Title: BBN and the change of couplings and mass scales

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Abstract:

Variation of Fundamental Constants

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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 (He+He+He=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], molecules[1] and nuclei
- Dependence on gravity

Search for variation of fundamental constants

- Big Bang Nucleosynthesis **evidence?**
- Quasar Absorption Spectra [1] **evidences?**
- Oklo natural nuclear reactor
- Atomic clocks [1]
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[1] *Based on atomic and molecular calculations*

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 $\alpha = e^2/hc = 1/137.036$
- Electron or quark mass/QCD strong interaction scale, $m_{e,q}/\Lambda_{QCD}$

$\alpha_{strong}(r) = const/ln(r\,\Lambda_{QCD}/ch)$

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

Relation between variations of different coupling constants

Grand unification models (Calmet,Fritzch; Langecker, Segre, Strasser;…)

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

$$Variation\ of\ GUT\ const\ \alpha_{GUT}$$

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

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

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

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

$$\frac{\Delta\left(m/\Lambda_{QCD}\right)}{m/\Lambda_{QCD}} = \frac{1}{b_3\alpha_3}\frac{\Delta\alpha_3}{\alpha_3} = \frac{const}{\alpha}\frac{\Delta\alpha}{\alpha} \sim 35\frac{\Delta\alpha}{\alpha}$$

. Proton mass $M_p \sim 4\Lambda_{QCD}$, measure m_e / M_p

. Nuclear magnetic moments

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

. Nuclear energy levels and resonances

Dependence on quark mass

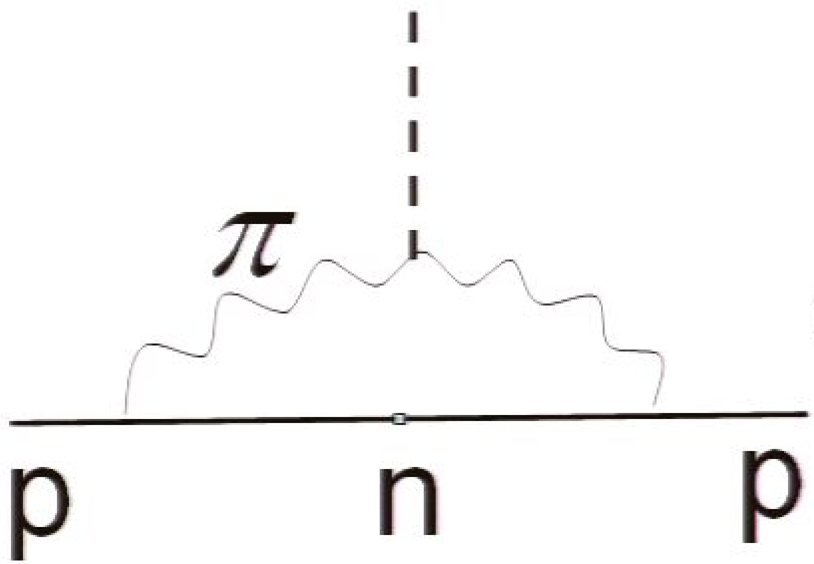
- Dimensionless parameter is m_q/Λ_{QCD} . It is convenient to assume Λ_{QCD} =const, i.e. measure m_q in units of Λ_{QCD}
- m_π is proportional to $(m_q \Lambda_{QCD})^{1/2}$
  $\Delta m_\pi/m_\pi = 0.5 \Delta m_q/m_q$
- Other meson and nucleon masses remains finite for m_q=0. $\Delta m/m = K \Delta m_q/m_q$

Argonne: K are calculated for p,n,ρ,ω,σ.

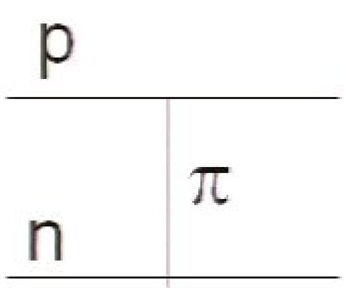
$$m_q = \frac{m_u + m_d}{2} \approx 4 MeV, \Lambda_{QCD} = 220 MeV \to K = 0.02 - 0.06$$

Strange quark mass $m_s = 120 MeV$

Nuclear magnetic moments depends on π-meson mass m_π



Nucleon magnetic moment



Spin-spin interaction between valence and core nucleons

Nucleon magnetic moment

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

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 energy $p^2/2M$

Big Bang nucleosynthesis: dependence on quark mass

- Flambaum, Shuryak 2002
- Flambaum, Shuryak 2003
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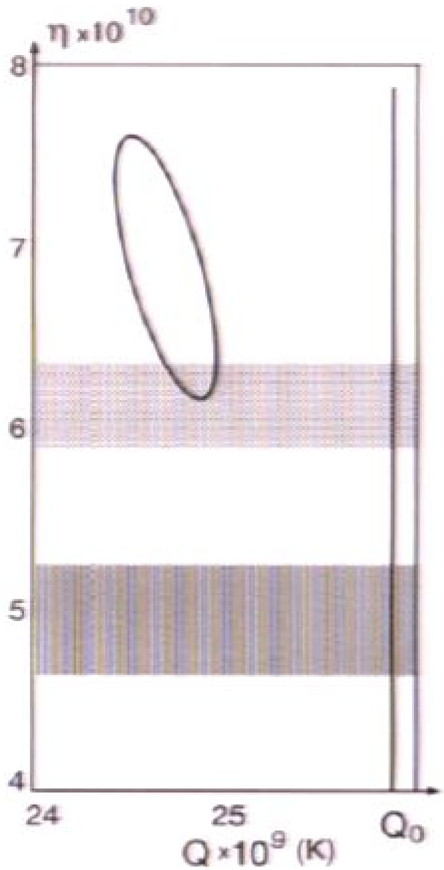
Big Bang Nucleosynthesis
(Dmitriev, Flambaum, Webb)



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

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 ($Q = |E_d|$)

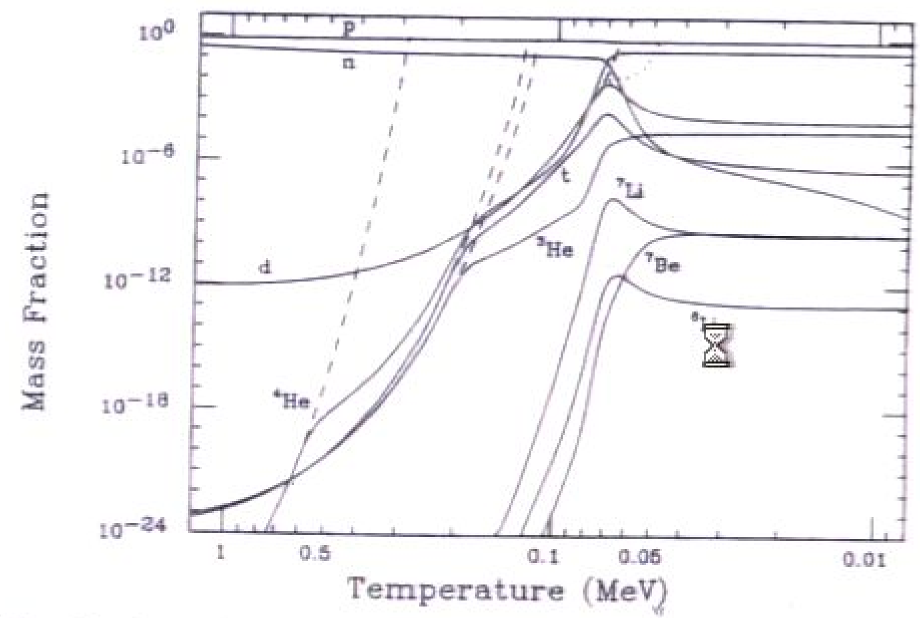


FIG. 2.—Evolution of light-element abundances with temperature, for a baryon-to-photon ratio $\eta_{10} = 3.16$. The dashed curves give the NSE curves of ^{4}He, t, ^{3}He, and d, respectively. The dotted curve is explained in the text.

Deuterium bottleneck

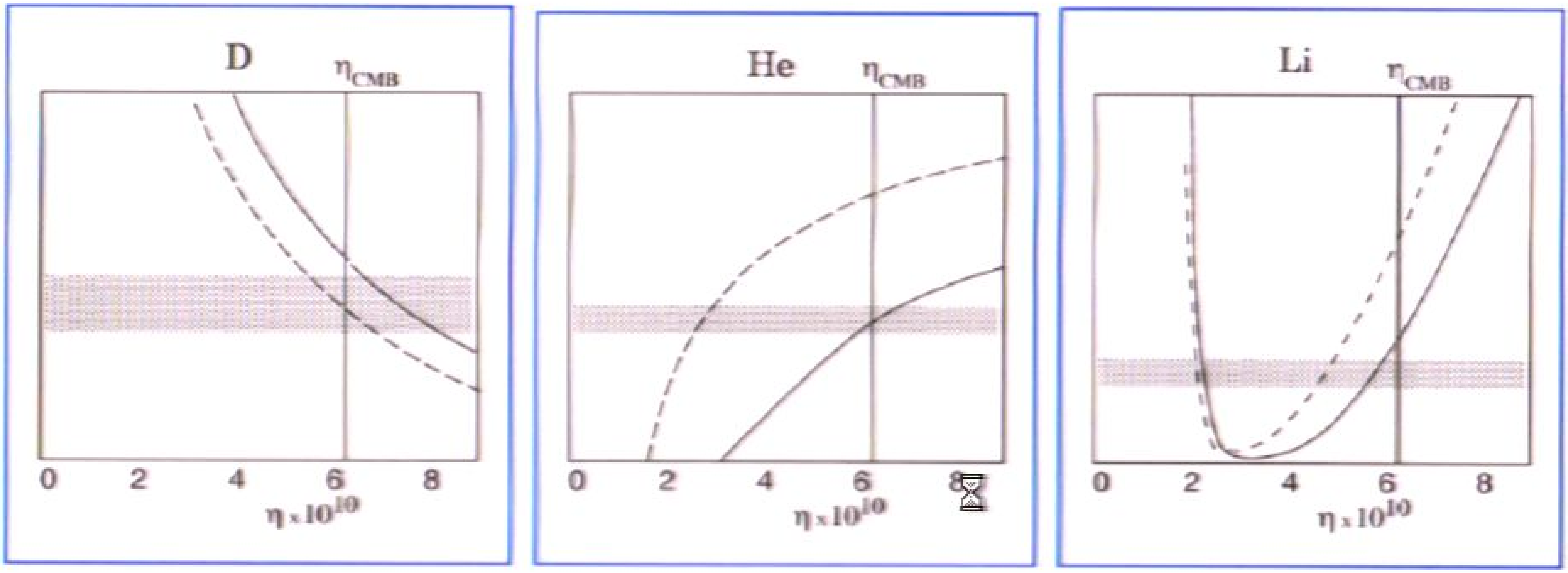
At temeperature $T<0.3$ Mev all abundances follow deuteron abundance

(no other nuclei produced if there are no deuterons)

Reaction γ d – n p , exponentially small number of energetic photons, $e^{-(Ed/T)}$

Exponetilal sensitivity to deuteron binding energy E_d , E_d=2 Mev ,

Freezeout temeperure T_f =30 KeV



Comparison with observations gives

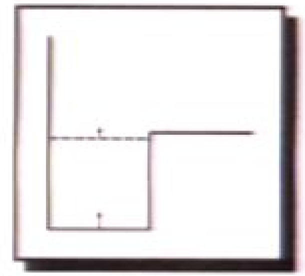
$$\frac{\delta E_d}{E_d} = -0.019 \pm 0.005$$

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.

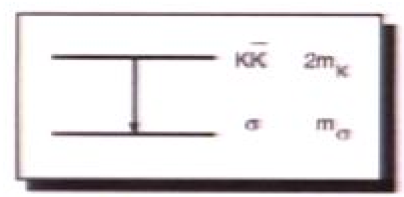


Virtual level in $n+p \to d+\gamma$ is even more sensitive to the variation of the potential.

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

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

New BBN result

- Dent,Stern,Wetterich 2007; Berengut, Dmitriev, Flambaum 2008: dependence of BBN on energies of $^{2,3}H$,$^{3,4}He$,$^{6,7}Li$,$^{7,8}Be$
- Flambaum,Wiringa 2007 : dependence of binding energies of $^{2,3}H$,$^{3,4}He$,$^{6,7}Li$, $^{7,8}Be$ on nucleon and meson masses,
- Flambaum,Holl,Jaikumar,Roberts,Write, Maris 2006: dependence of nucleon and meson masses on light quark mass m_q.

Big Bang Nucleosynthesis: Dependence on m_q/Λ_{QCD}

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

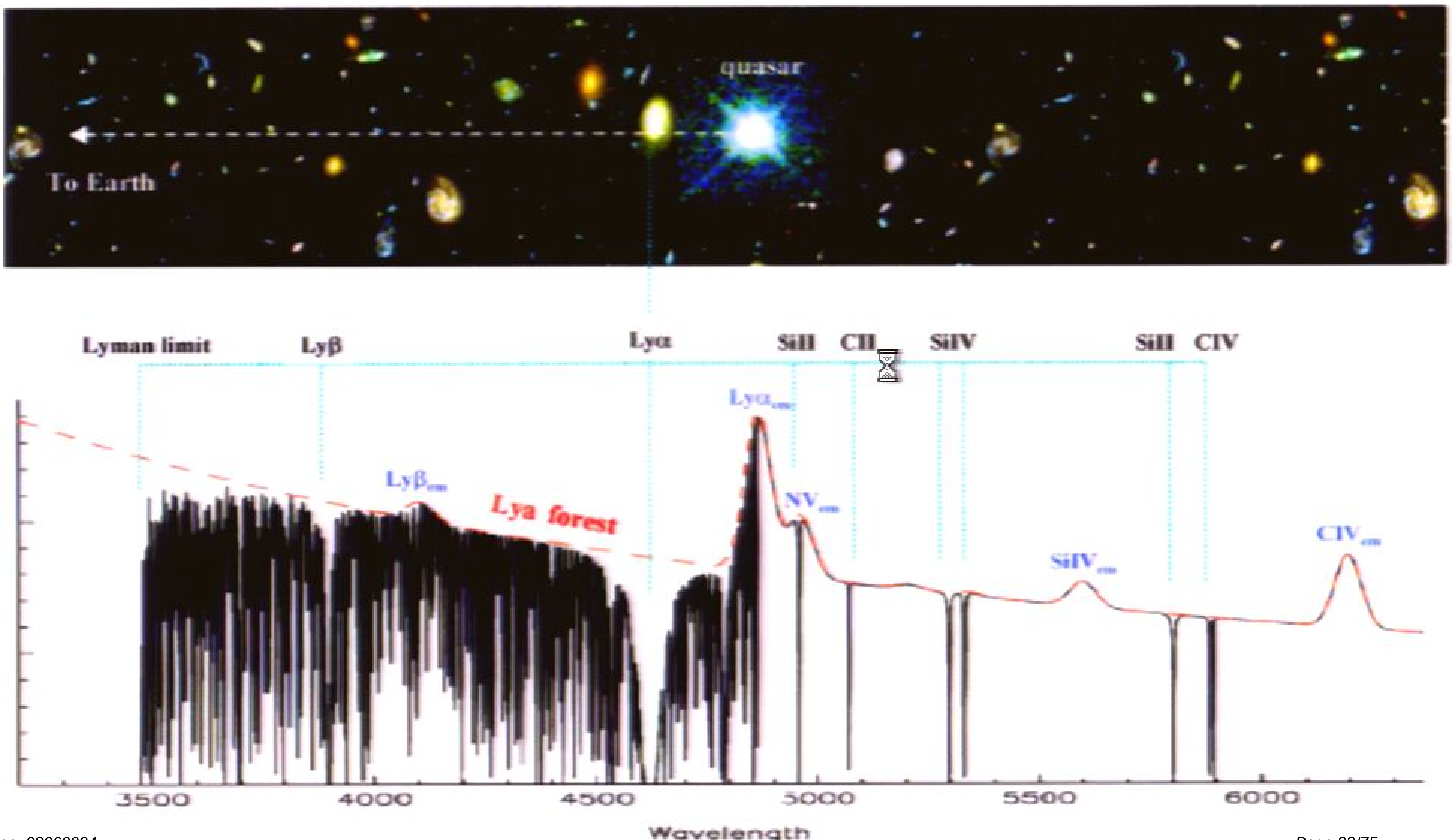
Final result

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

Dominated by ^7Li abundance (3 times difference), consistent with ^2H, ^4He

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

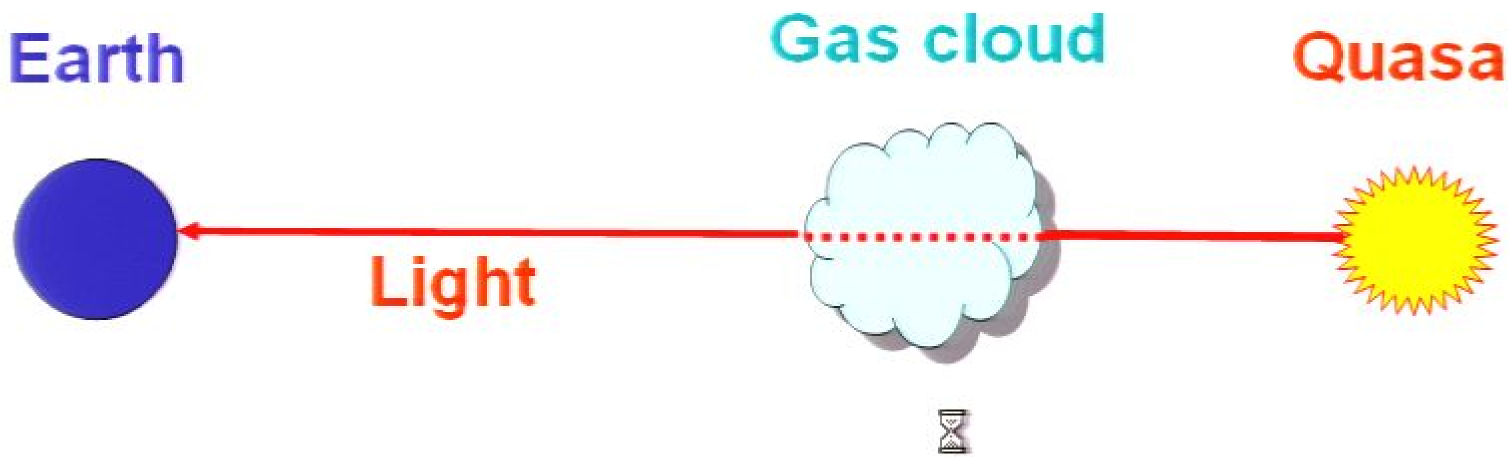
Many-Multiplet Method

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



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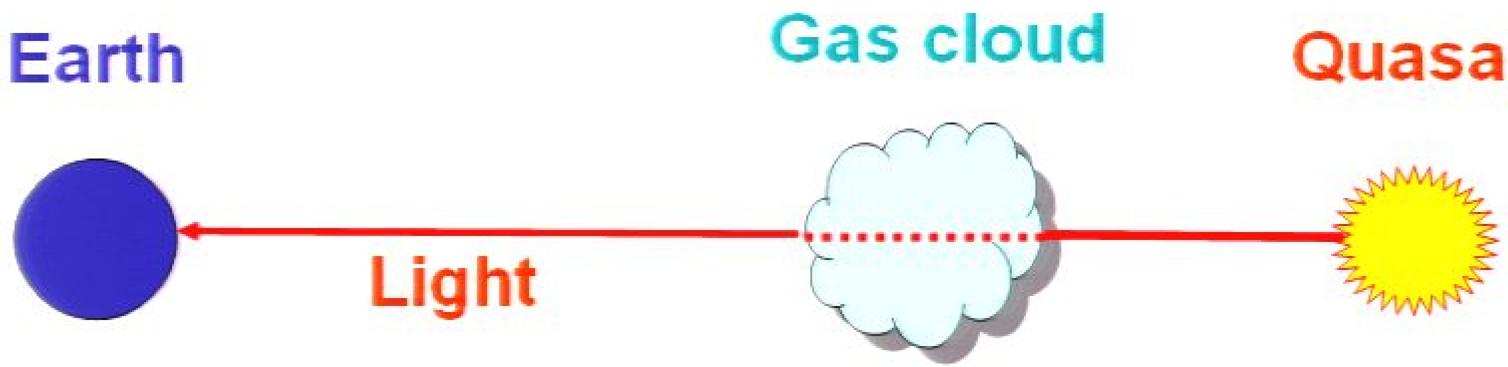

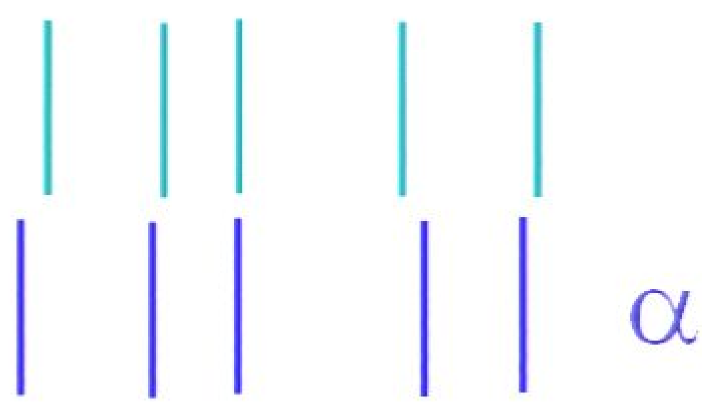

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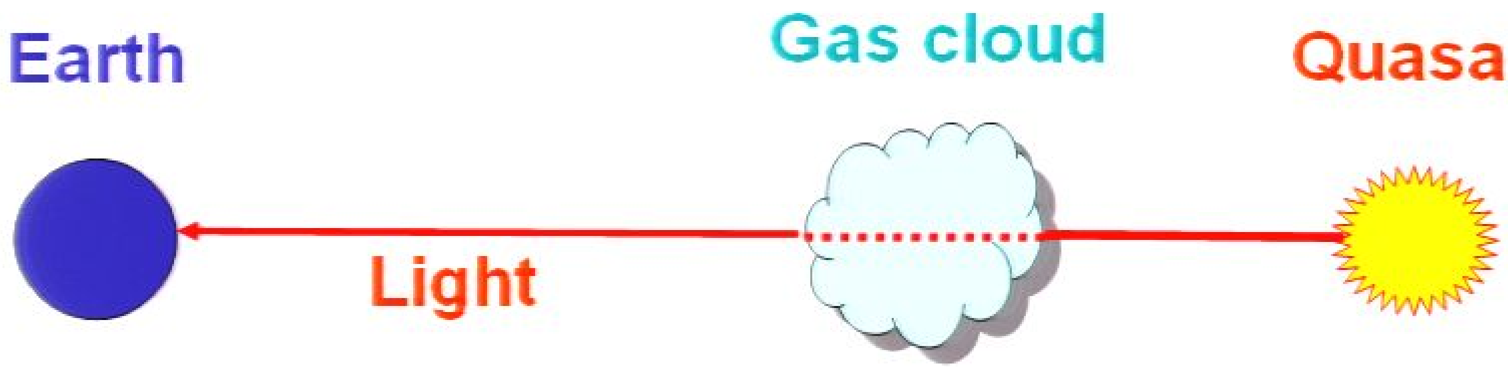

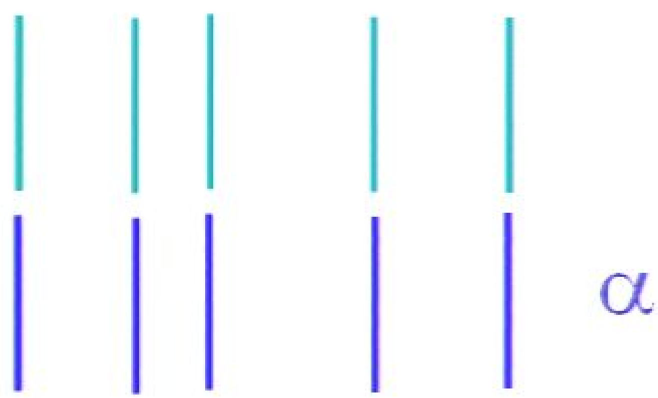

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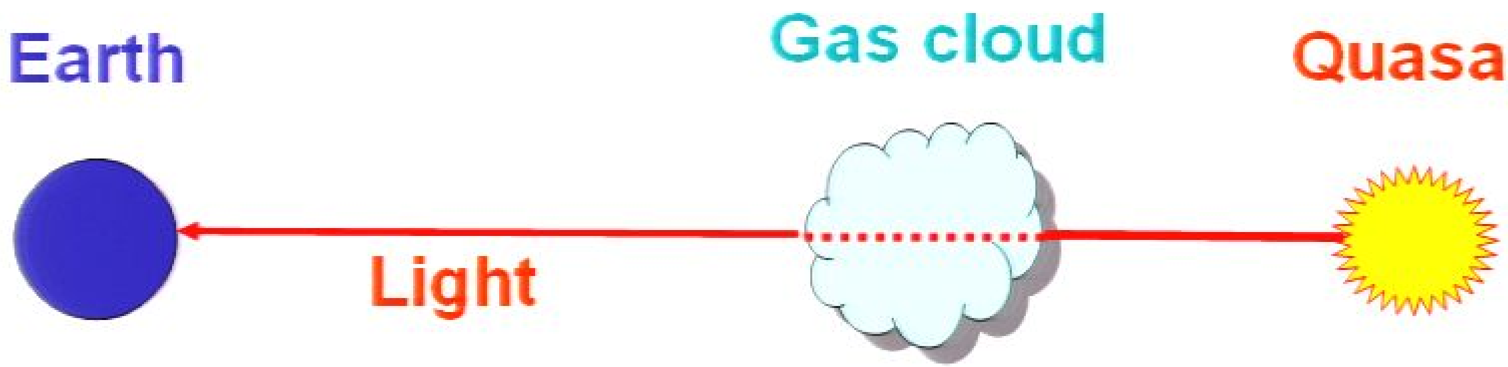
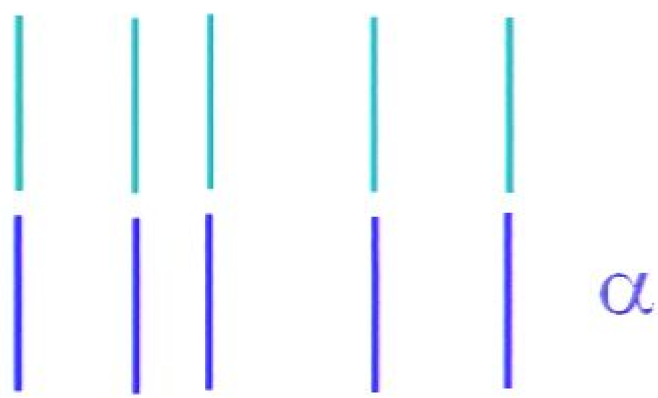




One needs to know $E(\alpha^2)$ for each line to do the fitting

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

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

q is found by varying α in computer codes:

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

α =e²/hc=0 corresponds to non-relativistic limit (infinite c).

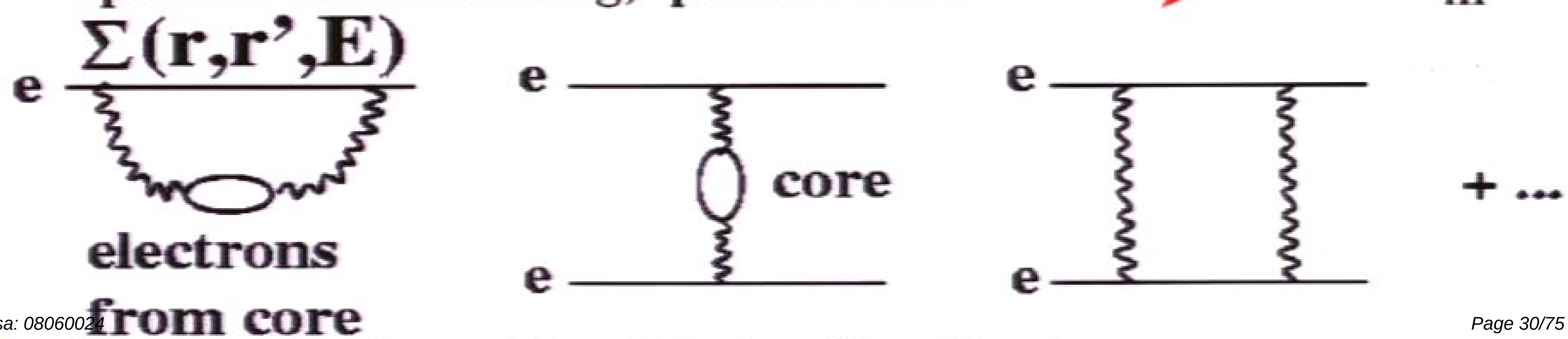
Methods were used for many important problems:

- 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** → $V = H - H_{HF}$



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
Fe II	38458.9871	1330
Zn II	49355.002	2490
Zn II	48841.077	1584

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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

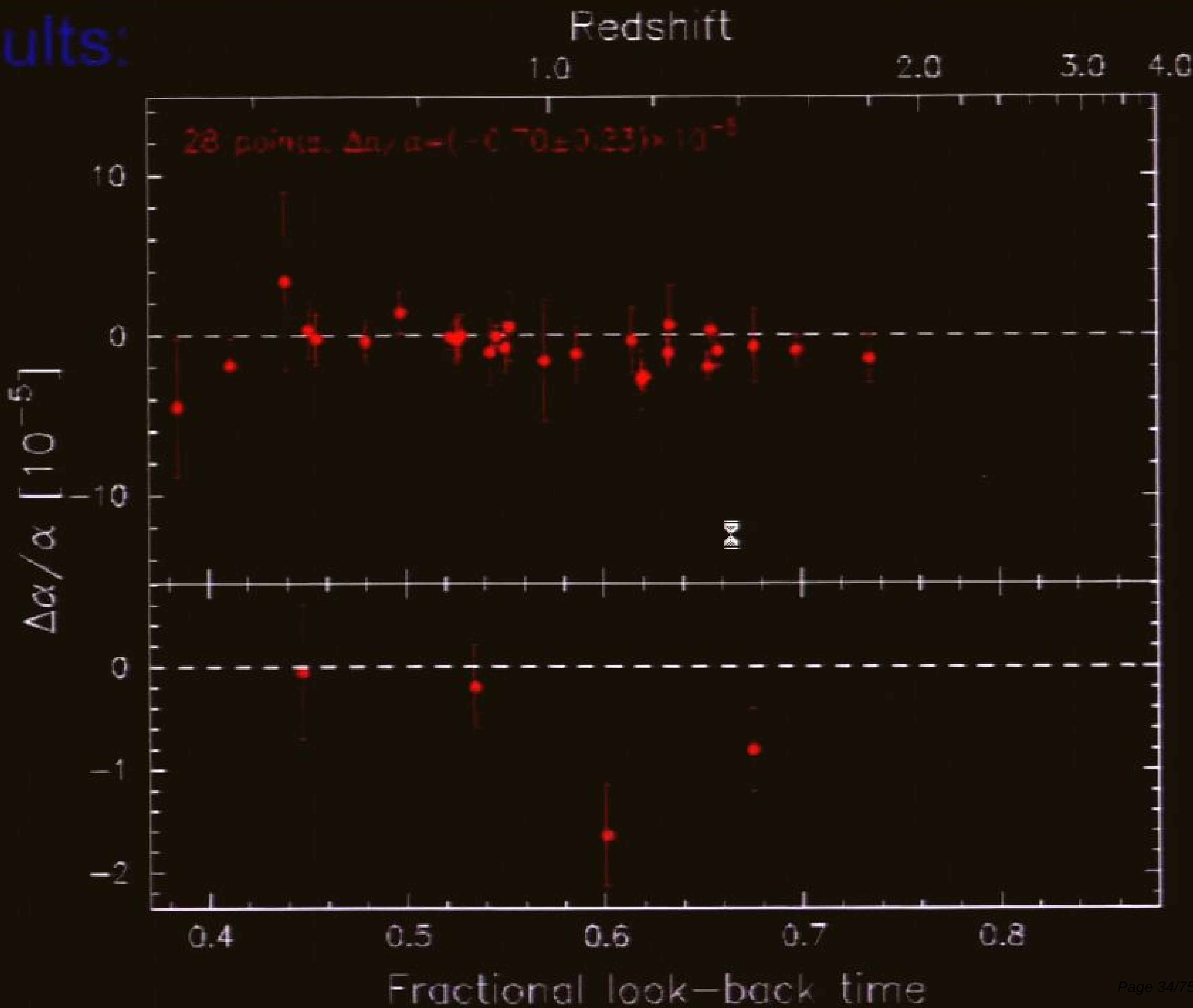
Variation in the fine structure constant?: Recent results and the future

Radio constraints:

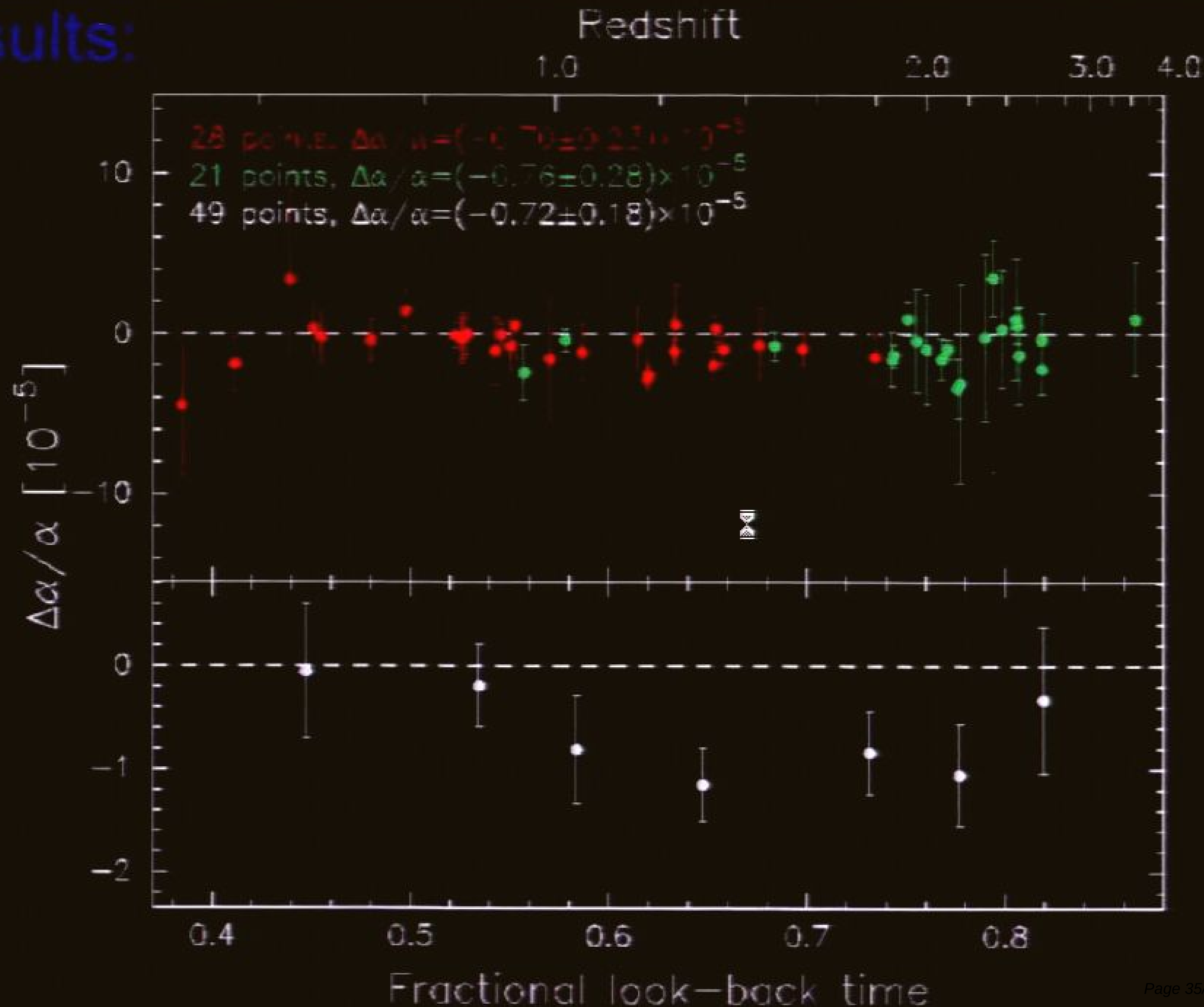
- Hydrogen hyperfine transition at λ_H = 21cm.
- Molecular rotational transitions CO, HCO^+, HCN, HNC, CN, CS …
- $\omega_H/\omega_M \propto \alpha^2 g_P$ where g_P is the proton magnetic *g*-factor.

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

Results:

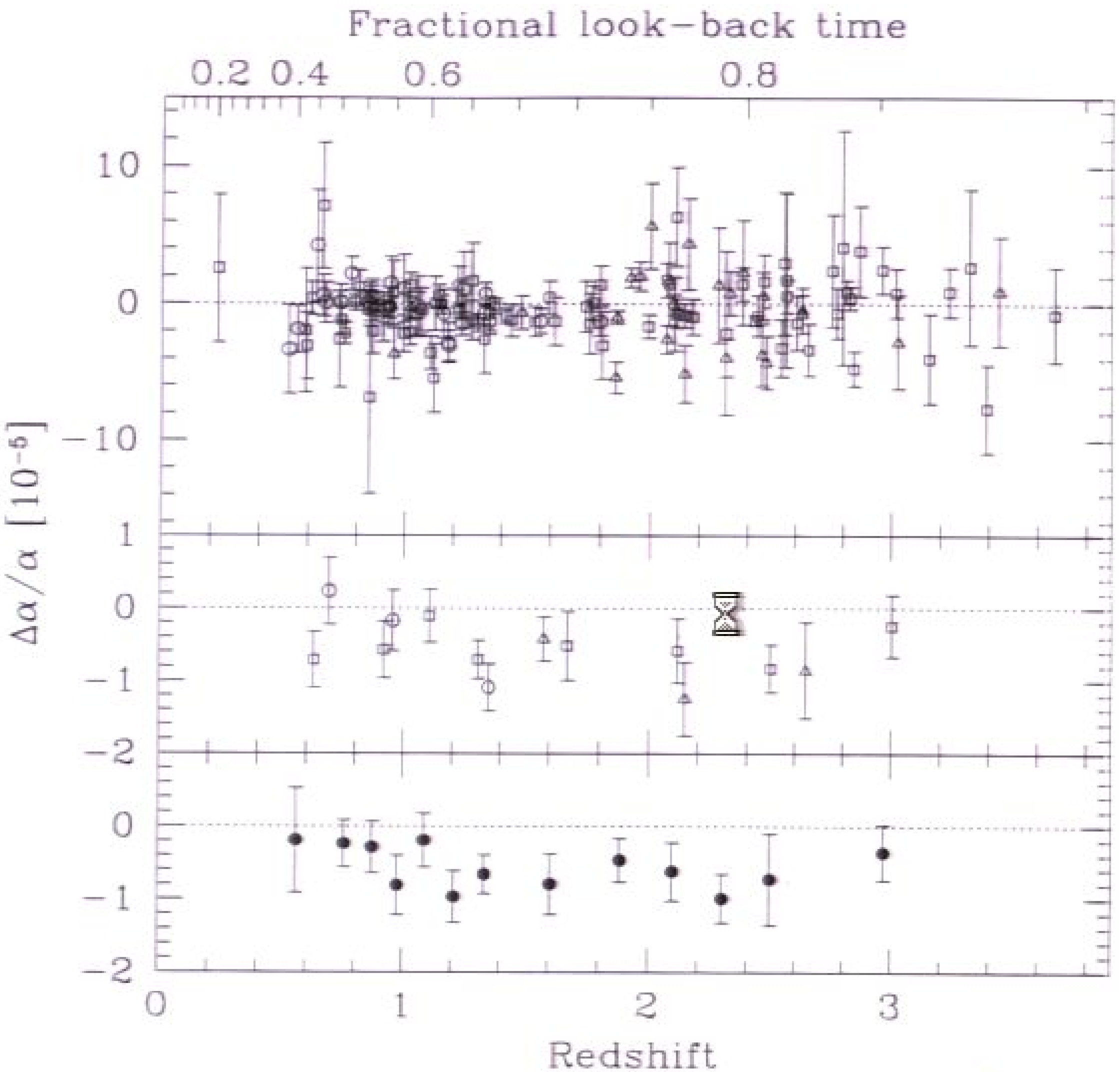

Redshift
1.0
2.0
3.0
4.0
10
0
−10
0
−1
−2
Δα/α [10⁻⁵]
0.4
0.5
0.6
0.7
0.8
Fractional look−back time

Results:



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

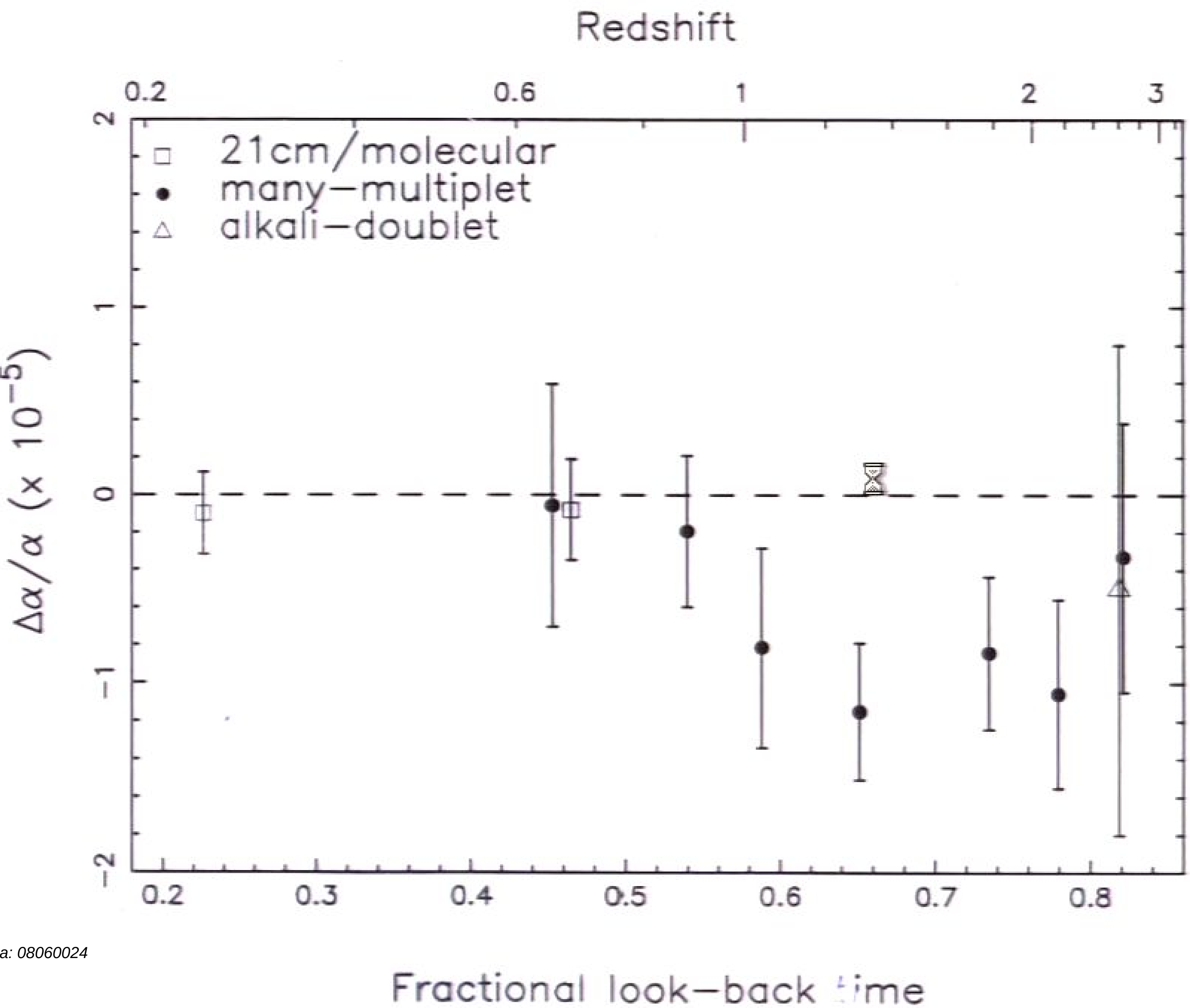
Murphy, Webb, Flambaum 2003



$$\frac{\Delta\alpha}{\alpha} = (-0.574 \pm 0.102) \cdot 10^{-5}$$

$5.62\,\sigma$ from $\Delta\alpha = 0$

fiducial result $(-0.543 \pm 0.116) \cdot 10^{-5}$ $4.7\,\sigma$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0
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Δα/α (x 10⁻⁵)
21cm/molecular
many−multiplet
alkali−doublet
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0.5
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- 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.

Possible systematic effect:

isotopic ratio evolution.

Different isotope abundancies
→ shift of line.

We calculated isotopic shifts for
Mg II, Si II (p→s), Si IV, Zn II. However,
calculations are too complicated
for open d-shell atoms Cr II, Fe II, Ni II,
(also Si II $s^2p \to sp^2$) – in progress.

Measure, please!!!

"Conspiracy" of isotopic shifts and
isotopic abundances?

Line removal test.

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 $\Delta\alpha/\alpha$.

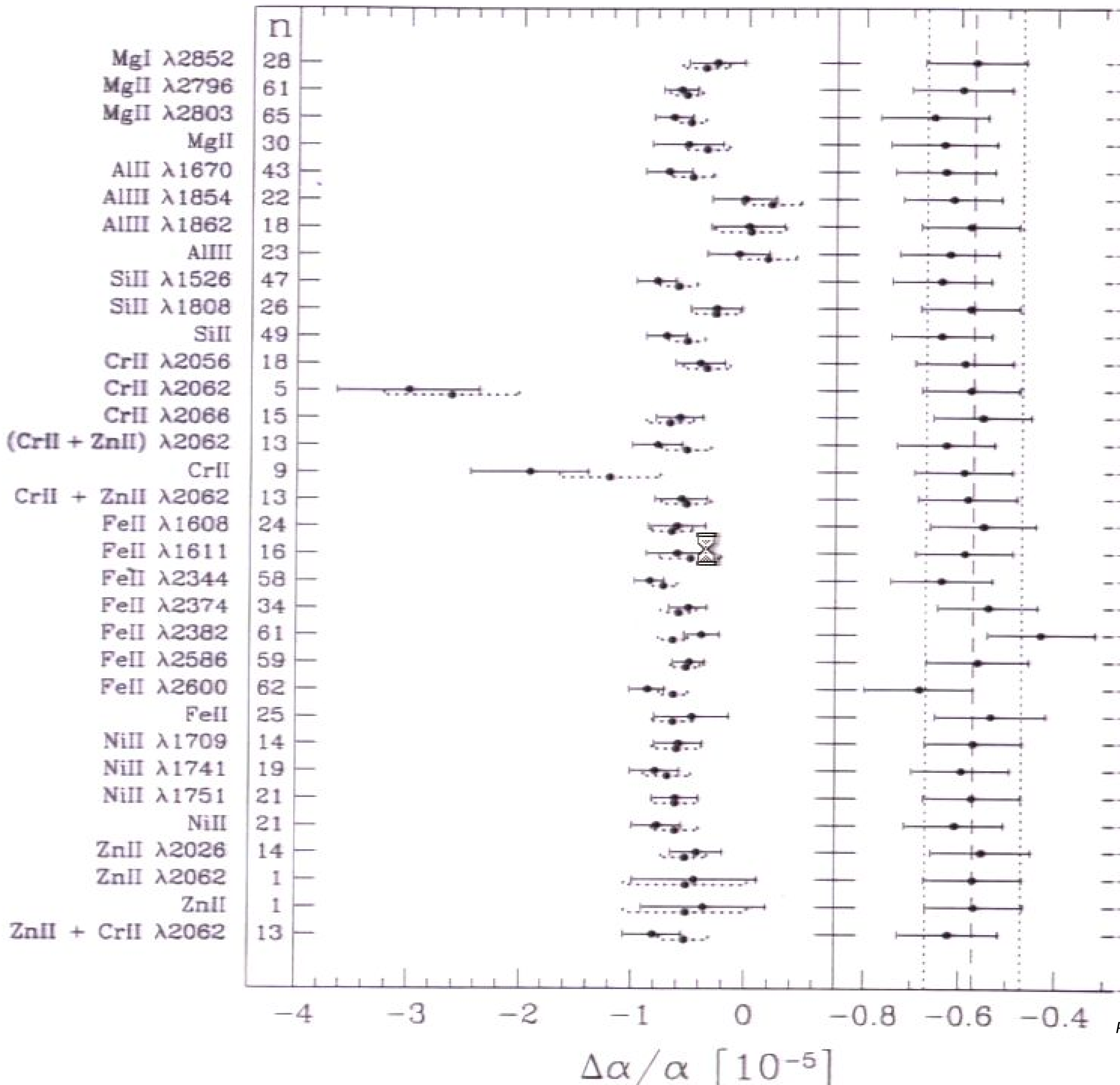
  Results: subset contains 12 systems (only in high z sample)

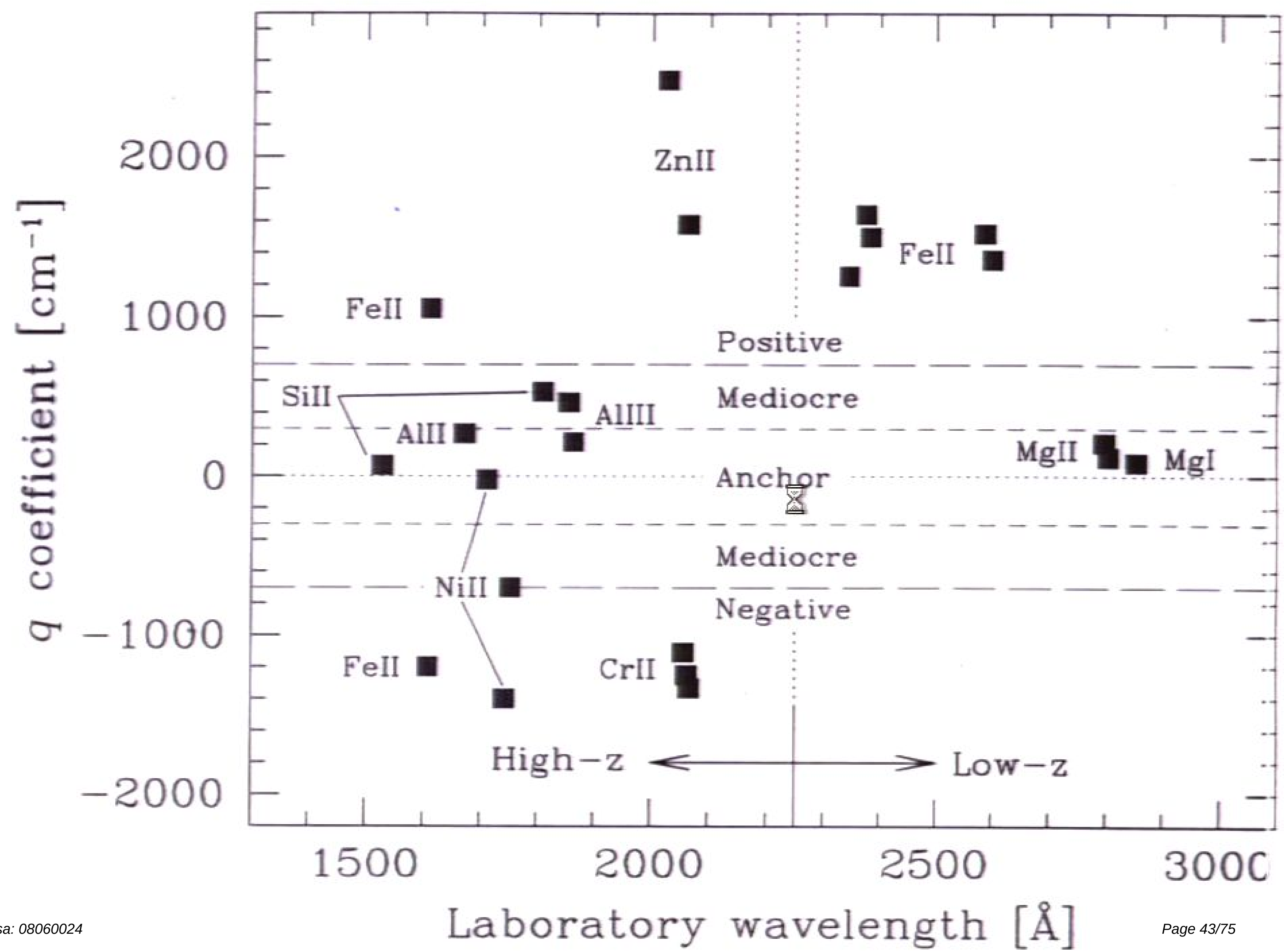
  No lines removed: $\Delta\alpha/\alpha = (-1.31 \pm 0.39) \times 10^{-5}$

  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: $\Delta\alpha/\alpha = (-1.41 \pm 0.65) \times 10^{-5}$


n
MgI λ2852 28
MgII λ2796 61
MgII λ2803 65
MgII 30
AlII λ1670 43
AlIII λ1854 22
AlIII λ1862 18
AlIII 23
SiII λ1526 47
SiII λ1808 26
SiII 49
CrII λ2056 18
CrII λ2062 5
CrII λ2066 15
(CrII + ZnII) λ2062 13
CrII 9
CrII + ZnII λ2062 13
FeII λ1608 24
FeII λ1611 16
FeII λ2344 58
FeII λ2374 34
FeII λ2382 61
FeII λ2586 59
FeII λ2600 62
FeII 25
NiII λ1709 14
NiII λ1741 19
NiII λ1751 21
NiII 21
ZnII λ2026 14
ZnII λ2062 1
ZnII 1
ZnII + CrII λ2062 13
−4 −3 −2 −1 0 −0.8 −0.6 −0.4
Δα/α [10⁻⁵]

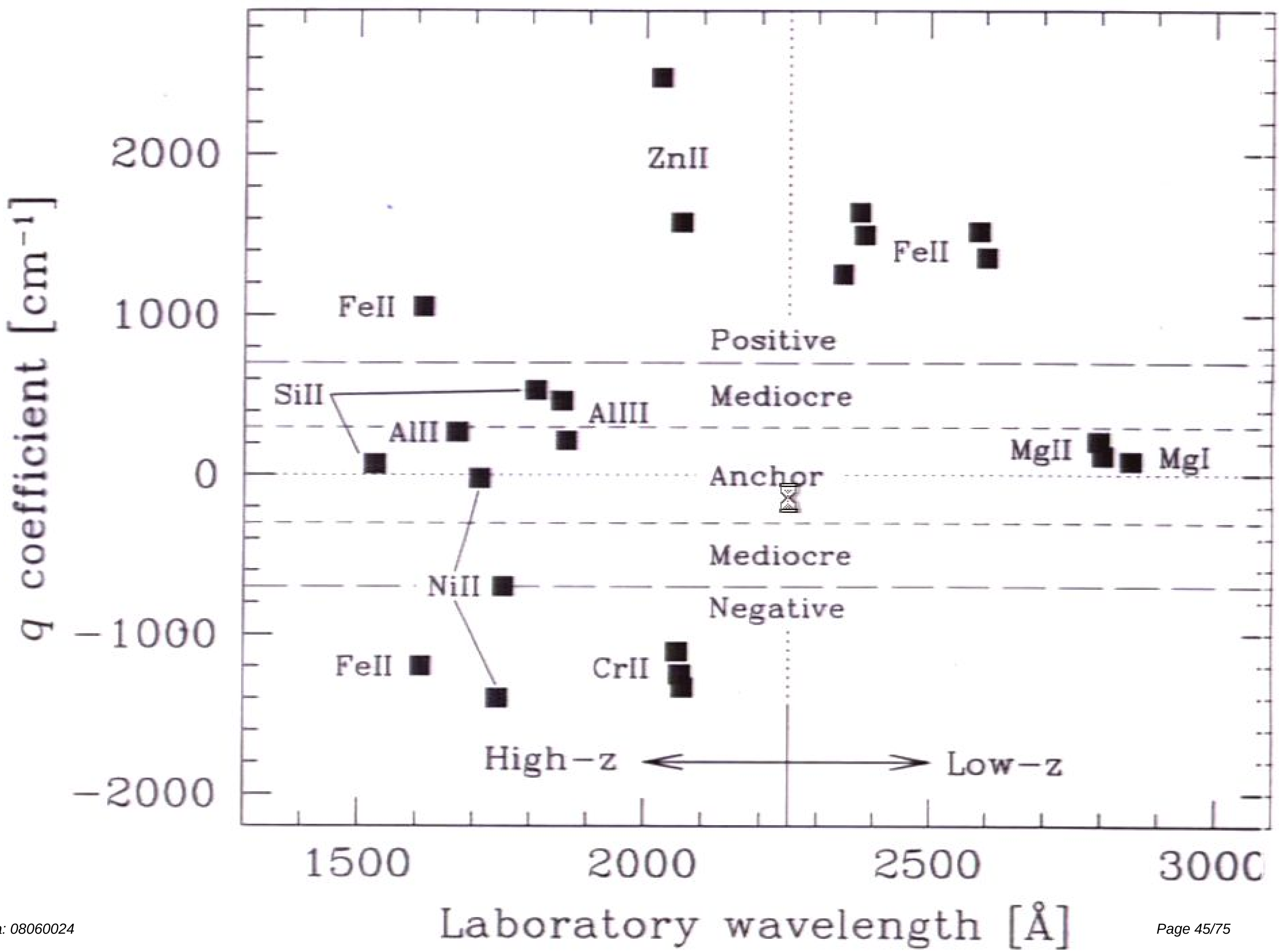


q coefficient [cm⁻¹]
2000
1000
0
−1000
−2000
ZnII
FeII
FeII
Positive
Mediocre
SiII
AlIII
AlII
MgII
MgI
Anchor
Mediocre
NiII
Negative
FeII
CrII
High−z
Low−z
1500
2000
2500
3000
Laboratory wavelength [Å]

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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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)

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- Murphy et al, 2003: **Keck telescope,** 143 systems, 23 lines, 0.2<z<4.2

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

- 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.

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Measurements m_e / M_p or m_e / Λ_{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 NH_3

Flambaum, Kozlov PRL2007

Inversion spectrum: exponentially small "quantum tunneling" frequency ω_{inv}=W exp(-S)

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

ω_{inv} is exponentially sensitive to m_e / M_p

First enhanced effect in quasar spectra, 5 times

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

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

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

Measurements m_e / M_p or m_e / Λ_{QCD}

- Reinhold, Buning, Hollenstein, Ivanchik,

Petitjean, Ubachs PRL 2006 , H_2 molecule, 2 systems

$\Delta(m_e / M_p) / (m_e / M_p) = -2.4(0.6) 10^{-5}$ Variation 4 σ ! Higher redshift, z=2.8

Space-time variation? Grand Unification model?

Oklo natural nuclear reactor

1.8 billion years ago

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

Shlyakhter; Damour, Dyson; Fujii et al

$\Delta E_r = 1$ MeV $\Delta\alpha/\alpha$

Limits on variation of alpha

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Limits on variation of alpha

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

Flambaum,Shuryak 2002,2003 Dmitriev,Flambaum 2003
Flambaum,Wiringa 2007

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

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

Fujii et al $|\Delta E_r| < 0.02$ eV $|x| < 2.10^{-9}$

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

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

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

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: α, $(m_e, m_q)/\Lambda_{QCD}$

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^+

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

Results for variation of fundamental constants

Source	$Clock_1/Clock_2$	$d\alpha/dt/\alpha(10^{-16}\,yr^{-1})$
Blatt *et al*, 2007	Sr(opt)/Cs(hfs)	-3.1(3.0)
Fortier *et al* 2007	Hg+(opt)/Cs(hfs)	-0.6(0.7)[a]
Rosenband *et al*/08	Hg+(opt)/Al+(opt)	-0.16(0.23)
Peik *et al*, 2006	Yb+(opt)/Cs(hfs)	4(7)
Bize *et al*, 2005	Rb(hfs)/Cs(hfs)	1(10)[a]

[a]assuming $m_q/\Lambda_{QCD} = Const$

Combined results: $d/dt \ln\alpha = -1.6(2.3) \times 10^{-17}\ yr^{-1}$
$d/dt \ln(m_q/\Lambda_{QCD}) = 8(22) \times 10^{-15}\ yr^{-1}$
m_e/M_p or m_e/Λ_{QCD} $-1.9(4.0) \times 10^{-16}\ yr^{-1}$

Enhancement of relative effect

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

$4f^{9}5d^{2}6s$ E=19797.96… cm^{-1} , q= -23000 cm^{-1}

Interval $\Delta\omega = 10^{-4}$ 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)x 10^{-15} yr^{-1}**

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

Cancellation between fine structure and vibrations

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

SiBr, Cl_2^+ … microwave transitions between narrow excited states, sensitive to α and $\mu = m_e/M_p$

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

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

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

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

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

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 2006; He,Re 2007; Dobaczewski, Feldmayer, Flambaum, Litvinova 2008; Flambaum, Wiringa2008; Dmitriev, Flambaum2008

Nuclear/QCD estimate: Enhancement $\mathbf{10^5}$,

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

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

Shift 10^4 Hz for $\Delta\alpha/\alpha = 10^{-16}$

Compare with atomic clock shift 0.1 Hz

Problem – to find this narrow transition using laser

Search: Peik et al, Lu et al, Habs et al, DeMille et al

^{235}U energy 76 eV, width 6 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

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

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

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

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_α=-8.7(6.6) 10^{-6}

K_e=4.9(3.9) 10^{-6} K_q=6.6(5.2) 10^{-6}

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

New best limits

$K_{\alpha}=2.5(3.1)\ 10^{-6}$
$K_{e}=-1.1(1.7)\ 10^{-6}$
$K_{q}=-1.9(2.7)\ 10^{-6}$

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 4 σ . 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 $<3\ 10^{-9}$
- 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

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

$$\text{Rotation} = m_e / M_p \text{ atomic units}$$

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.

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

Big Bang Nucleosynthesis: Dependence on m_q / Λ_{QCD}

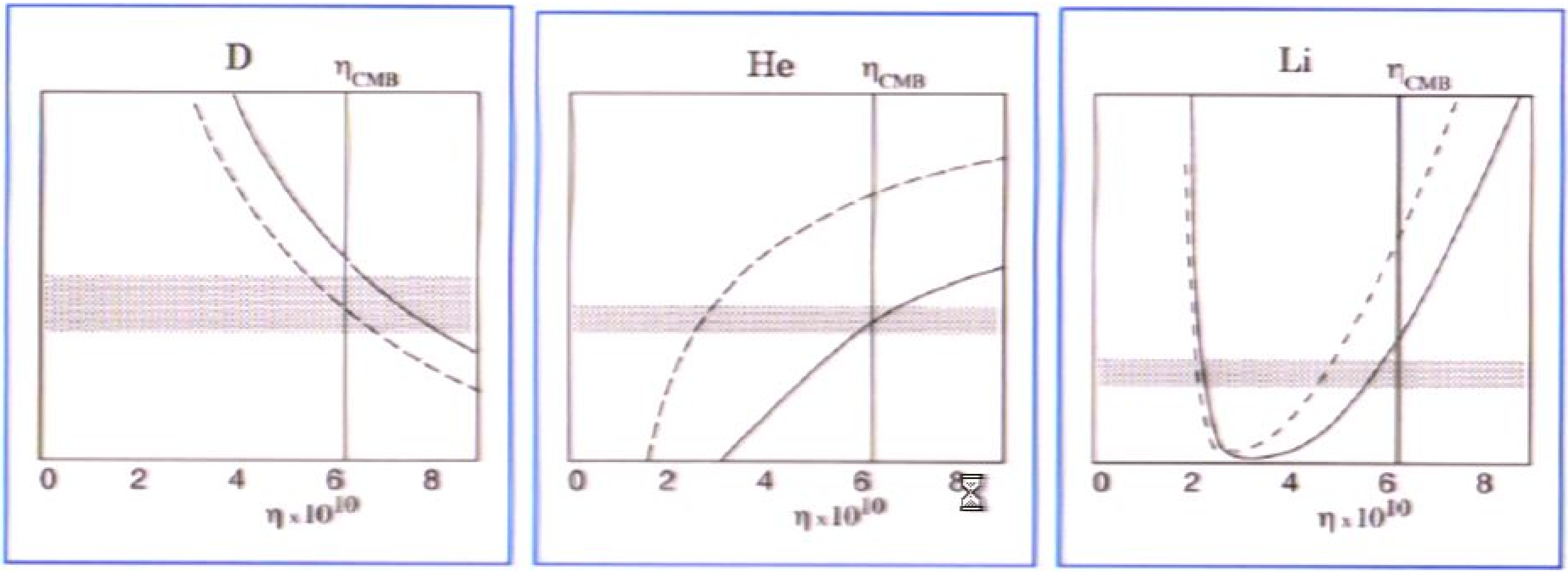
- ^{2}H $1+7.7x=1.07(15)$ $x=0.009(19)$
- ^{4}He $1-0.95x=1.005(36)$ $x=-0.005(38)$
- ^{7}Li $1-50x=0.33(11)$ $x=0.013(02)$

Final result

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

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

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



Comparison with observations gives

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

This also leads to agreement

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