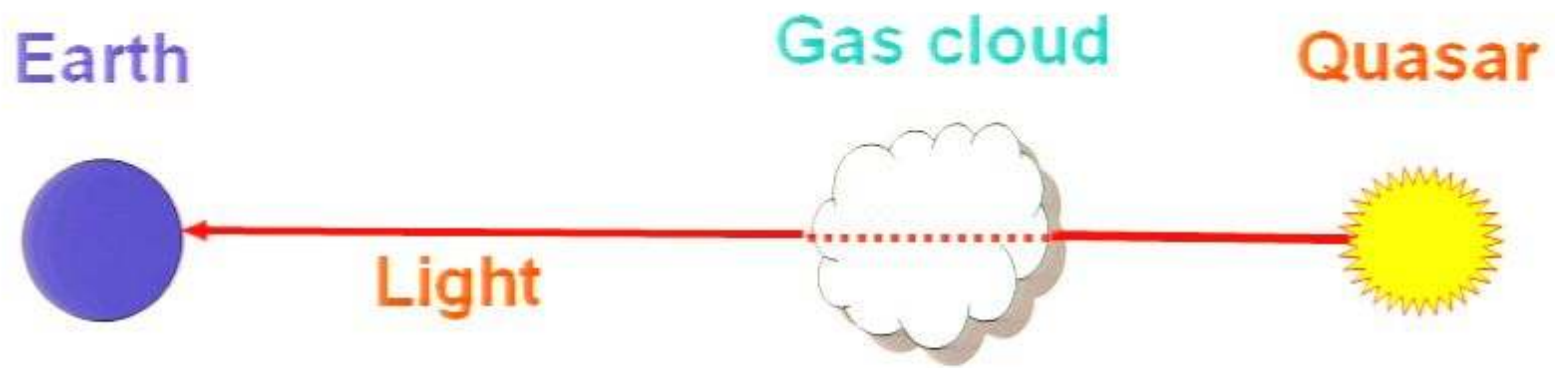
Quasar absorption spectra



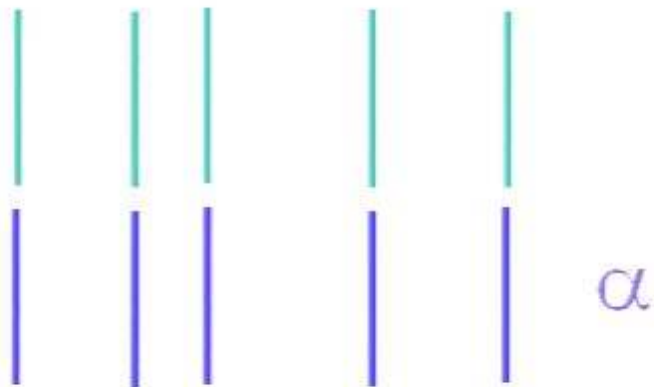
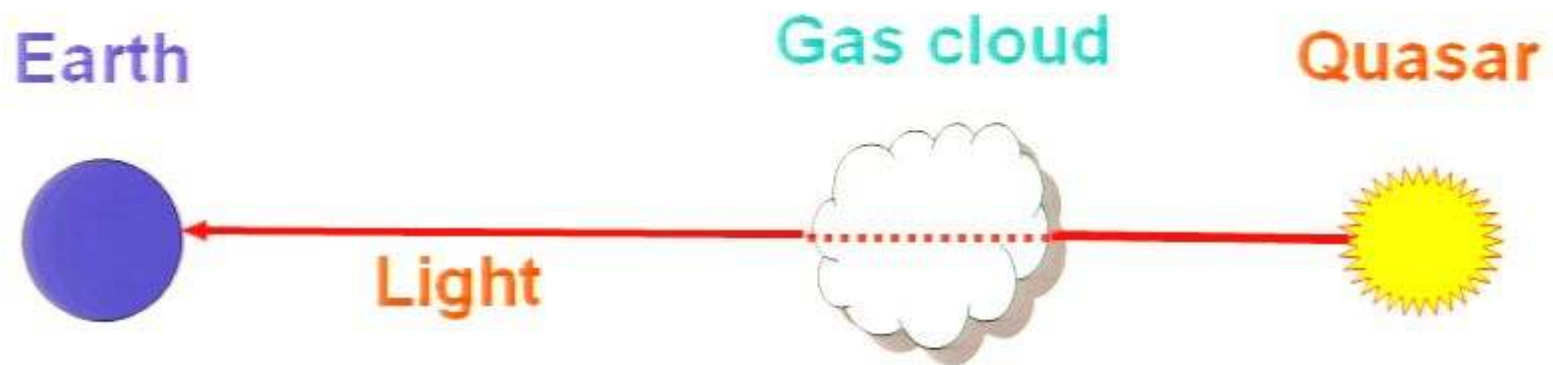
Quasar absorption spectra



Quasar absorption spectra



Quasar absorption spectra



One needs to know $E(\alpha^2)$ for each line to do the fitting

Use atomic calculations to find $\omega(\alpha)$.

For α close to α_0 $\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$

q is found by varying α in computer codes:

$$q = d\omega/dx = [\omega(0.1) - \omega(-0.1)]/0.2, \quad x = \alpha^2/\alpha_0^2 - 1$$

$\alpha = e^2/hc = 0$ corresponds to non-relativistic limit (infinite c).

Methods were used for many important problems:

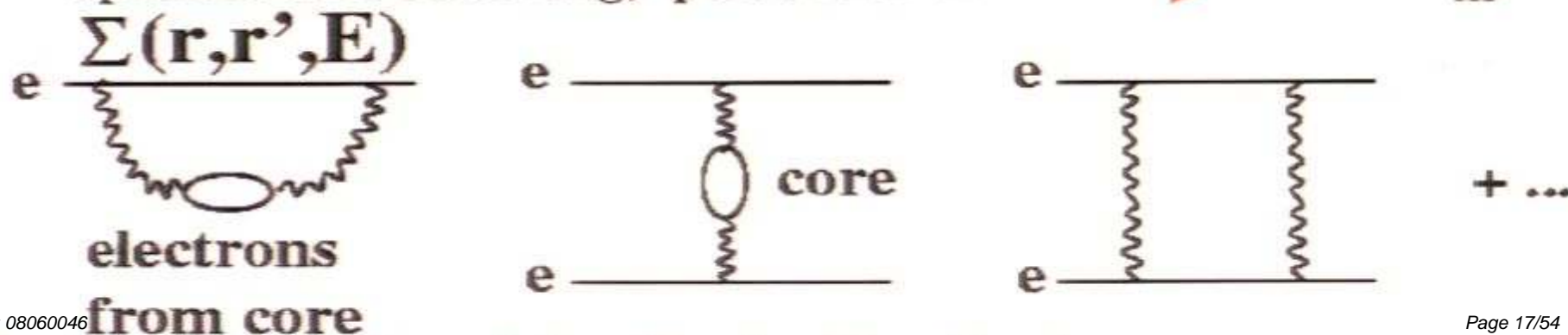
- Test of Standard Model using Parity Violation in Cs, Tl, Pb, Bi
- Predicting spectrum of **Fr (accuracy 0.1%)**, etc.

Probing the variability of α with QSO absorption lines

To find dependence of atomic transition frequencies on α we have performed calculations of atomic transition frequencies for different values of α .

1. Zero Approximation – Relativistic Hartree-Fock method: energies, wave functions, Green's functions

2. Many-body perturbation theory to calculate effective Hamiltonian for valence electrons including self-energy operator and screening; perturbation $\longrightarrow V = H - H_{\text{HF}}$



3. Diagonalization of the effective Hamiltonian

Results of calculations (in cm^{-1})

Anchor lines

Atom	ω_0	q
Mg I	35051.217	86
Mg II	35760.848	211
Mg II	35669.298	120
Si II	55309.3365	520
Si II	65500.4492	50
Al II	59851.924	270
Al III	53916.540	464
Al III	53682.880	216
Ni II	58493.071	-20

Also, many transitions in Mn II, Ti II, Si IV, C II, C IV, N V, O I, Ca I, Ca II, Ge II, O II, Pb II

Negative shifters

Atom	ω_0	q
Ni II	57420.013	-1400
Ni II	57080.373	-700
Cr II	48632.055	-1110
Cr II	48491.053	-1280
Cr II	48398.862	-1360
Fe II	62171.625	-1300

Positive shifters

Atom	ω_0	q
Fe II	62065.528	1100
Fe II	42658.2404	1210
Fe II	42114.8329	1590
Fe II	41968.0642	1460
Fe II	38660.0494	1490
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Different signs and magnitudes of q provides opportunity to study systematic errors!

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hyperfine = $\alpha^2 g_p m_e / M_p$ atomic units

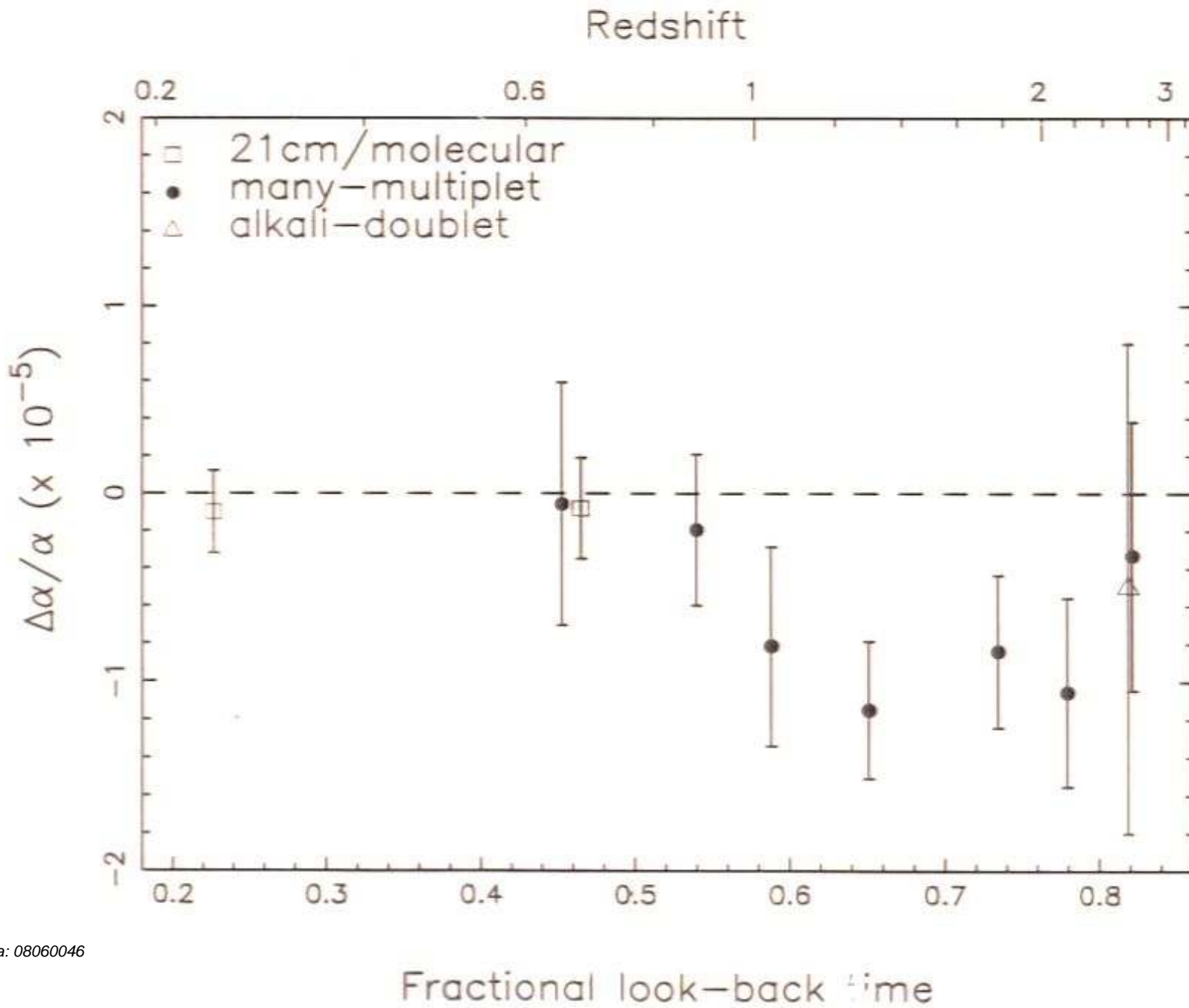
Rotation = m_e / M_p atomic units

Variation in the fine structure constant?: Recent results and the future

Radio constraints:

- Hydrogen hyperfine transition at $\lambda_H = 21\text{cm}$.
- Molecular rotational transitions CO, HCO⁺, HCN, HNC, CN, CS ...
- $\omega_H / \omega_M \propto \alpha^2 g_p$ where g_p is the proton magnetic g -factor.

$$g_p = g_p \left(\frac{m_p}{\Lambda_{QED}} \right)$$



- Murphy et al, 2003: **Keck telescope**, 143 systems, 23 lines, $0.2 < z < 4.2$
 $\Delta\alpha/\alpha = -0.54(0.12) \times 10^{-5}$

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$$\Delta\alpha/\alpha = -0.54(0.12) \times 10^{-5}$$

- Quast et al, 2004: **VL telescope**, 1 system, Fe II, 6 lines, 5 positive q -s, one negative q , $z=1.15$

$$\Delta\alpha/\alpha = -0.4(1.9)(2.7) \times 10^{-6}$$

- Srianand et al, 2004: **VL telescope**, 23 systems, 12 lines, Fe II, Mg I, Si II, Al II, $0.4 < z < 2.3$

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

Murphy et al 2007 $\Delta\alpha/\alpha = -0.64(0.36) \times 10^{-5}$
Further revision may be necessary.

Spatial variation (Steinhardt list update)

$$10^5 \Delta\alpha/\alpha$$

Murphy et al

- North hemisphere -0.66(12)
- South (close to North) -0.36(19)

Strianand et al (South) -0.06(06)??

Murphy et al (South) -0.64(36)

Measurements m_e / M_p or $m_e / \Lambda_{\text{QCD}}$

- Tsanavaris, Webb, Murphy, Flambaum, Curran PRL 2005

Hyperfine H/optical , 9 quasar absorption systems with Mg, Ca, Mn, C, Si, Zn, Cr, Fe, Ni

Measured $X = \alpha^2 g_p m_e / M_p$

$\Delta X / X = 0.6(1.0) 10^{-5}$ **No variation**

Best limit from ammonia NH₃

Flambaum, Kozlov PRL2007

Inversion spectrum: exponentially small “quantum tunneling”
frequency $\omega_{\text{inv}} = W \exp(-S)$

$$S = \frac{(m_e / M_p)^{-0.5}}{(m_e / M_p)^{-0.5}} f(E_{\text{vibration}}/E_{\text{atomic}}), \quad E_{\text{vibration}}/E_{\text{atomic}} = \text{const}$$

ω_{inv} is exponentially sensitive to m_e / M_p

First enhanced effect in quasar spectra, 5 times

$$\Delta(m_e / M_p) / (m_e / M_p) = -0.6(1.9)10^{-6} \quad \text{No variation}$$

$z=0.68$, 6.5 billion years ago, $-1(3)10^{-16}$ /year

More accurate measurements Murphy, Flambaum, Henkel,
Muller Science 2008 $-0.74(0.47)10^{-6}$

Measurements m_e / M_p or $m_e / \Lambda_{\text{QCD}}$

- Reinhold, Buning, Hollenstein, Ivanchik, Petitjean, Ubachs PRL 2006 , H₂ molecule, 2 systems

$$\Delta(m_e / M_p) / (m_e / M_p) = -2.4(0.6) 10^{-5} \quad \text{Variation } 4\sigma!$$

Higher redshift, $z=2.8$

Space-time variation? Grand Unification model?

Oklo natural nuclear reactor

1.8 billion years ago

$n + {}^{149}\text{Sm}$ capture cross section is dominated
by $E_r = 0.1 \text{ eV}$ resonance

Shlyakhter; Damour, Dyson; Fujii et al

$$\Delta E_r = 1 \text{ MeV } \Delta\alpha/\alpha$$

Limits on variation of alpha

Oklo: limits on $X_q = m_q / \Lambda_{\text{QCD}}$

Flambaum, Shuryak 2002, 2003 Dmitriev, Flambaum 2003

Flambaum, Wiringa 2007

$$^{150}\text{Sm} \quad \Delta E_r = 10 \text{ MeV} \quad \Delta X_q / X_q = 1 \text{ MeV} \quad \Delta \alpha / \alpha$$

Limits on $x = \Delta X_q / X_q = 0.1 \Delta \alpha / \alpha$ from

$$\text{Fujii et al} \quad |\Delta E_r| < 0.02 \text{ eV} \quad |x| < 2 \cdot 10^{-9}$$

$$\text{Petrov et al} \quad |\Delta E_r| < 0.07 \text{ eV} \quad |x| < 8 \cdot 10^{-9}$$

$$\text{Gould et al} \quad |\Delta E_r| < 0.026 \text{ eV} \quad |x| < 3 \cdot 10^{-9}, < 1.6 \cdot 10^{-18} \text{ y}^{-1}$$

There is second, non-zero solution $x = 1.0(1) \cdot 10^{-8}$

Atomic clocks:

Comparing rates of different clocks over long period of time can be used to study time variation of fundamental constants!

Optical transitions: α

Microwave transitions: $\alpha, (m_e, m_q)/\Lambda_{\text{QCD}}$

Calculations to link change of frequency to change of fundamental constants:

Optical transitions: atomic calculations (as for quasar absorption spectra) for many narrow lines in Al II, Ca I, Sr I, Sr II, In II, Ba II, Dy I, Yb I, Yb II, Yb III, Hg I, Hg II, Tl II, Ra II .

$$\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$$

Microwave transitions: hyperfine frequency is sensitive to nuclear magnetic moments and nuclear radii

We performed atomic, nuclear and QCD calculations of powers κ, β for H, D, Rb, Cd⁺, Cs, Yb⁺, Hg⁺

$$V = C(\text{Ry})(m_e/M_p)\alpha^{2+\kappa} (m_q/\Lambda_{\text{QCD}})^\beta, \quad \Delta\omega/\omega = \Delta V/V$$

Results for variation of fundamental constants

Source	Clock ₁ /Clock ₂	$d\alpha/dt/\alpha(10^{-16} \text{ yr}^{-1})$
Blatt <i>et al.</i> 2007	Sr(opt)/Cs(hfs)	-3.1(3.0)
Fortier <i>et al.</i> 2007	Hg+(opt)/Cs(hfs)	-0.6(0.7) ^a
Rosenband <i>et al.</i> 08	Hg+(opt)/Al+(opt)	-0.16(0.23)
Peik <i>et al.</i> 2006	Yb+(opt)/Cs(hfs)	4(7)
Bize <i>et al.</i> 2005	Rb(hfs)/Cs(hfs)	1(10) ^a

^aassuming $m_q/\Lambda_{QCD} = \text{Const}$

Combined results: $d/dt \ln \alpha = -1.6(2.3) \times 10^{-17} \text{ yr}^{-1}$
 $d/dt \ln(m_q/\Lambda_{QCD}) = 8(22) \times 10^{-15} \text{ yr}^{-1}$

m_e/M_p or $m_e/\Lambda_{QCD} -1.9(4.0) \times 10^{-16} \text{ yr}^{-1}$

Enhancement of relative effect

Dy: $4f^{10}5d6s$ $E=19797.96\dots \text{ cm}^{-1}$, $q= 6000 \text{ cm}^{-1}$

$4f^95d^26s$ $E=19797.96\dots \text{ cm}^{-1}$, $q= -23000 \text{ cm}^{-1}$

Interval $\Delta\omega = 10^{-4} \text{ cm}^{-1}$



Enhancement factor **$K = 10^8$** (!), i.e. $\Delta\omega/\omega_0 = 10^8 \Delta\alpha/\alpha$

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Measurement Berkeley **$d\ln\alpha/dt = -2.9(2.6) \times 10^{-15} \text{ yr}^{-1}$**

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Close narrow levels in molecules and nucleus ^{229}Th

Cancellation between fine structure and vibrations in molecules

Flambaum, Kozlov PRL2007 **$K = 10^4 - 10^5$** ,

SiBr, Cl₂⁺ ... microwave transitions between narrow excited states, sensitive to α and $\mu = m_e/M_p$

$$\omega_0 = E_{\text{fine}} - E_{\text{vibrational}} = E_{\text{fine}}/K$$

$$\Delta\omega/\omega_0 = K (\Delta\alpha/\alpha - 1/4 \Delta\mu/\mu)$$

Enhancement **$K = 10^4 - 10^5$**

E_{fine} is proportional to $Z^2\alpha^2$

$E_{\text{vibrational}} = n\omega$ is proportional to $n\mu^{0.5}$, $n=1,2,\dots$

Enhancement for all molecules along the lines $Z(\mu, n)$

Shift 0.003 Hz for $\Delta\alpha/\alpha = 10^{-16}$; **width 0.01 Hz**

Compare with Cs/Rb hyperfine shift 10^{-6} Hz

HfF⁺ **$K = 10^3$** shift 0.1 Hz

Nuclear clocks

(suggested by Peik, Tamm 2003)

Very narrow UV transition between first excited and ground state in ^{229}Th nucleus

Energy 7.6(5) eV, width 10^{-4} Hz

Flambaum PRL2006

Nuclear/QCD estimate: Enhancement 10^5 ,

$$\Delta\omega/\omega_0 = 10^5 (0.1\Delta\alpha/\alpha + \Delta X_q/X_q)$$

$$X_q = m_q / \Lambda_{\text{QCD}},$$

Shift 10^5 Hz for $\Delta\alpha/\alpha = 10^{-15}$

Compare with atomic clock shift 1 Hz

^{235}U energy 76 eV, width $6 \cdot 10^{-4}$ Hz

Dependence of fundamental constants on gravitational potential

Projects –atomic clocks at satellites in space or close to Sun

Earth orbit is elliptic, 3% change in distance to Sun

Fortier et al – Hg^{+(opt)}/Cs , Ashby et al -H/Cs

Flambaum, Shuryak : limits on dependence of α , m_e/Λ_{QCD} and m_q/Λ_{QCD} on gravity

$$\delta\alpha/\alpha = K_\alpha \delta(\mathbf{GM}/rc^2)$$

$$K_\alpha + 0.17K_e = -3.5(6.0) 10^{-7}$$

$$K_\alpha + 0.13 K_q = 2(17) 10^{-7}$$

New results from Dy, Sr/Cs

Dysprosium $\delta\alpha/\alpha = K_\alpha \delta(GM/rc^2)$

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Measurements Ferrel et al 2007

$$K_\alpha = -8.7(6.6) \cdot 10^{-6}$$

$$K_e = 4.9(3.9) \cdot 10^{-6} \quad K_q = 6.6(5.2) \cdot 10^{-6}$$

Sr(optical)/Cs comparison : S.Blatt et al 2008

New best limits

$$K_{\alpha} = 2.5(3.1) \cdot 10^{-6}$$

$$K_e = -1.1(1.7) \cdot 10^{-6}$$

$$K_q = -1.9(2.7) \cdot 10^{-6}$$

Conclusions

- Quasar data: MM method provided sensitivity increase 100 times. Anchors, positive and negative shifters-control of systematics. Keck-variation of α , VLT-?. Systematics or spatial variation.
- m_e/M_p : hyperfineH/optical, NH_3 — no variation, H_2 - variation 4σ . Space-time variation? Grand Unification model?
- Big Bang Nucleosynthesis: may be interpreted as a variation of m_q/Λ_{QCD} ?
- Oklo: sensitive to m_q/Λ_{QCD} , effect $< 3 \cdot 10^{-9}$
- Atomic clocks: present time variation of α , m/Λ_{QCD}
- Transitions between narrow close levels in atoms and molecules – huge enhancement of the **relative** effect
- ^{229}Th nucleus – **absolute** enhancement (10^5 times larger shift)
- Dependence of fundamental constants on gravitational potential

No variation for small red shift, hints for variation at high red shift

Slides Outline

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Dysprosium $\delta\alpha$ $\alpha = K_\alpha \delta(GM/rc^2)$

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Click to add notes

Cancellation between fine structure and rotation in light molecules

Bethlem, Bunning, Meijer, Ubach 2007

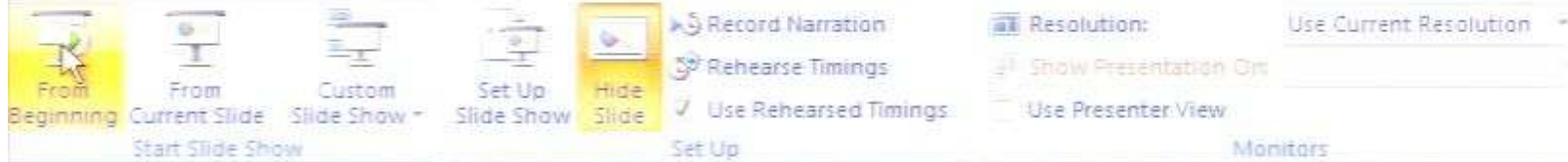
OH, OD, CN, CO, CH, LiH, ...

E_{fine} is proportional to $Z^2\alpha^2$

$E_{\text{rotational}}$ is proportional to $L\mu$, $L=0,1,2,\dots$

$\mu = m_e/M_p$

Enhancement for all molecules along the lines $Z(\mu, L)$



Calculations to link change of frequency to change of fundamental constants:

Optical transitions: atomic calculations (as for quasar absorption spectra) for many narrow lines in Al II, Ca I, Sr I, Sr II, In II, Ba II, Dy I, Yb I, Yb II, Yb III, Hg I, Hg II, Tl II, Ra II .

$$\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$$

Microwave transitions: hyperfine frequency is sensitive to nuclear magnetic moments and nuclear radii

We performed atomic, nuclear and QCD calculations of powers κ, β for H, D, Rb, Cd⁺, Cs, Yb⁺, Hg⁺

$$V = C(Ry)(m_e/M_p)\alpha^{2+\kappa} (m_q/\Lambda_{\text{QCD}})^\beta, \quad \Delta\omega/\omega = \Delta V/V$$

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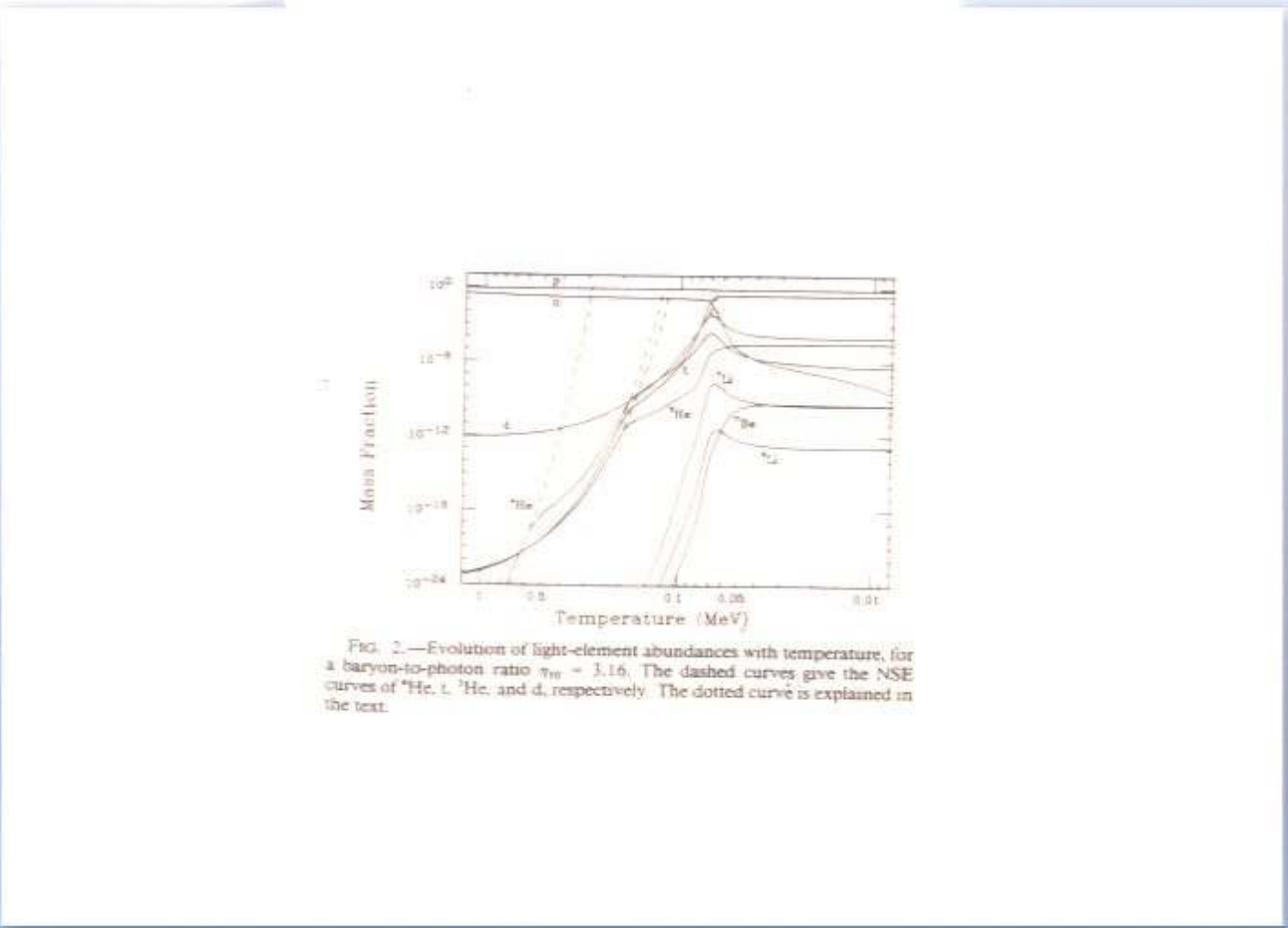


FIG. 2.—Evolution of light-element abundances with temperature, for a baryon-to-photon ratio $\eta_B = 1.16$. The dashed curves give the NSE curves of ${}^3\text{He}$, ${}^4\text{He}$, and d , respectively. The dotted curve is explained in the text.

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Measurements m_e / M_p or $m_e / \Lambda_{\text{QCD}}$

- Tsanavaris, Webb, Murphy, Flambaum, Curran PRL 2005

Hyperfine H/optical , 9 quasar absorption systems with Mg, Ca, Mn, C, Si, Zn, Cr, Fe, Ni

Measured $X = \alpha^2 g_p m_e / M_p$

$\Delta X / X = 0.6(1.0) 10^{-5}$ **No variation**

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Two sets of line pairs

1. $\delta\alpha < 0$ imitated by compression of the spectrum
2. $\delta\alpha < 0$ imitated by expansion of the spectrum

Both sets give $\delta\alpha < 0$!

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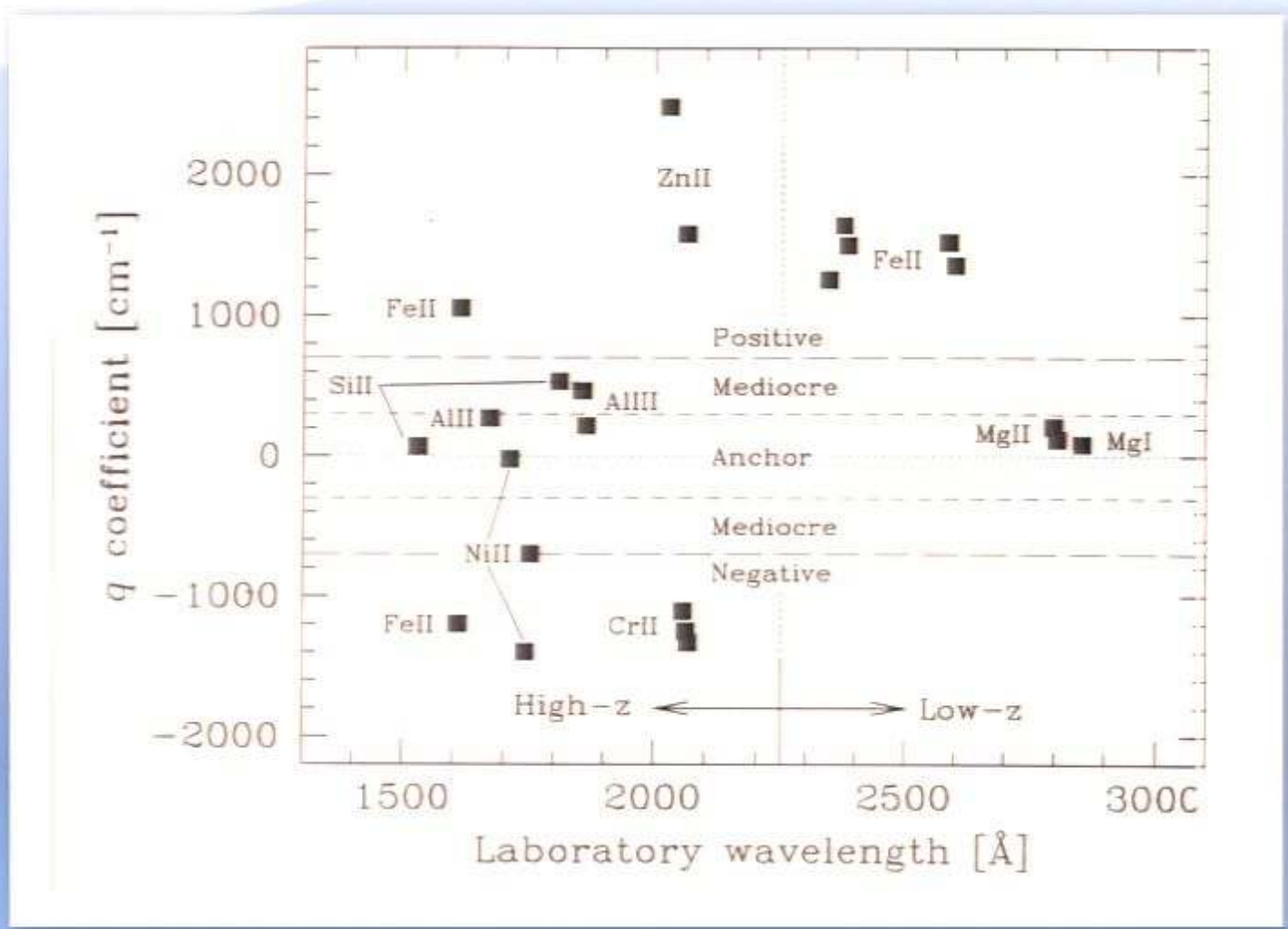
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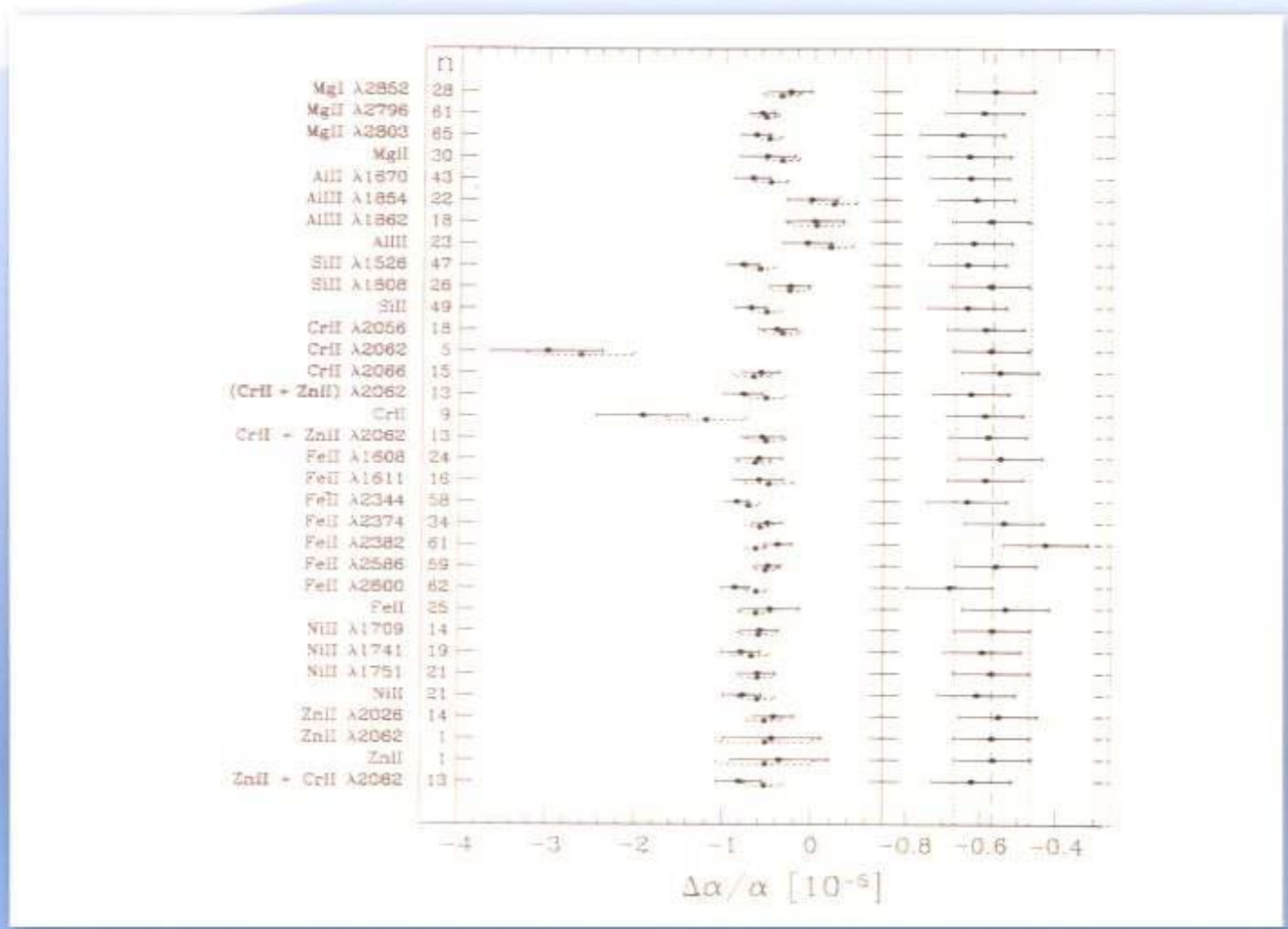
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Probing the variability of α with QSO absorption lines

Checks on general, unknown systematics:

- **Line removal:** In each system, remove each transition and iterate to find $\Delta\alpha/\alpha$ 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, line blending, isotopic ratio and hyperfine structure variation.
- **Positive-negative shifter test:** Find the subset of systems that contain an anchor line, a positive shifter AND a negative shifter. Remove each type of line collectively and recalculate $\Delta\alpha/\alpha$.
 - Results:** subset contains 12 systems (only in high z sample)
 - No lines removed:** $\Delta\alpha/\alpha = (-1.31 \pm 0.39) \times 10^{-5}$
 - Anchors removed:** $\Delta\alpha/\alpha = (-1.49 \pm 0.44) \times 10^{-5}$
 - +ve-shifters removed:** $\Delta\alpha/\alpha = (-1.54 \pm 1.03) \times 10^{-5}$
 - ve-shifters removed:** $\Delta\alpha/\alpha = (-1.41 \pm 0.65) \times 10^{-5}$

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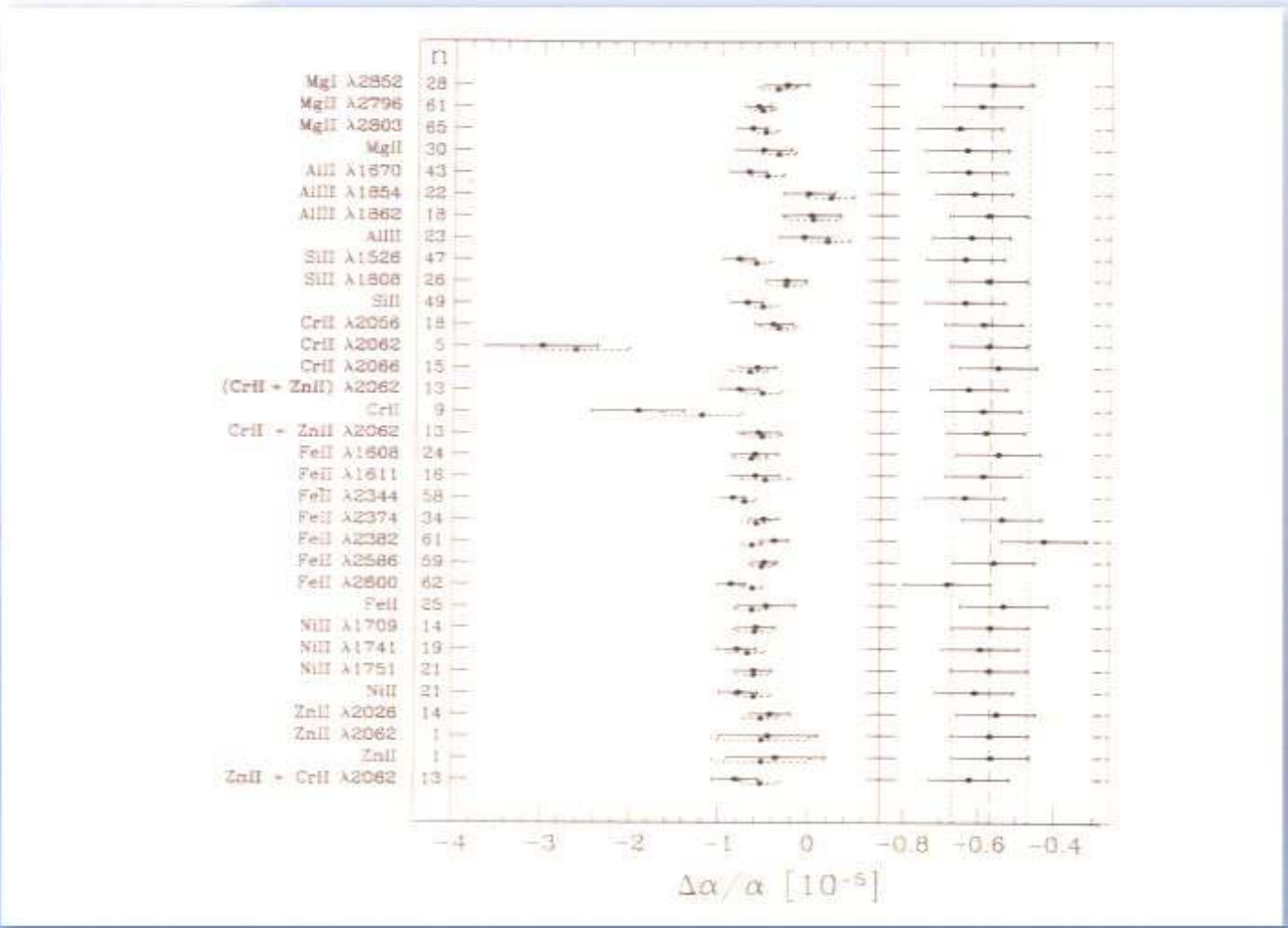
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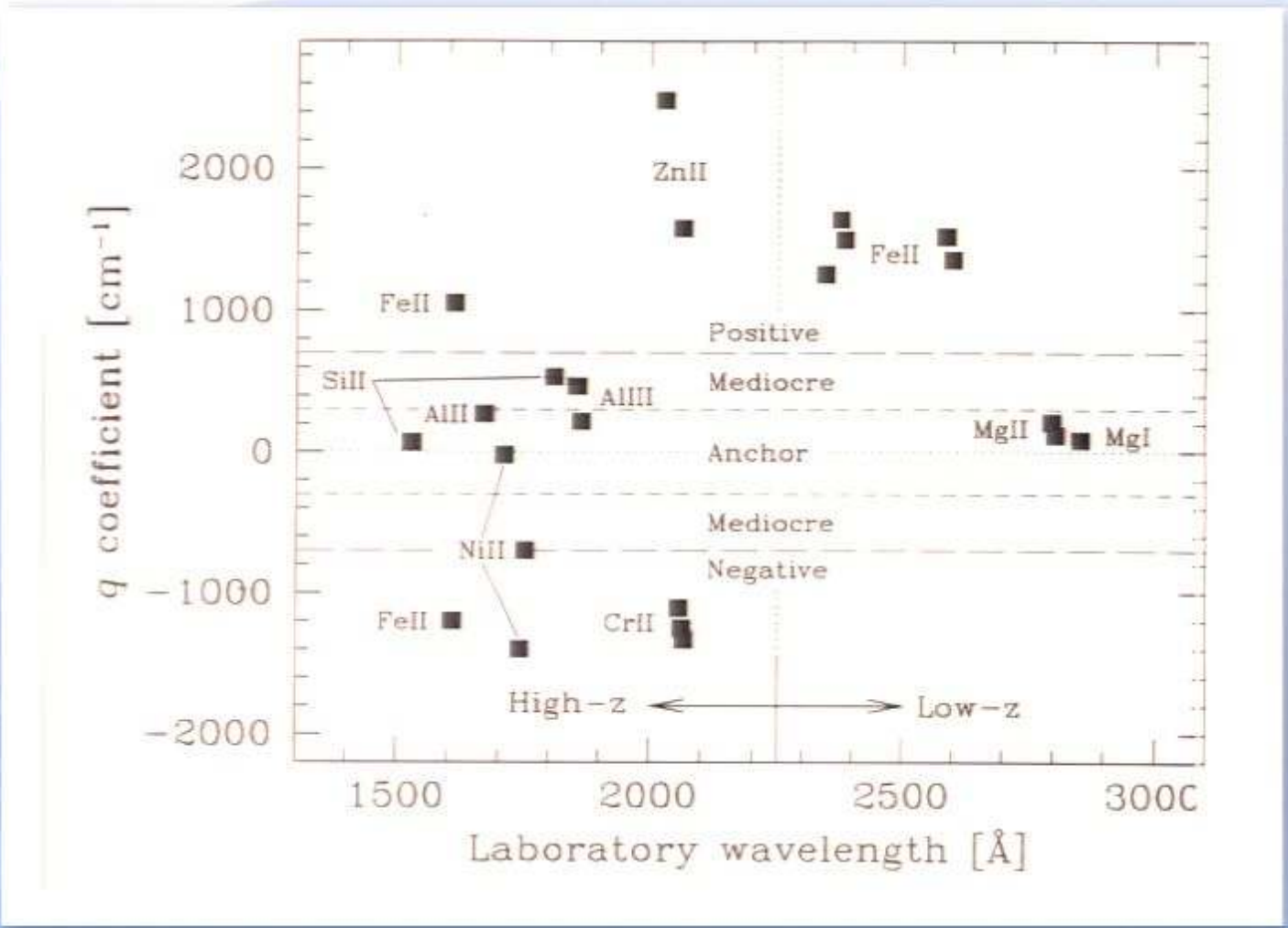
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