Effects of variation of fundamental constants from Big Bang to atomic clocks

Contributors:

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The possibility for the fundamental constants to vary is suggested by theories unifying **gravity** with **other** interactions.

Fine structure constant $\alpha = e^2/\hbar c$,
e -electron charge, c -speed of light.
Quark mass m_q/Strong interaction scale Λ_{QCD}.

The search goes in:

(1) Quasar absorption spectra (QAS)
(2) Big Bang Nucleosynthesis (BBN)
(3) Oklo natural nuclear reactor
(4) Atomic clocks

	Constants		Result
QAS	α $\frac{m_q}{\Lambda_{QCD}}$		$\Delta \neq 0$!?
BBN	α $\frac{m_q}{\Lambda_{QCD}}$	$\frac{\Lambda_{QCD}}{M_{Plank}}$	$\Delta \neq 0$!?
Oklo	α $\frac{m_q}{\Lambda_{QCD}}$		$\Delta \neq 0$!?
Clocks	α $\frac{m_{q,e}}{\Lambda_{QCD}}$		$\Delta < \delta$

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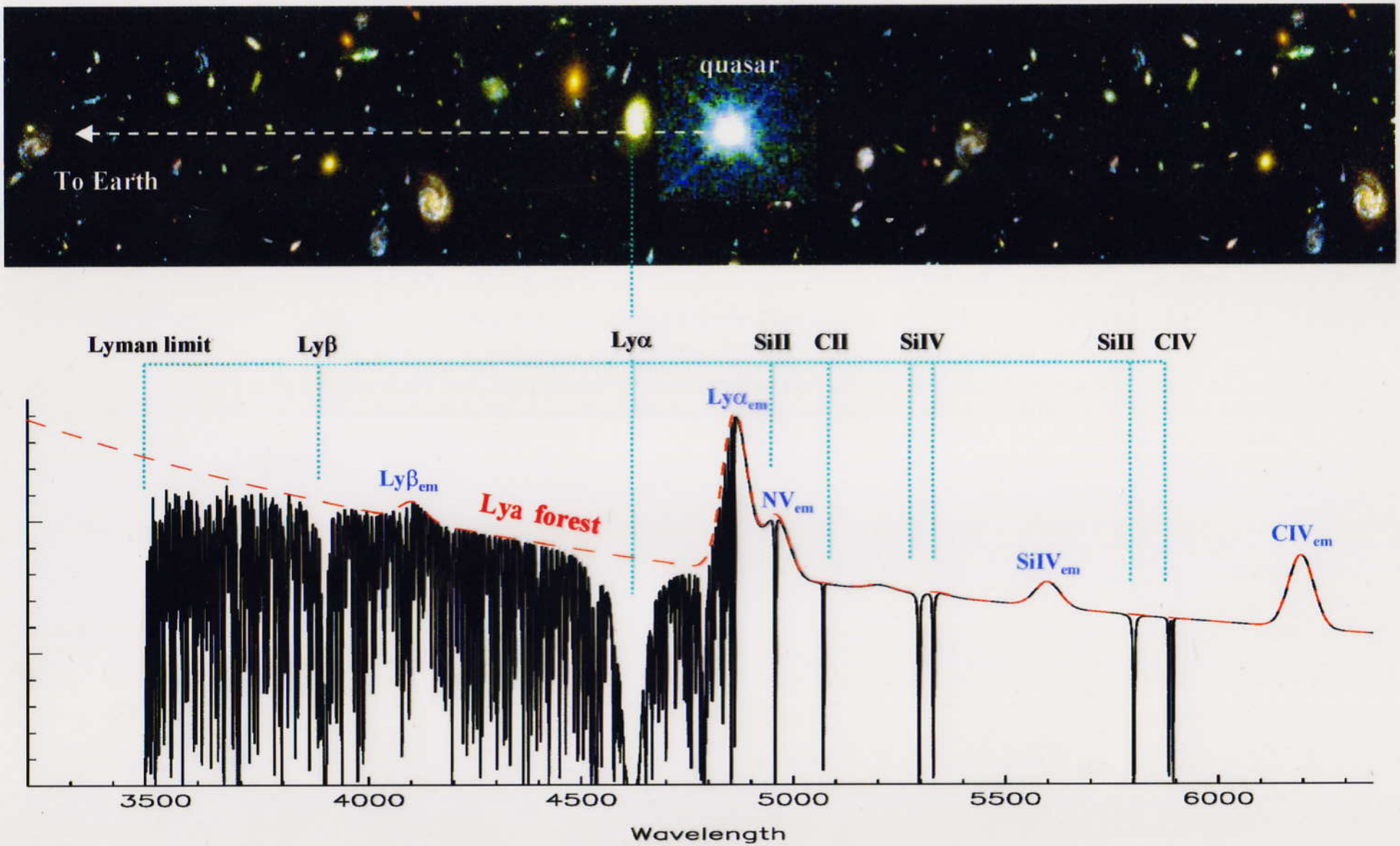
4.2 Astrophysical constraints:
Quasars - probing the universe back to much earlier times



Lines used in the analysis (cm^{-1})

Anchor lines				Negative shifters			
MgI	35051.277(1)	+	$86x$	NiII	57420.013(4)	-	$1400x$
MgII	35760.848(2)	+	$211x$	NiII	57080.373(4)	-	$700x$
MgII	35669.298(2)	+	$120x$	CrII	48632.055(2)	-	$1110x$
SiII	55309.3365(4)	+	$520x$	CrII	48491.053(2)	-	$1280x$
SiII	65500.4492(7)	+	$50x$	CrII	48398.868(2)	-	$1360x$
AlII	59851.924(4)	+	$270x$	FeII	62171.625(4)	-	$1300x$
AlIII	53916.540(1)	+	$464x$	**Positive shifters**			
AlIII	53682.880(2)	+	$216x$	FeII	62065.528(3)	+	$1100x$
NiII	58493.071(4)	-	$20x$	FeII	42658.2404(2)	+	$1210x$
				FeII	42114.8329(2)	+	$1590x$
				FeII	41968.0642(2)	+	$1460x$
				FeII	38660.0494(2)	+	$1490x$
				FeII	38458.9871(2)	+	$1330x$
				ZnII	49355.002(2)	+	$2490x$
				ZnII	48481.077(2)	+	$1584x$

$$\omega = \omega_{Lab} + qx$$

$$x = \frac{\alpha^2}{\alpha^2_{Lab}} - 1$$

Results:

1998-2003, Keck telescope, Hawaii, red shift $0.2 < z < 4.3$, 143 absorption systems, 23 transitions,
3 independent samples:
$\frac{\delta\alpha}{\alpha} = (-0.543 \pm 0.116) \cdot 10^{-5}$
Statistical significance 4.7 σ from zero.
2004, VLT-UVES, Chile (different hemisphere), red shift $0.4 < z < 2.8$
full sample, 74 systems $\frac{\delta\alpha}{\alpha} = (-0.020 \pm 0.092) \cdot 10^{-5}$
clean sample, 52 systems $\frac{\delta\alpha}{\alpha} = (-0.004 \pm 0.098) \cdot 10^{-5}$
Strianand et al sample, 23 systems $\frac{\delta\alpha}{\alpha} = (-0.061 \pm 0.126) \cdot 10^{-5}$
VLT: $|\frac{\delta\alpha}{\alpha}| < 0.1 \cdot 10^{-5}$. Zero!
Too large scatter, more realistic preliminary result
$\frac{\delta\alpha}{\alpha} = (-0.05 \pm 0.29) \cdot 10^{-5}$

Other groups results from VLT-UVES:

Strianand, Chand, Petitjean, Aracil (2004), 23 systems, 12 transitions, $0.4 < z < 2.3$:
$\frac{\delta\alpha}{\alpha} = (-0.06 \pm 0.06) \cdot 10^{-5}$
Quast, Reimer, Levshakov (2004): 1 system, Fe II only, 6 transitions, $z = 1.15$:
$\frac{\delta\alpha}{\alpha} = (-0.04 \pm 0.19 \pm 0.27_{syst}) \cdot 10^{-5}$

Difference between Keck and VLT data:
Undiscovered systematic effect?
Spatial variation of α?

Grand Unification models:

Calmet, Fritzsch; Langecker, Segre, Strasser; Dent, ...

variation of strong and weak scales may be larger than variation of α

$$\frac{\delta(m/\Lambda_{QCD})}{m/\Lambda_{QCD}} \sim 35 \frac{\Delta\alpha}{\alpha}$$

1. Proton mass $m_p \sim 3\Lambda_{QCD}$

$$\frac{m_e}{m_p} \sim \frac{m_e}{\Lambda_{QCD}}$$

2. Magnetic moments appear in hyperfine transition frequencies

$$\mu_p = g_p \frac{e\hbar}{2m_p c} \quad \text{proton}$$

$$g_p \left(\frac{m_q}{\Lambda_{QCD}} \right)$$

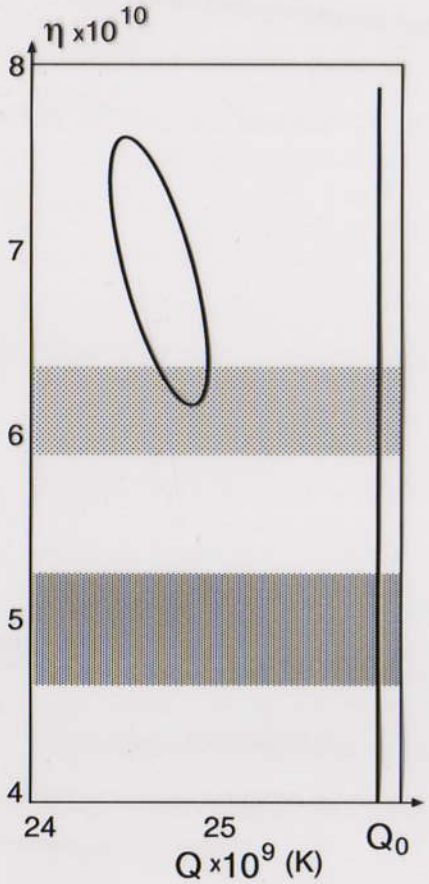
3. Nuclear resonances and binding energies

Measurements of $m_e/m_p \sim m_e/\Lambda_{QCD}$

Tsanavaris,Webb,Murphy,Flambaum,Curran
Phys.Rev.Lett. 2005
hyperfine 21 cm H/optical
Mg,Ca,Mn,Ti,C,Si,Zn,Cr,Fe,Ni
8 quasar absorption systems, $0.24 < z < 2.04$
Measured $X = \alpha^2 g_p m_e/m_p$
$\frac{\delta X}{X} = (1.17 \pm 1.01)10^{-5}$
$\frac{dlnX}{dt} = (-1.43 \pm 1.27)10^{-15}/year$
No variation.
Combined with measurements of α-variation
$\frac{\delta(m_e/m_p)}{(m_e/m_p)} = (2.31 \pm 1.03)10^{-5}$
$\frac{\delta(m_e/m_p)}{(m_e/m_p)} = (1.29 \pm 1.01)10^{-5}$
Recent result based on H_2 measurements
Reinhold,Bunning,Hollenstein,Ivanchik,Petitjean,
Ubach 2005.
$\frac{\delta(m_e/m_p)}{(m_e/m_p)} = (-2.4 \pm 0.6)10^{-5}$
Variation 4σ!

Big Bang Nucleosynthesis

(Dmitriev, Flambaum, Webb)



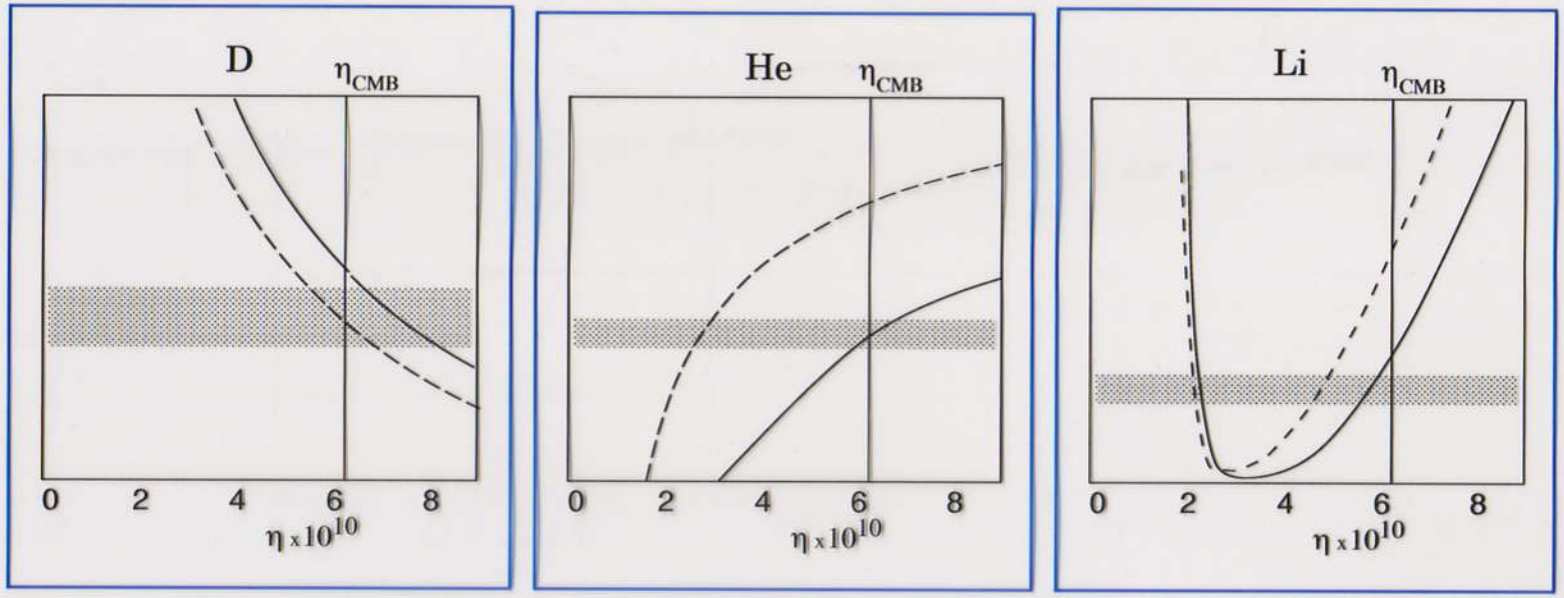
$$p + n \to d + \gamma, \quad 3 \text{ sec} \leq \text{t} \leq 6 \text{ min}$$

Productions of D, ^{4}He, ^{7}Li are exponentially sensitive to deuteron binding energy E_d

$$\sim e^{-\frac{E_d}{T_f}}$$

- η from cosmic microwave background fluctuations (η - barion to photon ratio).

- η from BBN for present value of Q ($Q = |E_d|$)



Comparison with observations gives

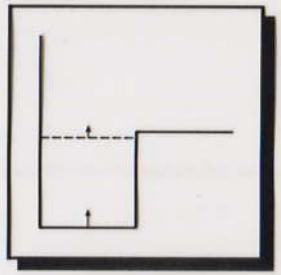
$$\frac{\delta E_d}{E_d} = -0.019 \pm 0.005$$

This also leads to agreement

$$\eta(BBN) \approx \eta(CMB)$$

Flambaum, Shuryak: Deuteron Binding Energy is very sensitive to variation of *strange* quark mass (4 factors of enhancement):

1. Deuteron is a shallow bound level.

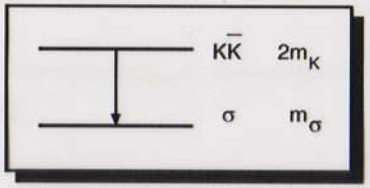


Virtual level in $n+p \to d+\gamma$ is even more sensitive to the variation of the potential.

2. Strong compensation between σ-meson and ω-meson exchange in potential (Walecka model): $4\pi r V = -g_s^2 e^{-m_\sigma r} + g_v^2 e^{-m_\omega r}$

3. $\sigma = \frac{1}{\sqrt{3}}(u\overline{u} + d\overline{d} + s\overline{s})$, $\quad m_\sigma \approx \frac{2}{3} m_s + 2\Lambda_{QCD}$

4. Repulsion of σ from $K\overline{K}$ threshold



Total $\frac{\delta E_d}{E_d} \approx -17\frac{\delta m_s}{m_s}$ and $\frac{\delta(m_s/\Lambda_{QCD})}{m_s/\Lambda_{QCD}} = (+1.1 \pm 0.3) \times 10^{-3}$

Comparing atomic clocks one can study:

Atomic	optical/optical	α^2	
	optical/hyperfine	α^2,	$m_{e,q}/\Lambda_{QCD}$
	hyperfine/hyperfine	"	"
Molecular	hyperfine/rotational	"	"
	hyperfine/Λ-doubling	"	"
	rotational/optical	"	"

Experiment			$\frac{1}{\alpha}\frac{d\alpha}{dt}(10^{-15}/\text{year})$
Marion et al	2003	$\frac{\text{Rb(hfs)}}{\text{Cs(hfs)}}$	$(0.05 \pm 1.3)^a$
Bize et al	2003	$\frac{\text{Hg}^+\text{(opt)}}{\text{Cs(hfs)}}$	$(-0.03 \pm 1.2)^a$
Fisher et al	2004	$\frac{\text{H(opt)}}{\text{Cs(hfs)}}$	$(-1.1 \pm 2.3)^a$
Peik et al	2004	$\frac{\text{Yb}^+\text{(opt)}}{\text{Cs(hfs)}}$	(-0.2 ± 2.0)
Bize et al	2004	$\frac{\text{Rb(hfs)}}{\text{Cs(hfs)}}$	$(0.1 \pm 1)^a$

^{a} assuming $m_q/\Lambda =$ Const.

Combined results:

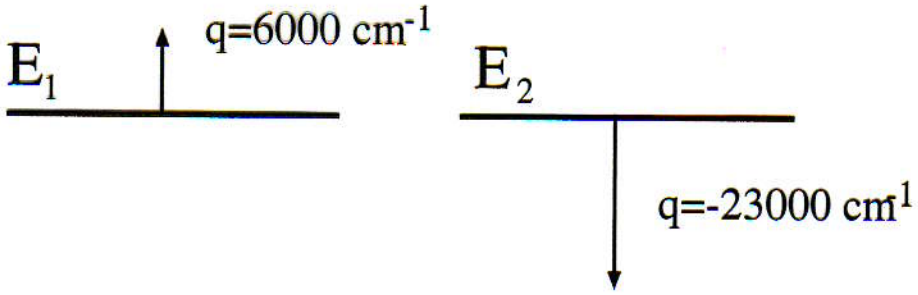
$$\frac{\partial \ln \alpha}{\partial t} = (-0.9 \pm 2.9) \times 10^{-15}\text{yr}^{-1}$$

$$\frac{\partial \ln (m_q/\Lambda_{QCD})}{\partial t} = (-4 \pm 10) \times 10^{-15}\text{yr}^{-1}$$

There is a possibility of 10^{10} times enhancement due to "degenerate" energy levels of different nature! Example: Dy atom.

1. $4f^{10}5d6s$, $E_1 = 19797.96...\ \mathrm{cm}^{-1}$
2. $4f^{9}5d^{2}6s$, $E_2 = 19797.96...\ \mathrm{cm}^{-1}$

Interval $\omega = E_2 - E_1 \sim 10^{-4}\ \mathrm{cm}^{-1} \sim 10^{-9} E_1$.



$$\omega = \omega_0 + (q_1 - q_2) 2 \frac{\Delta\alpha}{\alpha} =$$

$$= 10^{-4}\ \mathrm{cm}^{-1} + 60000\ \mathrm{cm}^{-1} \frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta\omega}{\omega}(1\ \mathrm{year})_{\mathrm{Lab}} \sim \frac{\Delta\omega}{\omega}(10^{10}\ \mathrm{years})_{\mathrm{astro}}$$

Preliminary result: UC Berkely - Los Alamos

$|\frac{\partial \ln \alpha}{\partial t}| < 4.3 \times 10^{-15} \mathrm{yr}^{-1}$

CONCLUSIONS

BBN/CMB data may be interpreted as variation of $\mathbf{m}_q/\Lambda_{QCD}$.

MM method provided sensitivity increase $\sim$100 times. Many lines, positive and negative shifters - control of systematics.
Keck data- 3 independent optical samples, 143 systems- variation of α.
VLT data- no variation.
Undiscovered systematics or spatial variation?

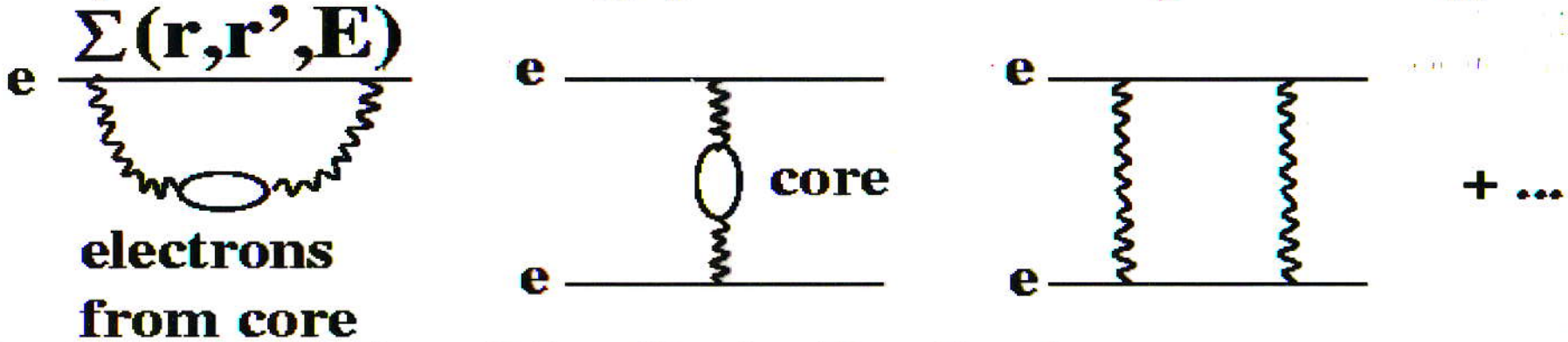
$\mathbf{m}_e/m_p$: 21 cm H/optical- no variation;
H_2 (Paris-Amsterdam-Peterburg)-variation!

Oklo data: variation of $\mathbf{m}_q/\Lambda_{QCD}$!?

- Atomic clocks are very sensitive to present time variation of α and $\mathbf{m}_q/\Lambda_{QCD}$. Transition between close levels - a billion times enhancement.

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** → $V = H - H_{HF}$



3. **Diagonalization of the effective Hamiltonian**

Test: Energy levels in Mg II to 0.2% accuracy

Optical atomic clocks

TABLE II: Experimental energies and calculated q coefficients for transitions from the ground state to the state shown.

Atom/Ion	Z	State		Wavelength, Å Experiment	q (cm^{-1})	Reference
Al II	13	$3s3p$	$^3P_0$	2674.30	146	[12]
		$3s3p$	$^3P_1$	2669.95	211	[12]
		$3s3p$	$^3P_2$	2661.15	343	[12]
		$3s3p$	$^1P_1$	1670.79	278	[12]
Ca I	20	$4s4p$	$^3P_0$	6597.22	125	[12]
		$4s4p$	$^3P_1$	6574.60	180	[12]
		$4s4p$	$^3P_2$	6529.15	294	[12]
		$4s4p$	$^1P_1$	4227.92	250	[12]
Sr I	38	$5s5p$	$^3P_0$	6984.45	443	[12]
		$5s5p$	$^3P_1$	6894.48	642	[12]
		$5s5p$	$^3P_2$	6712.06	1084	[12]
		$5s5p$	$^1P_1$	4608.62	924	[12]
Sr II	38	$4d$	$^2D_{3/2}$	6870.07	2828	[9]
		$4d$	$^2D_{5/2}$	6740.25	3172	[9]
In II	49	$5s5p$	$^3P_0$	2365.46	3787	[12]
		$5s5p$	$^3P_1$	2306.86	4860	[12]
		$5s5p$	$^3P_2$	2182.12	7767	[12]
		$5s5p$	$^1P_1$	1586.45	6467	[12]
Ba II	56	$5d$	$^2D_{3/2}$	20644.74	5844	[13]
		$5d$	$^2D_{5/2}$	17621.70	5976	[13]
Dy I	66	$4f^{10}5d6s$	$^3[10]_{10}$	5051.03	6008	[14]
		$4f^9 5d^2 6s$	$^9K_{10}$	5051.03	-23708	[14]
Yb I	70	$6s6p$	$^3P_0$	5784.21	2714	[12]
		$6s6p$	$^3P_1$	5558.02	3527	[12]
		$6s6p$	$^3P_2$	5073.47	5883	[12]
		$6s6p$	$^1P_1$	3989.11	4951	[12]
Yb II	70	$4f^{14}5d$	$^2D_{3/2}$	4355.25	10118	[14]
		$4f^{14}5d$	$^2D_{5/2}$	4109.70	10397	[14]
		$4f^{13}6S^2$	$^2F_{7/2}$	4668.81	-56737	[14]
Yb III	70	$4f^{13}5d$	$^3P_0$	2208.63	-27800	[14]
Hg I	80	$6s6p$	$^3P_0$	2656.39	15299	[12]
		$6s6p$	$^3P_1$	2537.28	17584	[12]
		$6s6p$	$^3P_2$	2270.51	24908	[12]
		$6s6p$	$^1P_1$	1849.50	22789	[12]
Hg II	80	$5d^9 6s^2$	$^2D_{5/2}$	2815.79	-56671	[9]
		$5d^9 6s^2$	$^2D_{3/2}$	1978.16	-44003	[9]
Tl II	81	$6s6p$	$^3P_0$	2022.20	16267	[12]
		$6s6p$	$^3P_1$	1872.90	18845	[12]
		$6s6p$	$^3P_2$	1620.09	33268	[12]
		$6s6p$	$^1P_1$	1322.75	29418	[12]
Ra II	88	$6d$	$^2D_{3/2}$	8275.15	18785	[13]
		$6d$	$^2D_{5/2}$	7276.37	17941	[13]

$$\omega = \omega_0 + q\left(\frac{\alpha^2}{\alpha_0^2} - 1\right) \approx \omega_0 + q \cdot \frac{2\Delta\alpha}{\alpha}$$

Table 99.1. Relative sensitivity of the hyperfine relativistic factors to the variation of α (parameter κ) and nuclear magnetic moments on the variation of the quark mass/strong interaction scale m_q/Λ_{QCD} (parameter β) for atoms involved in microwave standards.

Z	Atom	κ	β
1	^{1}H	0.00	-0.100
1	^{2}H	0.00	-0.063
37	^{87}Rb	0.34	-0.074
48	^{111}Cd^{+}	0.6	-0.117
55	^{133}Cs	0.83	0.127
70	^{171}Yb^{+}	1.5	-0.117
80	^{199}Hg^{+}	2.3	-0.117

Using parameters κ and *beta* we can present dependence of the microwave standards on the fundamental constants:

$$\frac{\partial \ln f}{\partial t} = \frac{\partial \ln V}{\partial t} \tag{99.5}$$

$$V = cR_\infty \cdot \frac{m_e}{m_p} \cdot \alpha^{2+\kappa} \cdot (\frac{m_q}{\Lambda_{QCD}})^\beta \tag{99.6}$$

In comparison of two microwave standards the factors cR_∞ and m_e/m_p are cancelled out. However, in comparison of optical and microwave standards the factor m_e/m_p survives. Its dependence on the fundamental constants is the following

$$\partial \ln \frac{m_e}{m_p} = \partial \ln[\frac{m_e}{\Lambda_{QCD}} \cdot (\frac{m_q}{\Lambda_{QCD}})^{-0.048}] \tag{99.7}$$

We may assume that the electron mass and all quark masses have the same relative variation . This assumption seems to be natural if the Higgs mechanism of mass generation is correct.

Some special "tuning" of fundamental constants is neeeded for humans to exist.

Example: low-energy resonance in carbon production reaction in stars:

$$^4He + ^4He + ^4He = ^{12}C$$

Different coupling constants $\rightarrow$ no low-energy resonance $\rightarrow$ no carbon $\rightarrow$ no life.

Variation of coupling constants in space could provide a natural explanation of "fine tuning": we appeared in area of the Universe where values of fundamental constants are consitent with our existence.

η M_{Plank} fixed to have BBN

$$\eta \approx 6 \cdot 10^{-10} = \frac{\text{number of baryons}}{\text{number of photons}}$$

$$M_{Plank} \sim \sqrt{\frac{\hbar c}{G_N}} \sim 10^{19}\,\text{GeV}$$

Potential systematic effects:

- ☺ Wavelength calibration errors
- ☺ Laboratory wavelength errors
- ☺ Heliocentric velocity variation
- ☺ Temperature changes during observations
- ☺ Line blending
- ☺ Differential isotopic saturation
- ☺ Hyperfine structure effects
- ☺ Instrumental profile variations
- ☺ … and of course, Magnetic fields
- ~~☹ Atmospheric dispersion effects~~
- ☹ Isotopic ratio evolution

C. L. Steinhardt, Phys. Rev. D, 71, 043509 (2005):
It might be spatial variation!

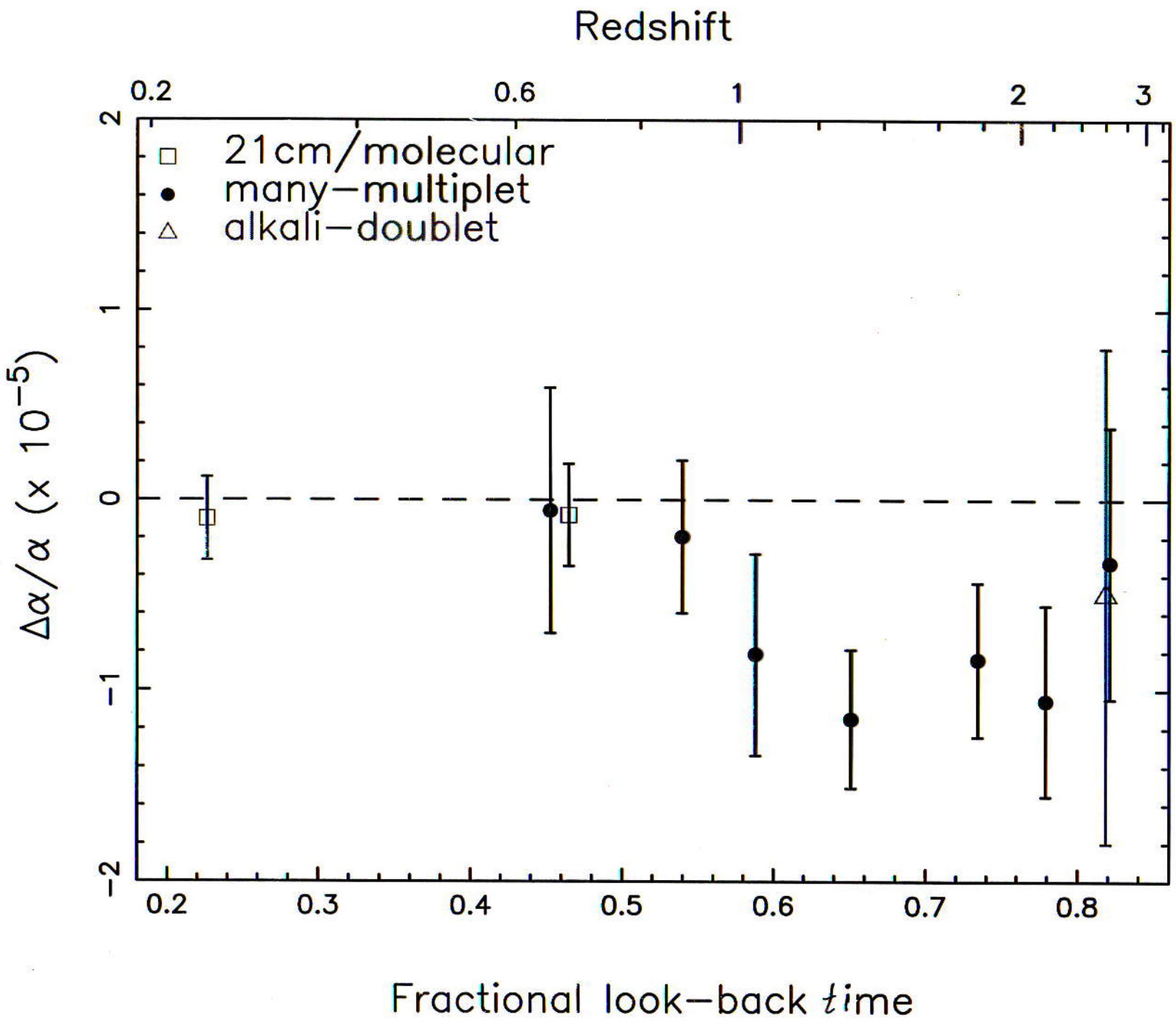
Srianand et al use data from Southern Hemisphere only

$$(\frac{\Delta\alpha}{\alpha})_{\text{South}} = (-0.06 \pm 0.06) \times 10^{-5}$$

Murphy et al use both:

$$(\frac{\Delta\alpha}{\alpha})_{\text{South}} = (-0.36 \pm 0.19) \times 10^{-5}$$

$$(\frac{\Delta\alpha}{\alpha})_{\text{North}} = (-0.66 \pm 0.12) \times 10^{-5}$$


Redshift
0.2
0.6
1
2
3
21cm/molecular
many−multiplet
alkali−doublet
2
1
0
−1
−2
Δα/α (x 10^−5)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Fractional look−back time

Many-Multiplet Method

Relativistic correction to electron energy E_n:

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

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

Our Measurments

$$\frac{\delta(\alpha^2 g_p)}{(\alpha^2 g_p)} = \frac{\delta X}{X} = (-0.16 \pm 0.54) \cdot 10^{-5}$$

$z \simeq 0.7$, 6 bn years ago

$$X = \alpha^2 \left(\frac{m_q}{\Lambda_{QCD}} \right)^{-0.09}$$

Flambaum
Leinweber
Thomas
Young

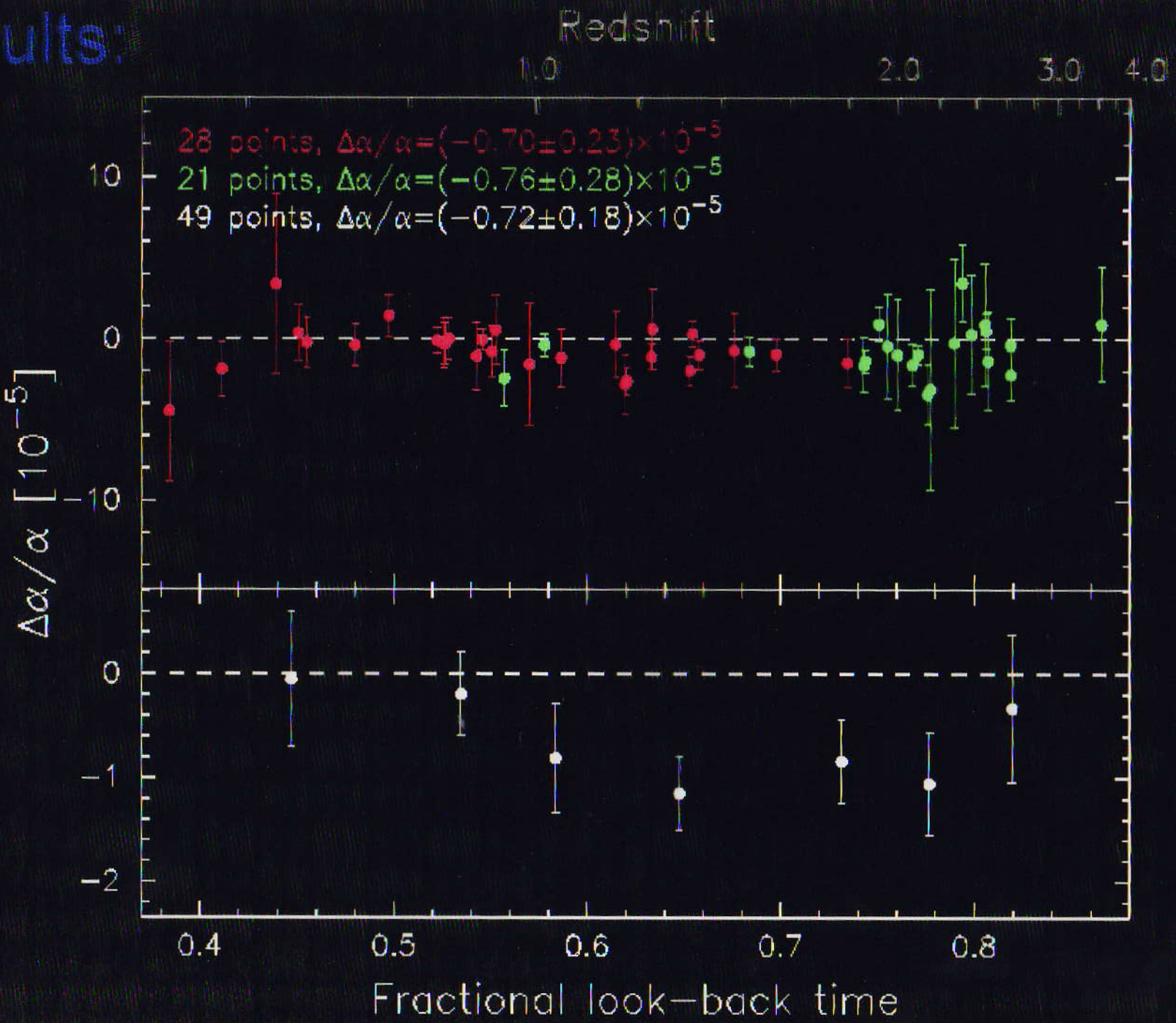
GUT models:

Calmet, Fritzsch; Langecker, Segre, Strassler

$$\frac{\delta(m/\Lambda_{QCD})}{m/\Lambda_{QCD}} \sim 35 \frac{\delta\alpha}{\alpha}$$

weak / strong variation may be more important!

Results:


Redshift
1.0
2.0
3.0
4.0
28 points, Δα/α=(−0.70±0.23)×10^−5
21 points, Δα/α=(−0.76±0.28)×10^−5
49 points, Δα/α=(−0.72±0.18)×10^−5
10
0
−10
Δα/α [10^−5]
0
−1
−2
0.4
0.5
0.6
0.7
0.8
Fractional look−back time

Procedure:

1. **Compare heavy (Z~30) and light (Z<10) atoms, OR**
2. **Compare s → p and d → p transitions in heavy atoms.**

Shifts can be of opposite sign.

Basic formula:

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

$E_{z=0}$ is the laboratory frequency. 2nd term is non-zero only if α has changed. q is derived from atomic calculations.

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

Relativistic shift of the central line in the multiplet

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

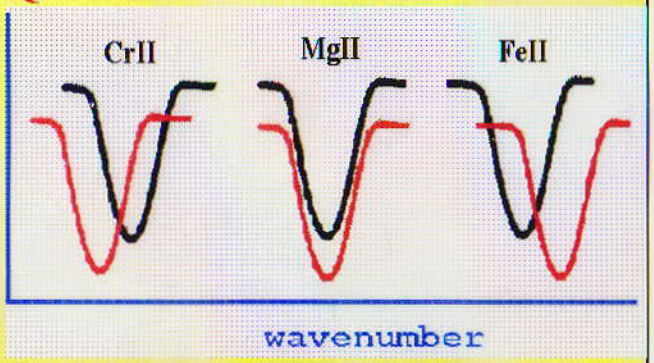
Numerical examples: (units = cm^{-1})

Z=26 (s → p) FeII 2383A: ω_0 = 38458.987(2) + 1449x

Z=12 (s → p) MgII 2796A: ω_0 = 35669.298(2) + 120x

Z=24 (d → p) CrII 2066A: ω_0 = 48398.666(2) - 1267x

$$x = (\alpha_z/\alpha_0)^2 - 1$$



MgII "anchor"

Radio constraints:

- Hydrogen hyperfine transition at λ_H = 21cm.
- 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.

$$g_P = g_P\left(\frac{m_q}{\Lambda_{QCD}}\right)$$