Space-time variation of Fundamental Constants

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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 $\alpha = e^2/2\varepsilon_0 hc = 1/137.036$
- Electron or quark mass/QCD strong interaction scale, $m_{e,q}/\Lambda_{QCD}$

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

Electron-to-proton mass ratio=const m_e/Λ_{QCD}

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

evidence?

evidences?

[1] *Based on atomic and molecular calculations*

Evidence for spatial variation of α

Quasar spectra

Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNARS2012

$$\alpha(x)= \alpha(0) + \alpha\,'(0)\, x + \ldots$$

$x=r\cos(\phi)$, $r=ct$ – distance (t - light travel time, c - speed of light)

Reconciles all measurements of the variation

Evidence for spatial variation of α

- Webb, King, Murphy, Flambaum, Carswell, Bainbridge,arxiv:1008.3907, PRL, MNRAS

$\alpha(x) = \alpha(0) + \alpha'(0)\, x + \ldots$

$x = r\cos(\phi)$, $r = ct$ – distance (instead of time)

Reconciles all measurements of the variation

- Berengut, Flambaum, arxiv:1008.3957,PRL

Manifestations on atomic clocks, Oklo, meteorites and cosmological phenomena

- Berengut, Flambaum,King,Curran,Webb,

Further astronomical evidence, 1009.0591,PRD

“ **Fine tuning”** of fundamental constants is needed for life to exist. If fundamental constants would be even slightly different, life could not appear!

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.

There are theories which suggest variation of the fundamental constants in expanding Universe.

Variation of strong interaction

Grand unification

$$\frac{\Delta\left(m/\Lambda_{QCD}\right)}{m/\Lambda_{QCD}} = R\frac{\Delta\alpha}{\alpha}$$

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

2. Nuclear magnetic moments

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

3. Nuclear energy levels and resonances

Variation of strong interaction

Grand unification (Calmet, Fritzsch; Langecker, Segre, Strasser; Wetterich, Dent)

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

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

2. Nuclear magnetic moments

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

3. Nuclear energy levels and resonances

Relation between variations of different coupling constants

Grand unification models Calmet,Fritzch; Langecker, Segre, Strasser; Wetterich,Dent

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

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

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

$$d\alpha_3 \;/\, \alpha_3^{\,2} = d\alpha_1 \,/\, \alpha_1^{\,2}$$

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

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

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

1. Proton mass $\mathrm{M_p} \sim 4\Lambda_{QCD}$, measure m_e/M_p
2. Nuclear magnetic moments

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

3. Nuclear energy levels and resonances

Dependence on quark mass

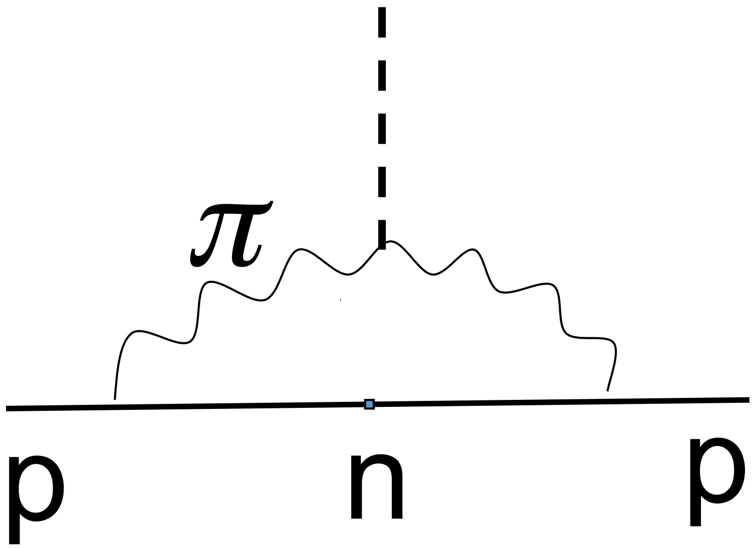
- Dimensionless parameter is m_q/Λ_{QCD} . It is convenient to assume Λ_{QCD} =const, i.e. measure m_q in units of Λ_{QCD}
- m_π is proportional to $(m_q\Lambda_{QCD})^{1/2}$ $\Delta m_\pi/m_\pi=0.5\Delta m_q/m_q$
- Other meson and nucleon masses remains finite for $m_q=0$. $\Delta m/m=K\,\Delta m_q/m_q$

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

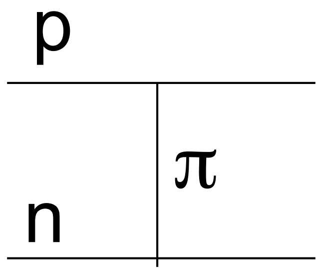
$$m_q = \frac{m_u + m_d}{2} \approx 4\,MeV,\ \Lambda_{QCD} = 220\ MeV \rightarrow\ K = 0.02 - 0.06$$

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.

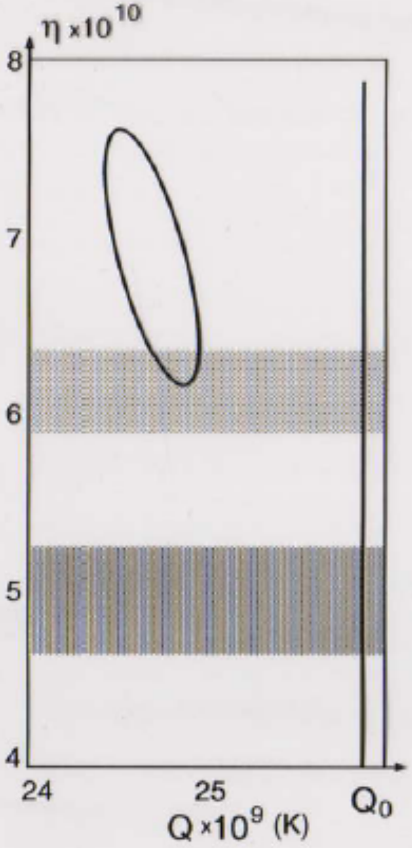
Nuclear calculations: meson exchange theory of strong interaction. Nucleon mass in kinetic energy $p^2/2M$

Big Bang nucleosynthesis: dependence on quark mass

- Flambaum, Shuryak 2002
- Flambaum, Shuryak 2003
- Dmitriev, Flambaum 2003
- Dmitriev, Flambaum, Webb 2004
- Coc, Nunes, Olive, Uzan,Vangioni 2007
- Dent, Stern, Wetterich 2007
- Flambaum, Wiringa 2007
- Berengut, Dmitriev, Flambaum 2009

Big Bang Nucleosynthesis

(Dmitriev, Flambaum, Webb)



$$p+n\rightarrow d+\gamma,\ \ 3\ \mathrm{sec}\leq \mathrm{t}\leq 6\ \mathrm{min}$$

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

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

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

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

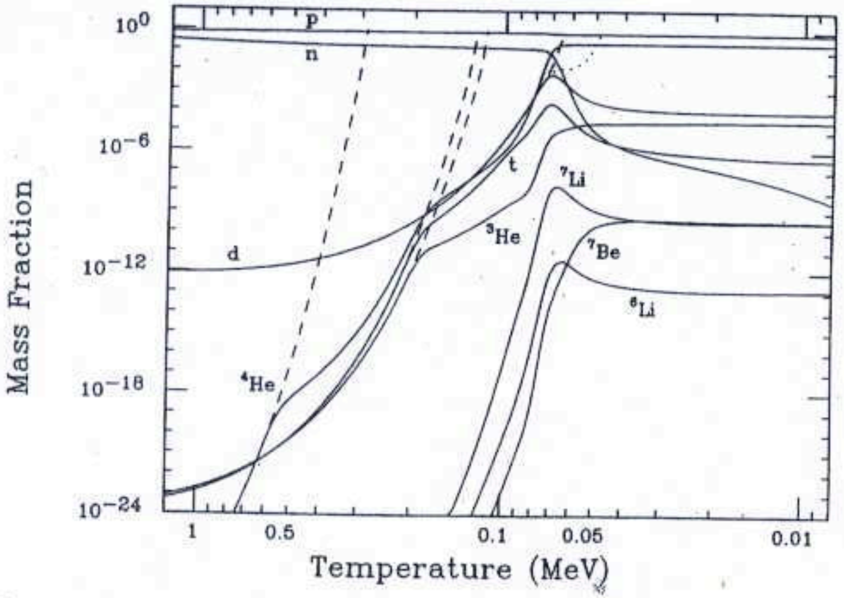


FIG. 2.—Evolution of light-element abundances with temperature, for a baryon-to-photon ratio $\eta_{10} = 3.16$. The dashed curves give the NSE curves of ^{4}He, t, ^{3}He, and d, respectively. The dotted curve is explained in the text.

Deuterium bottleneck

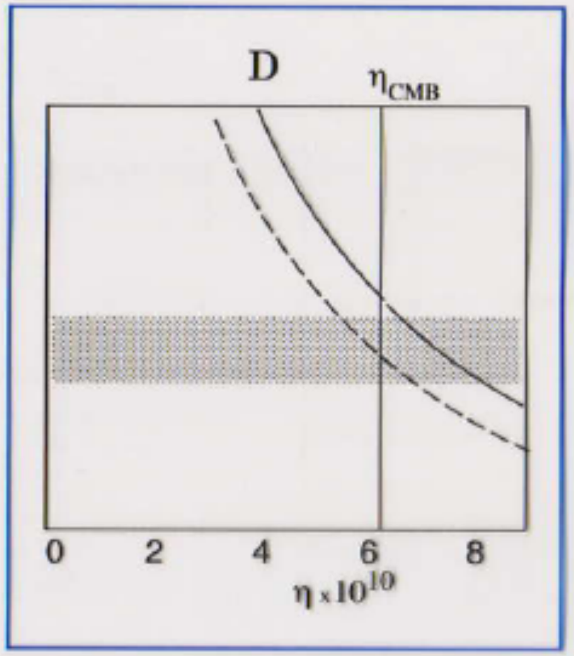
At temeperature $T<0.3$ Mev all abundances follow deuteron abundance

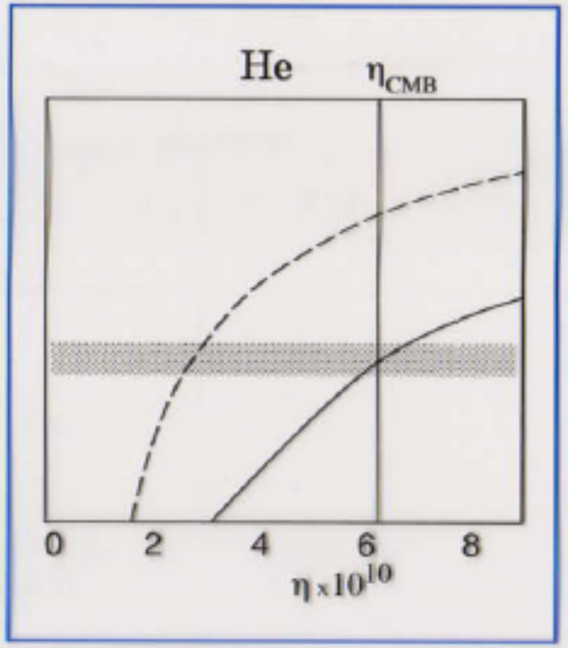
(no other nuclei produced if there are no deuterons)

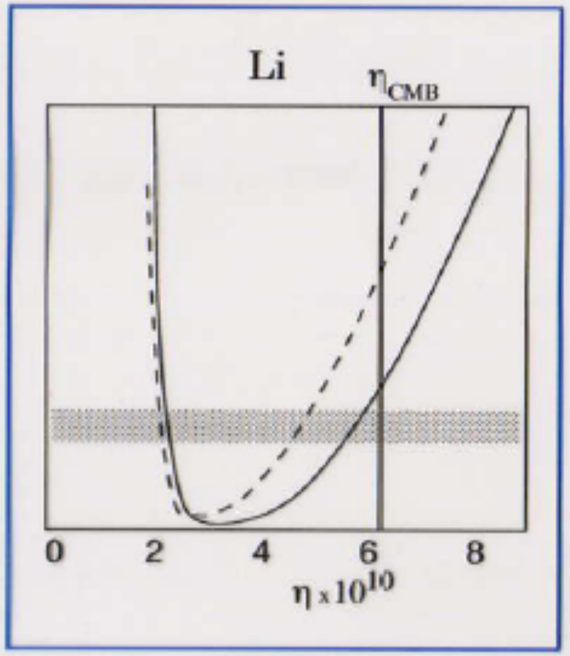
Reaction γ d – n p , exponentially small number of energetic photons, $e^{-(Ed/T)}$

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

Freezeout temeperure T_f =30 KeV







Comparison with observations gives

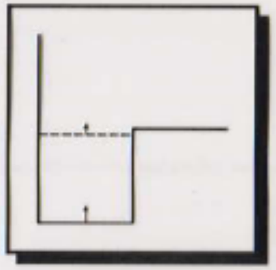
$$\boxed{\frac{\delta E_d}{E_d} = -0.019 \pm 0.005}$$

This also leads to agreement

$$\boxed{\eta(BBN) \approx \eta(CMB)}$$

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.

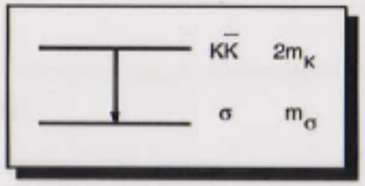


Virtual level in $n+p \to d+\gamma$ is even more sensitive to the variation of the potential.

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 2009: 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}

- ^{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), $X_q=m_q/\Lambda_{QCD}$

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 $1-50x=0.33(11)$ $x=0.013(02)$

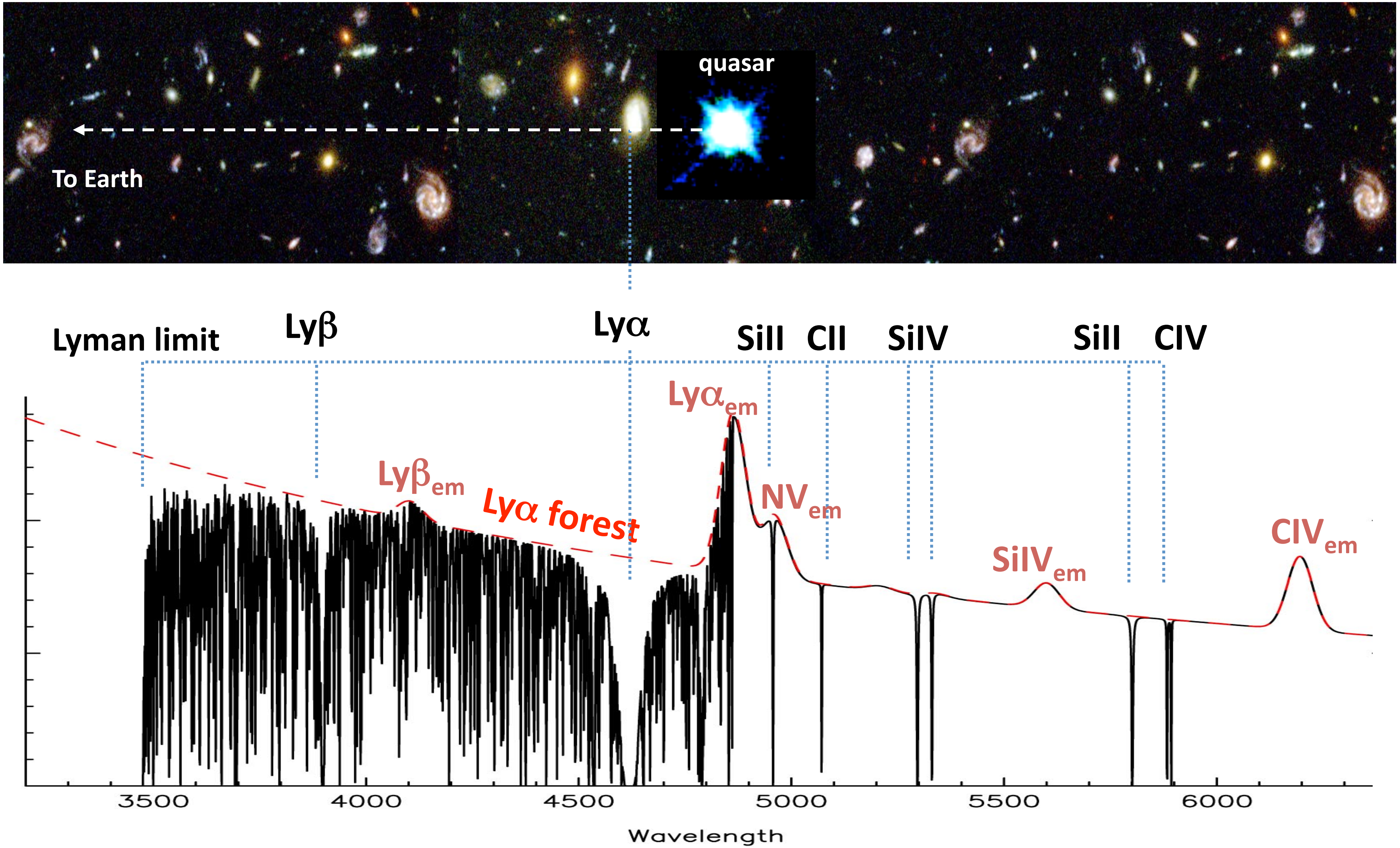
result

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

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

Nonlinear effects: $x=\Delta X_q/X_q=0.016\ (05)$

Quasars: physics laboratories in the early universe



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

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

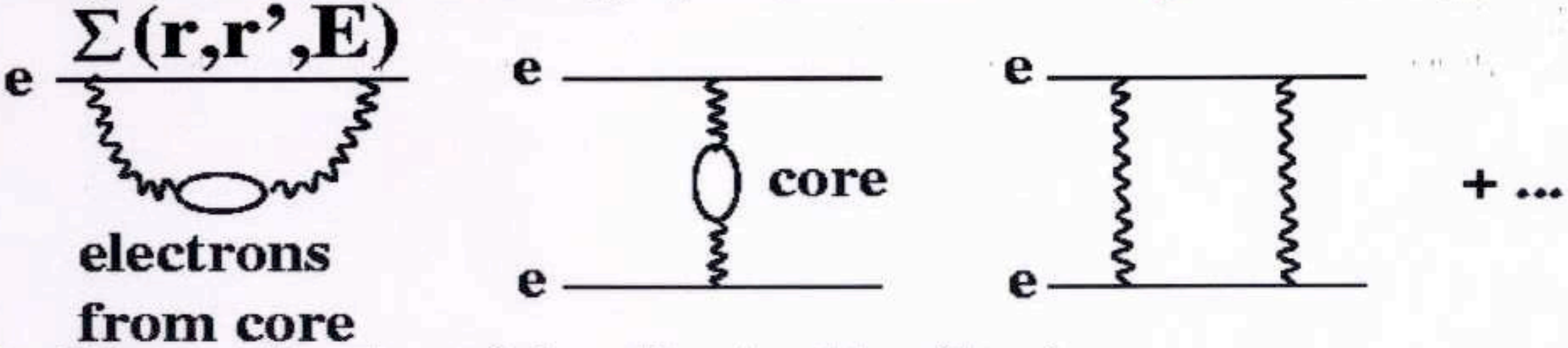
q is found by varying α in computer codes:

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

$\alpha = e^2/2\,\varepsilon_0 hc = 0$ corresponds to non-relativistic limit (infinite c). Dependence on α is due to relativistic corrections.

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** → $V = H - H_{\mathrm{HF}}$



3. **Diagonalization of the effective Hamiltonian**

Test: Energy levels in Mg II to 0.2% accuracy

Atomic transition frequencies

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

Units cancel in the ratio of frequenicies.

We use atomic units (Rydberg=1/2=const).

Dependence on α appears due to relativistic corrections

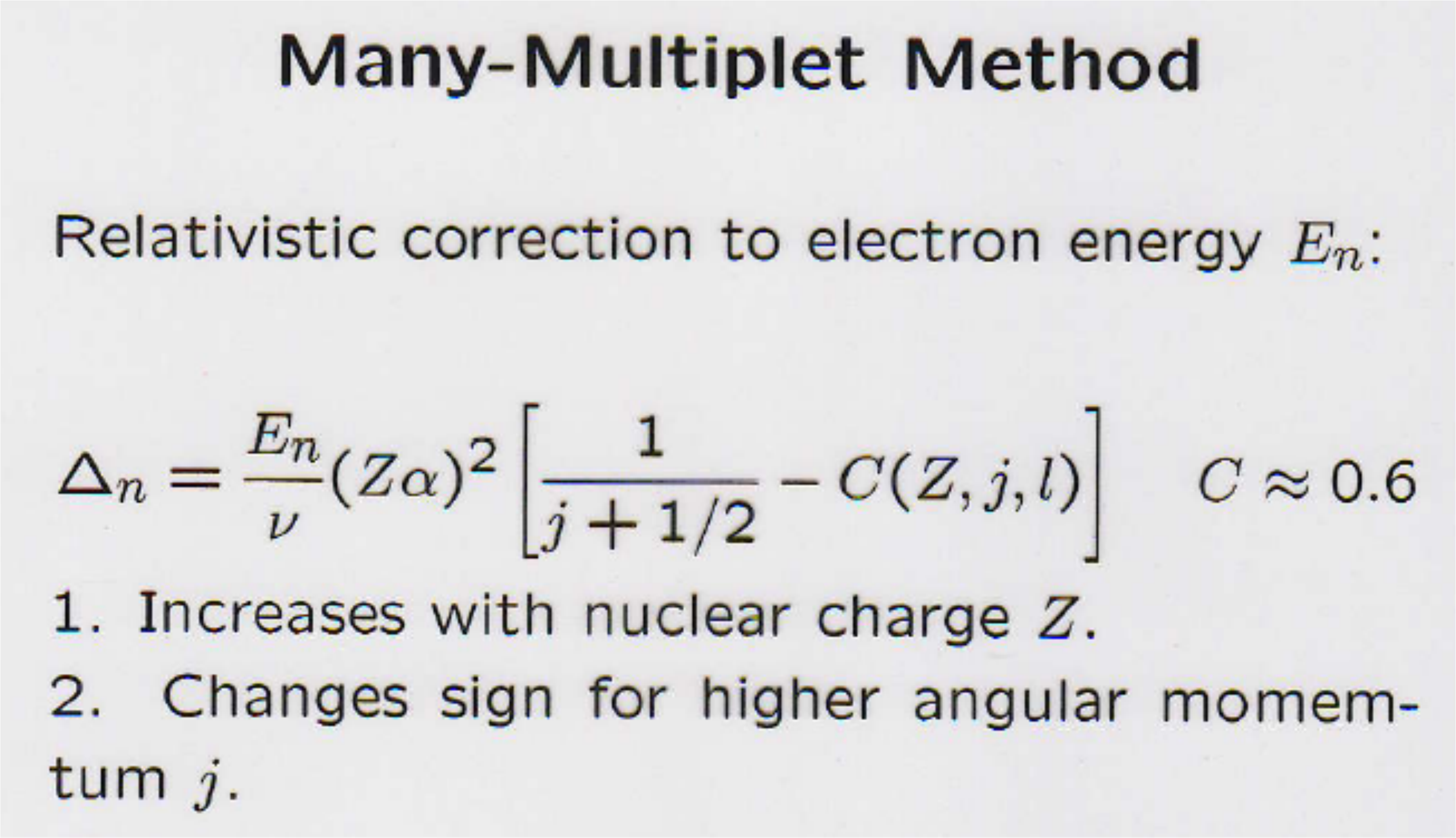
For α close to α_0 $\quad \omega = \omega_0 + q(\alpha^2/\alpha_0^2-1)$

q is found by varying α in computer codes:

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

Many-Multiplet Method
Dzuba,Flambaum,Webb 1998
quasar spectroscopy and atomic clocks

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 momem-tum j.

Methods of Atomic Calculations

N_{ve}	Relativistic Hartree-Fock +	Accuracy
1	All-orders sum of dominating diagrams	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%

These methods cover all periodic system of elements

They 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.

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

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	🔴

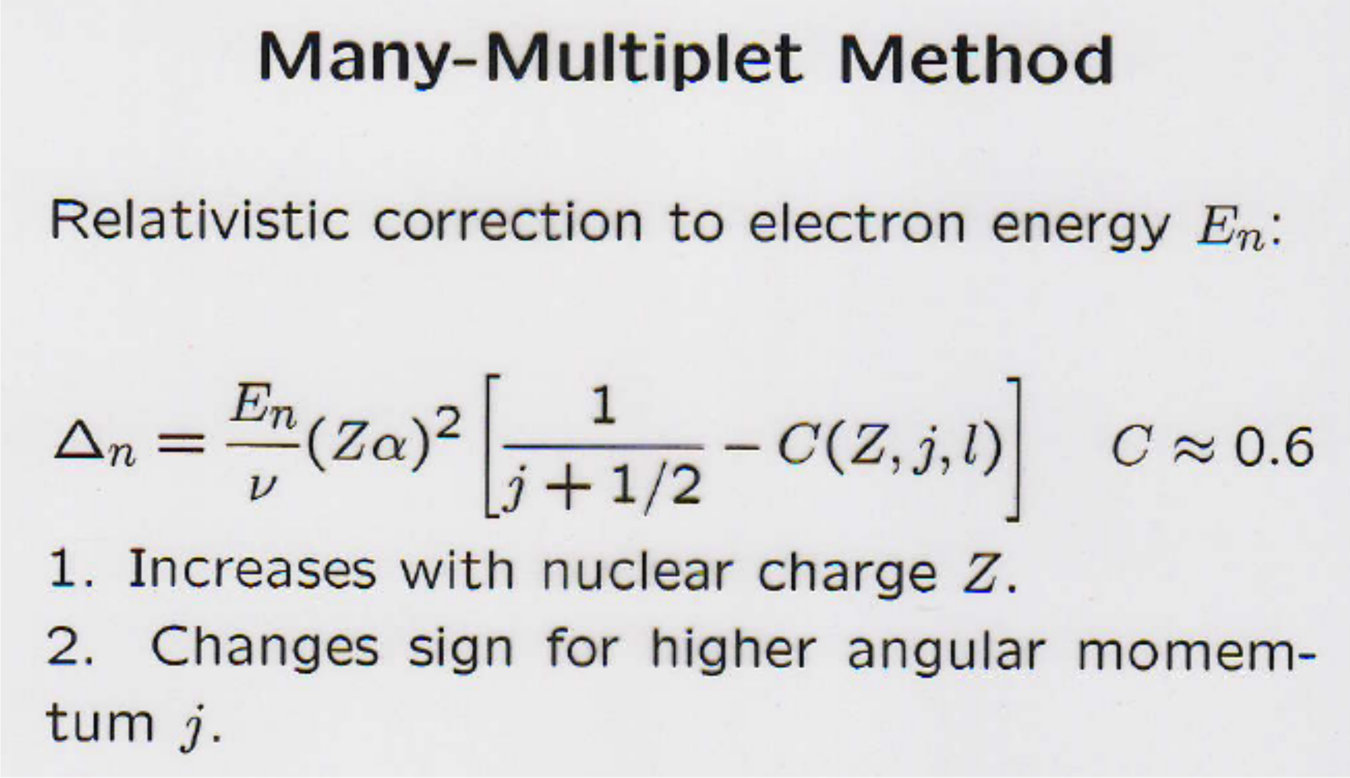
Positive shifters

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	

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,Co II,…

Different signs and magnitudes of q provides opportunity to study systematic errors!

Variation of fine structure constant α



Many-Multiplet Method

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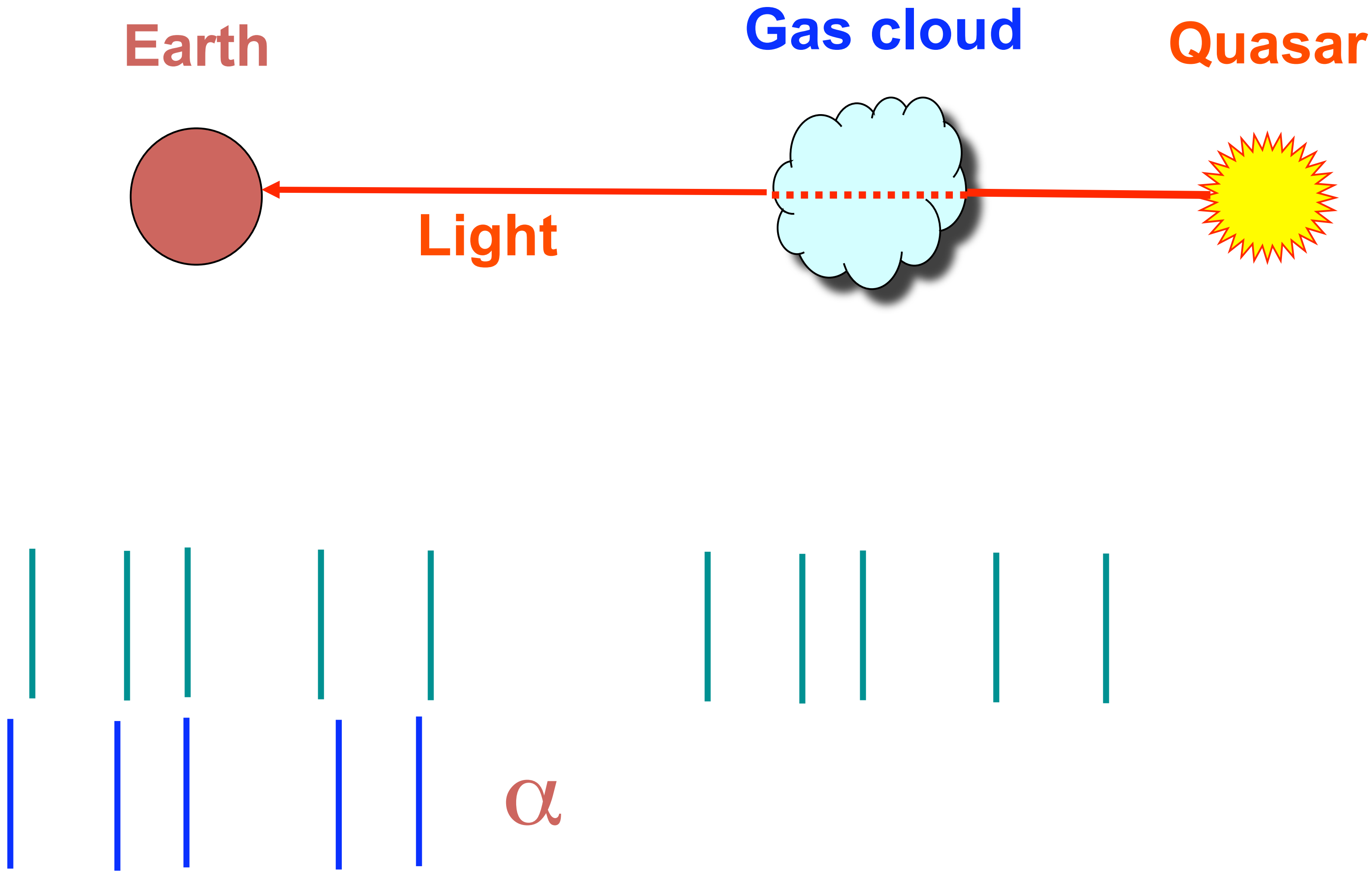
1. Increases with nuclear charge Z.
2. Changes sign for higher angular momem-tum j.

Quasar absorption spectra



Earth

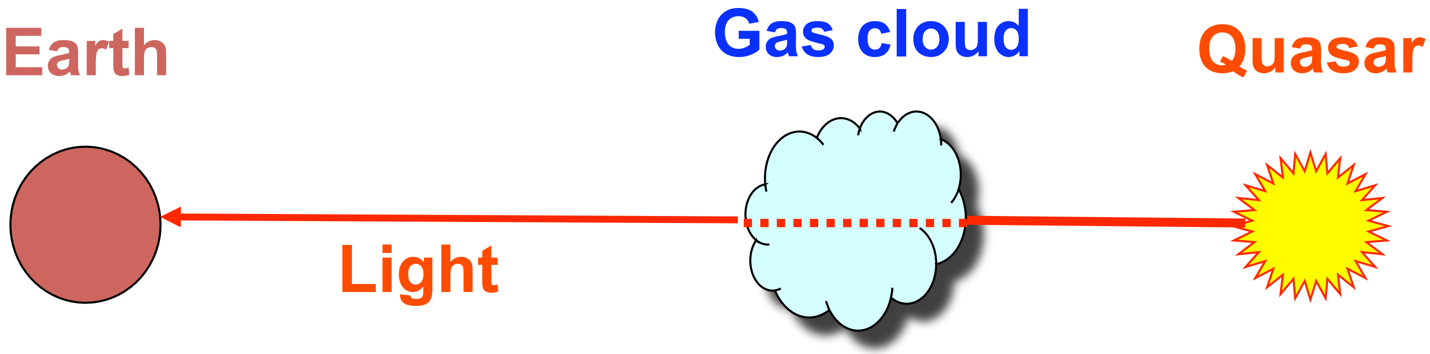
Gas cloud

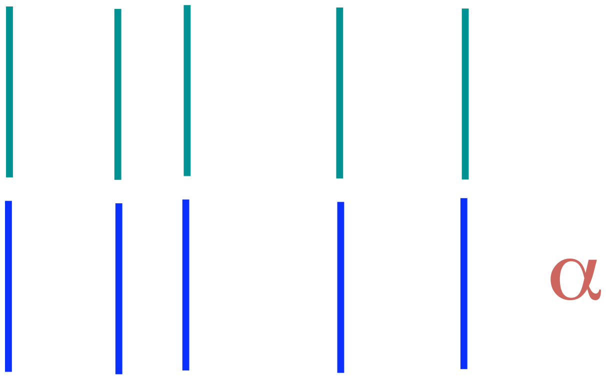
Quasar

Light

α

Quasar absorption spectra

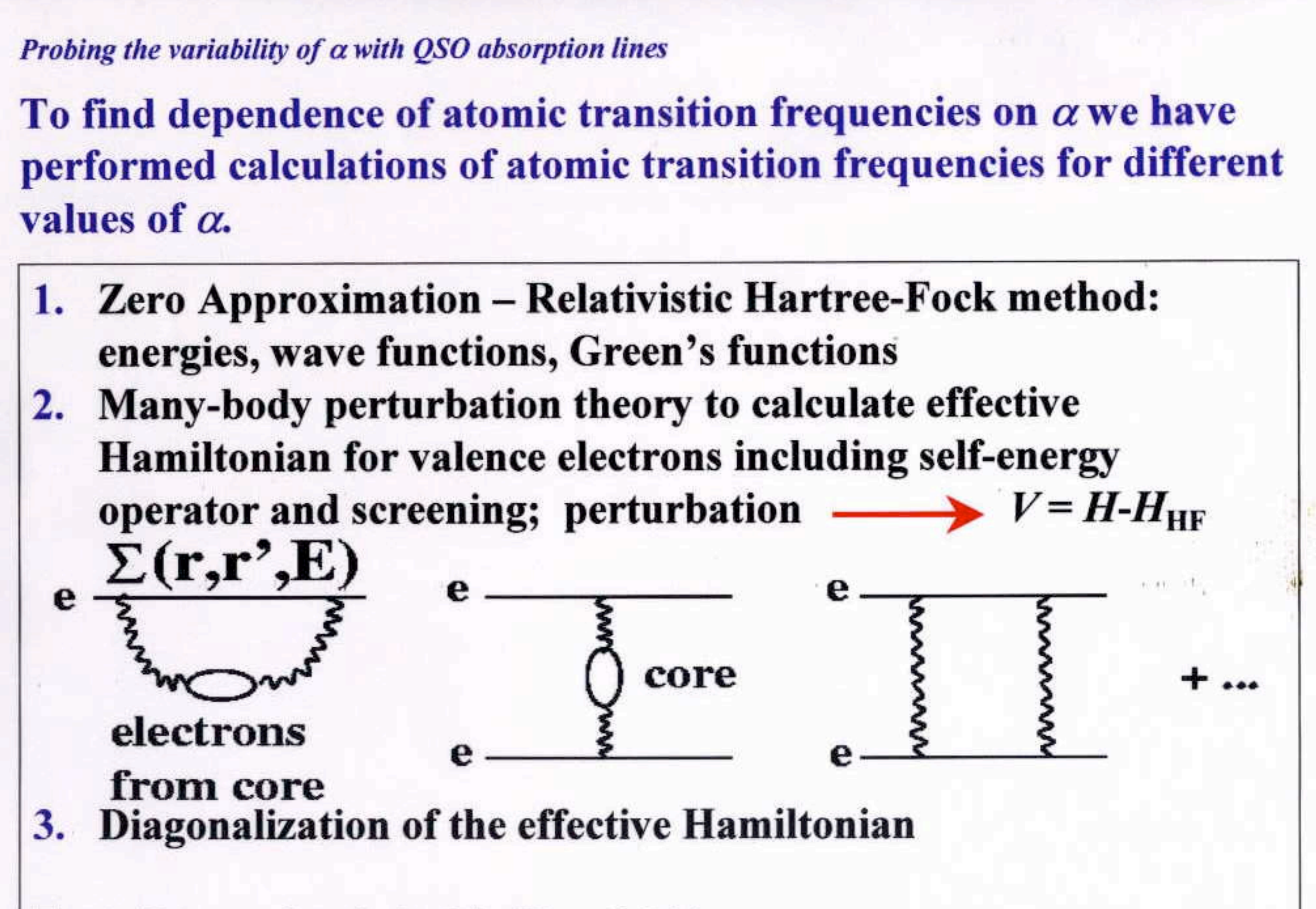




One needs to know $E(\alpha^2)$ for each line to do the fitting

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** → $V = H - H_{HF}$

$\Sigma(\mathbf{r},\mathbf{r}',E)$

3. **Diagonalization of the effective Hamiltonian**

Correlation potential method

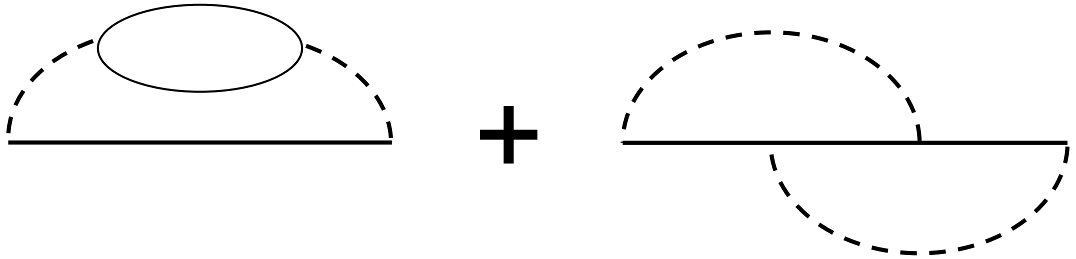
[Dzuba,Flambaum,Sushkov (1989)]

- Zeroth-order: relativistic Hartree-Fock. Perturbation theory in difference between exact and Hartree-Fock Hamiltonians.
- Correlation corrections accounted for by inclusion of a "correlation potential" ∑:

$$\boxed{V_{HF} \longrightarrow V_{HF} + \Sigma}$$

In the lowest order Σ is given by:

$$\Sigma =$$

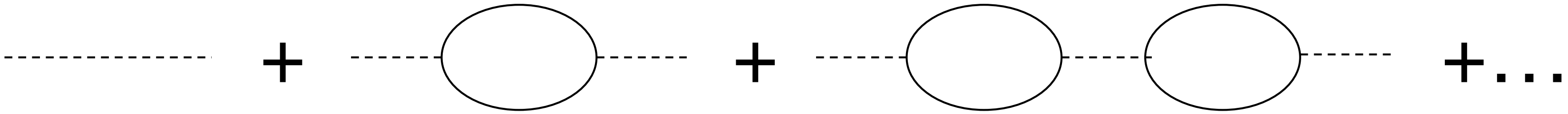


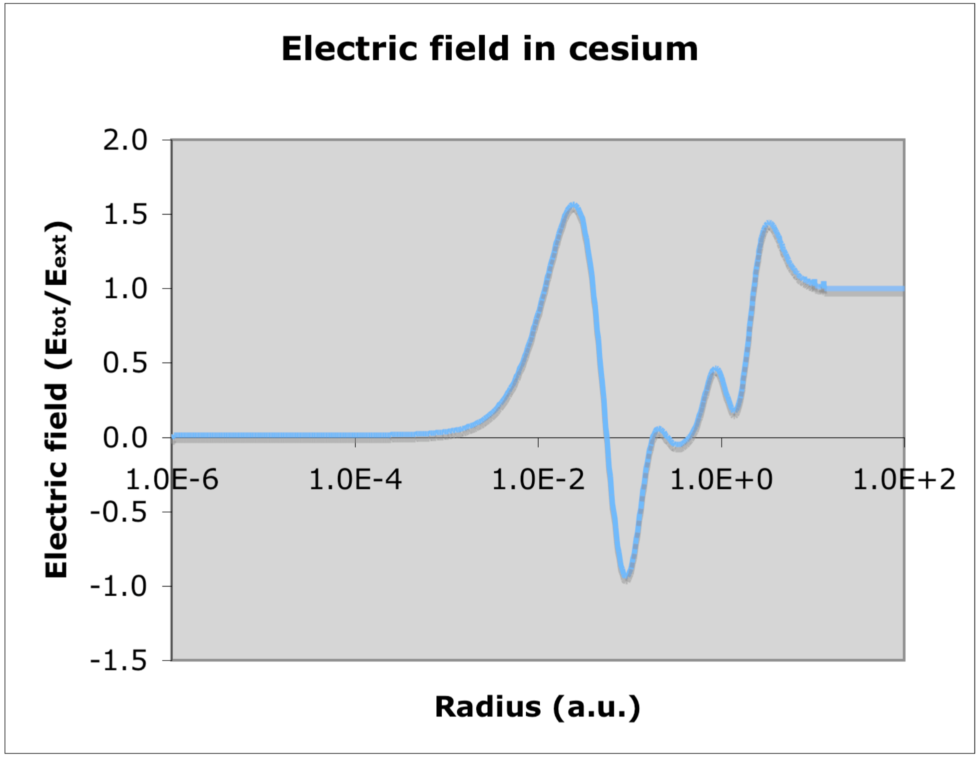
- External fields included using Time-Dependent Hartree-Fock (RPAE core polarization)+correlations

The correlation potential

Use the Feynman diagram technique to include three classes of diagrams to all orders:

1. electron-electron screening





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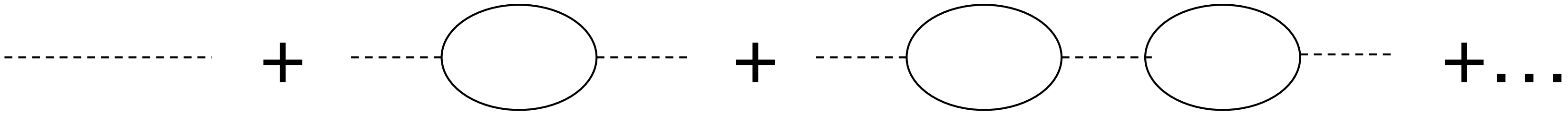
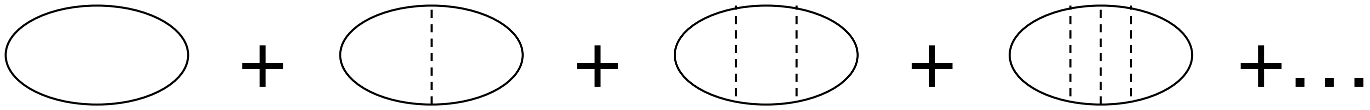
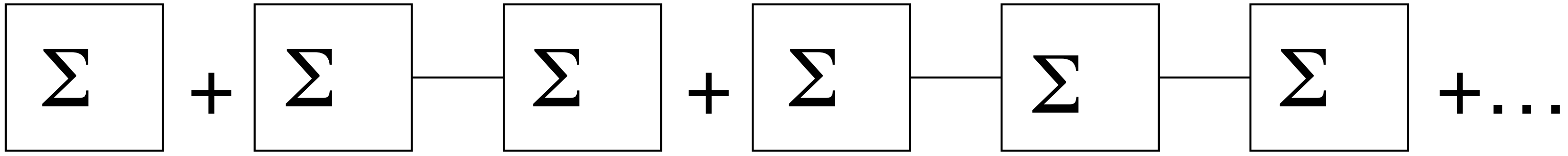


2. hole-particle interaction



3. nonlinear-in-Σ corrections



Atoms with several valence electrons: CI+MBPT

[Dzuba, Flambaum, Kozlov (1996)]

CI Hamiltonian: $\Sigma_i h_i + \Sigma_{i<j} e^2/r_{ij}$

$h = c\boldsymbol{\alpha p} + (\beta-1)mc^2 - Ze^2/r + V_{core}$

CI+MBPT Hamiltonian:

$h \to h + \Sigma_1;\quad e^2/r_{ij} \to e^2/r_{ij} + \Sigma_2$

MBPT is used to calculate core-valence correlation operator $\Sigma(r,r',E)$

Σ_1:

Σ_2:

Atoms of interest

Z	Atom / Ion	Transitions	N_{ve}[1]
6	C I, C II, C III	*p-s*	4, 3, 2
8	O I	*p-s*	4
11	Na I	*s-p*	1
12	Mg I, Mg II	*s-p*	2, 1
13	Al II, Al III	*s-p*	2, 1
14	Si II, Si IV	*p-s*	3, 1
16	S II	*s-p*	4
20	Ca II	*s-p*	1
22	Ti II	*s-p, d-p*	3
24	Cr II	*d-p*	5
25	Mn II	*s-p, d-p*	1
26	Fe II	*s-p, d-p*	7
28	Ni II	*d-p*	9
30	Zn II	*s-p*	1

[1] N_{ve} – number of valence electrons

Methods of Atomic Calculations

N_{ve}	Relativistic Hartree-Fock +	Accuracy
1	All-orders sum of dominating diagrams	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%

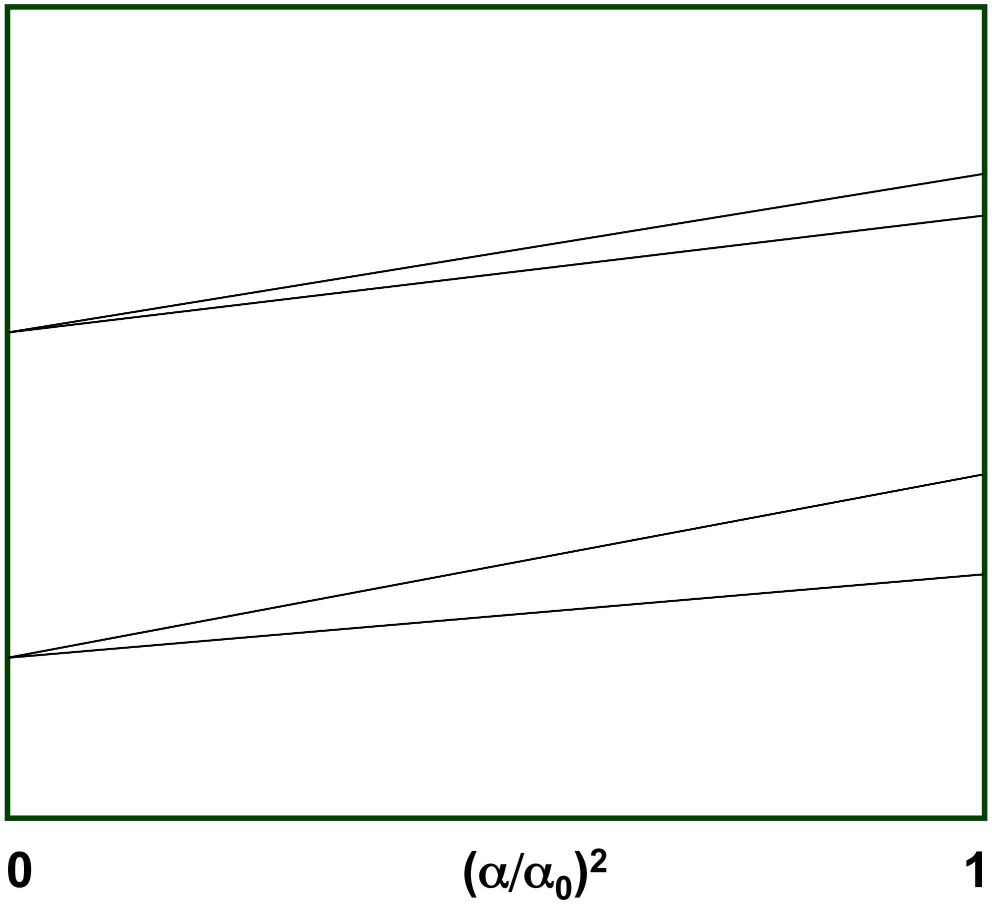
These methods cover all periodic system of elements

They 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.

Relativistic shifts-doublets

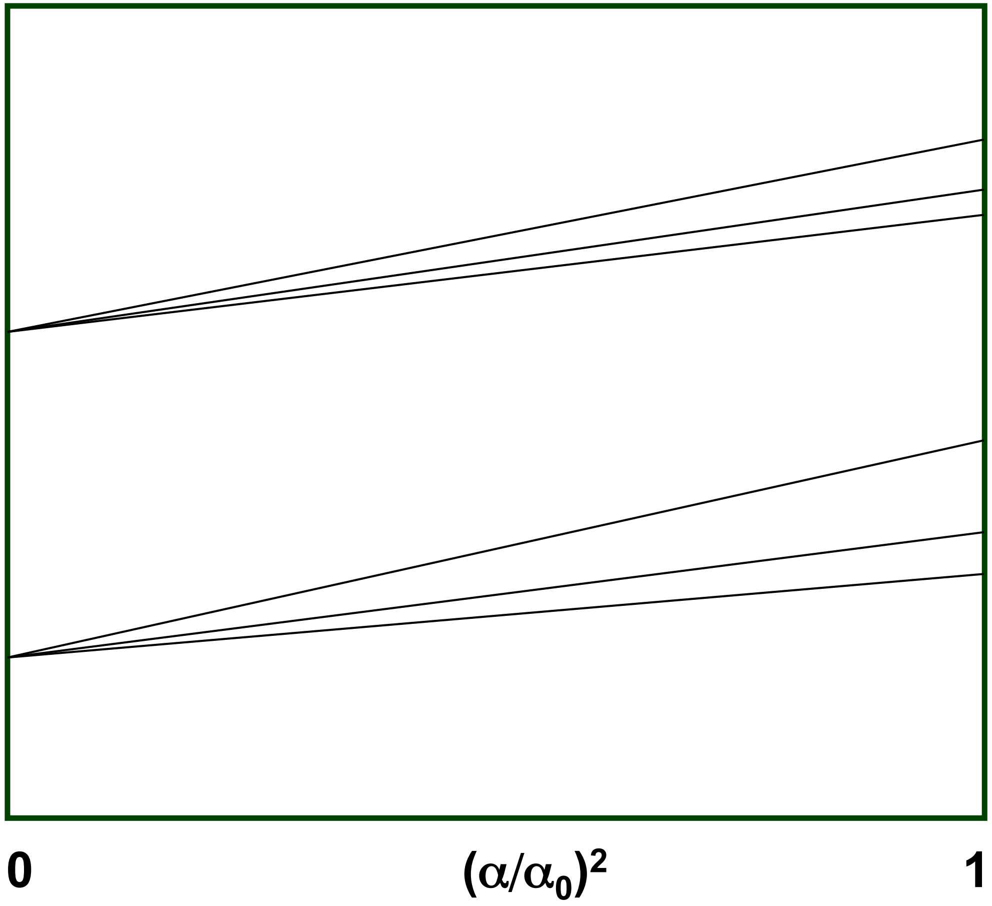
Energies of “normal” fine structure **doublets** as functions of α^2



$$\Delta E = A(Z\alpha)^2$$

Relativistic shifts-triplets

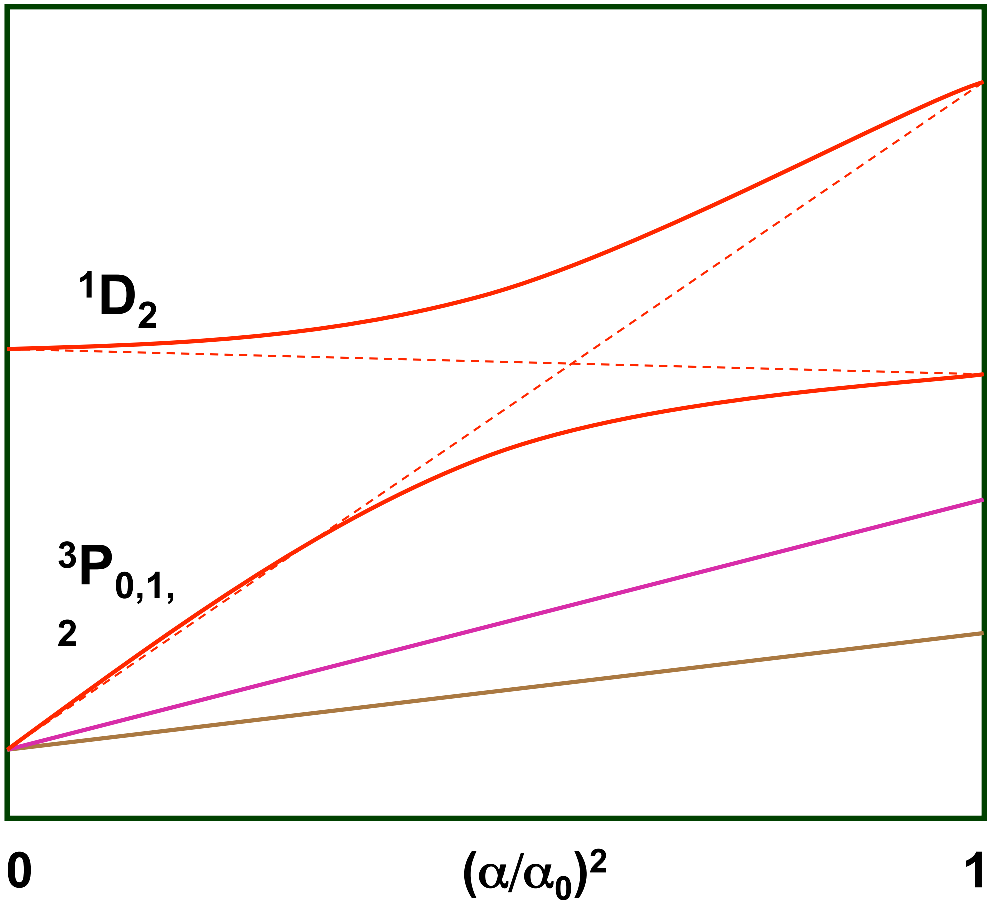
Energies of “normal” fine structure **triplets** as functions of α^2



$\Delta E = A(Z\alpha)^2$

Fine structure anomalies and level crossing

Energies of strongly interacting states as functions of α^2



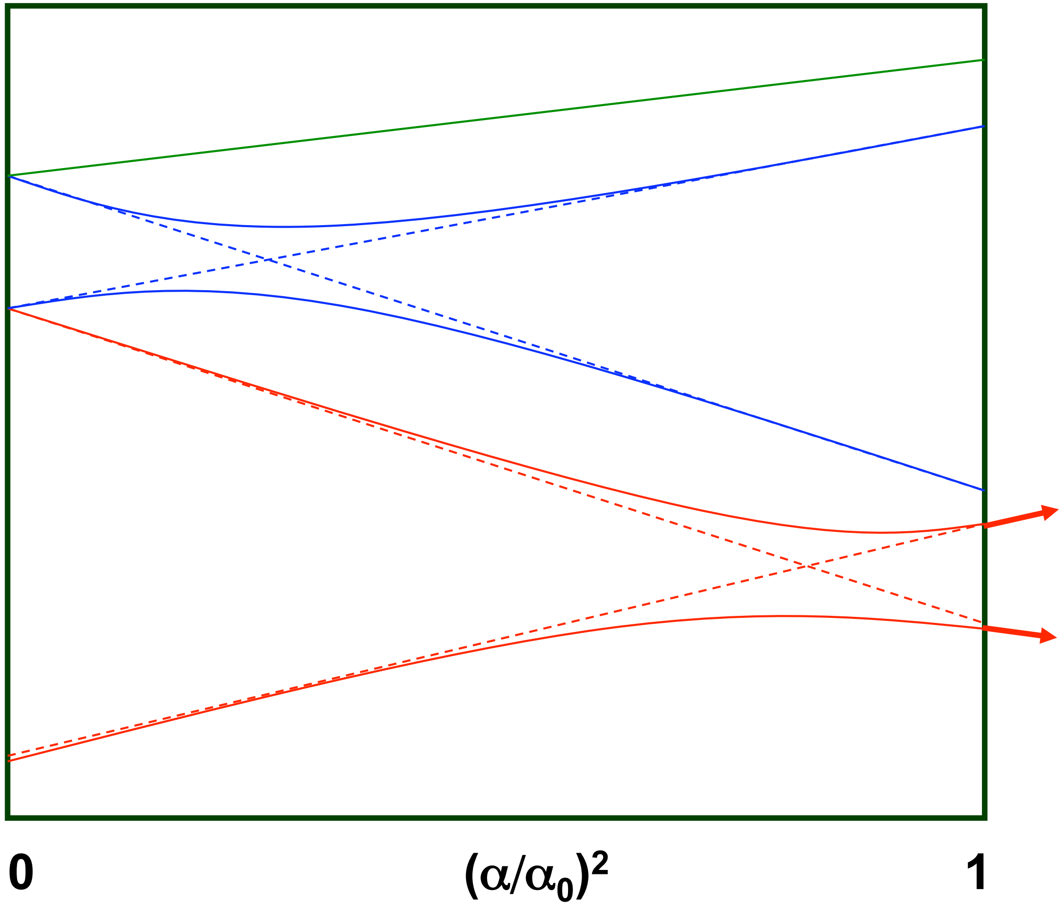
$\xcancel{\Delta E = A(Z\alpha)^2}$

Implications to study of α variation

- Not every energy interval behaves like $\Delta E = A + B(Z\alpha)^2$.
- Strong enhancement is possible (good!).
- Level crossing may lead to instability of calculations (bad!).

Problem: level pseudo crossing

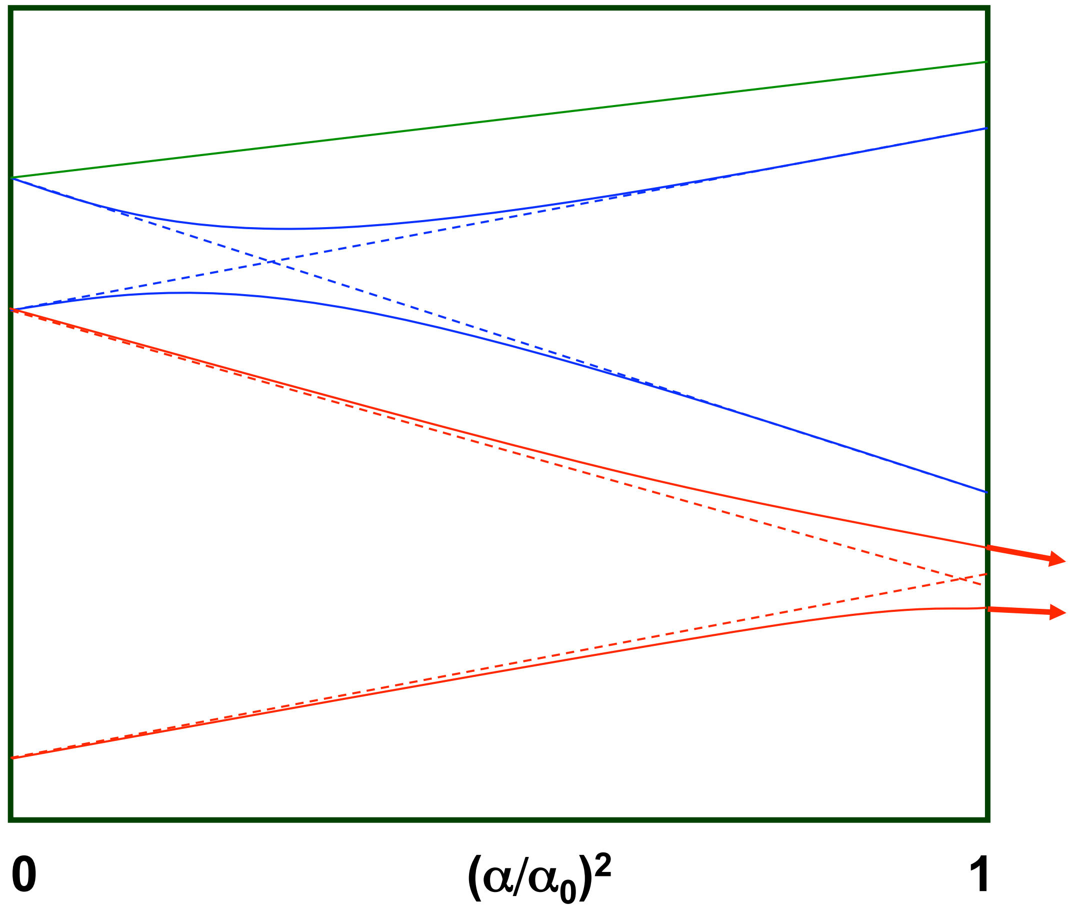
Energy levels of Ni II as functions of α^2



Values of $q=dE/d\alpha^2$ are sensitive to the position of level crossing

Problem: level pseudo crossing

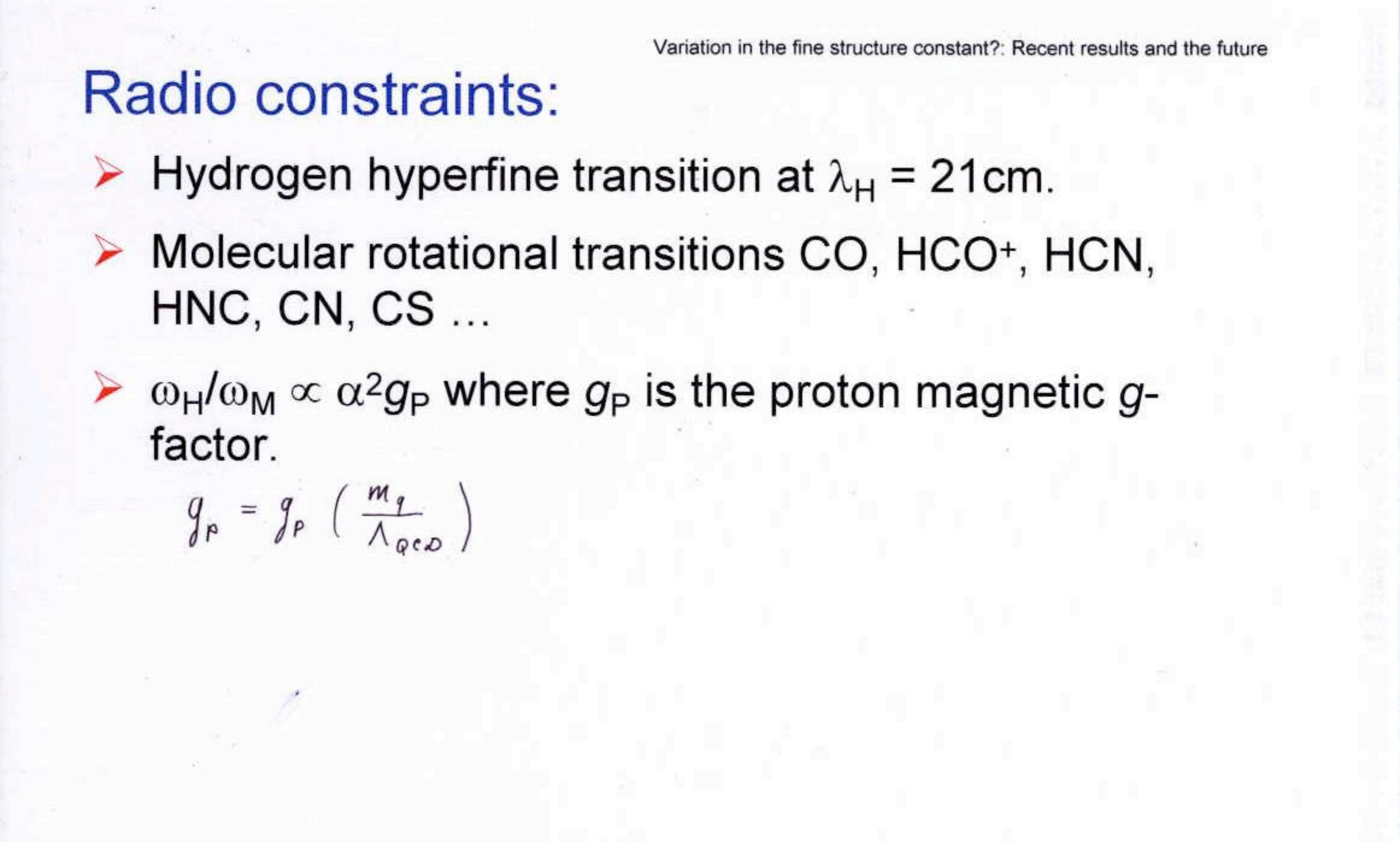
Energy levels of Ni II as functions of α^2



Values of $q=dE/d\alpha^2$ are sensitive to the position of level crossing

Solution: matching experimental *g*-factors

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



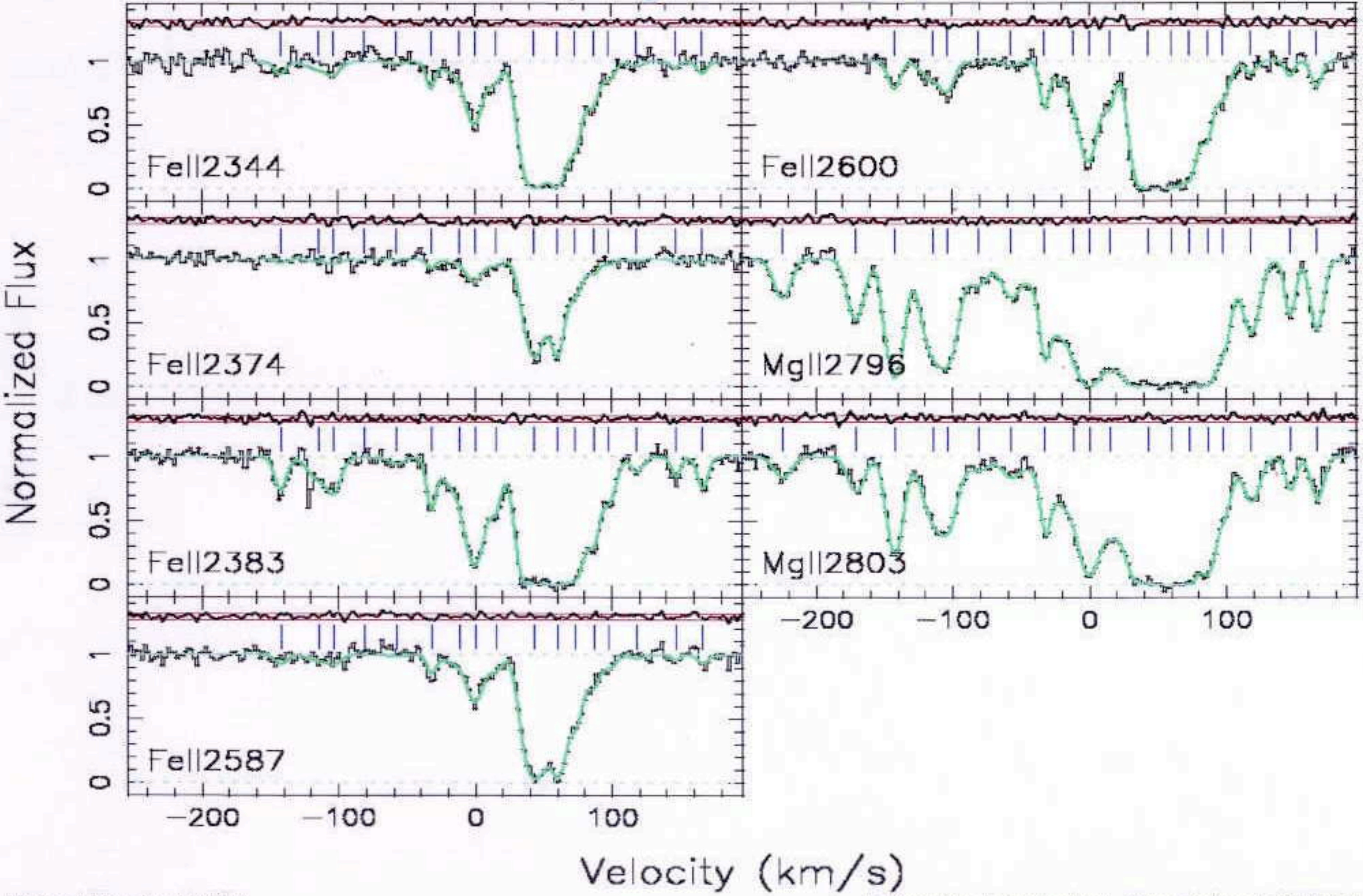
Variation in the fine structure constant?: Recent results and the future

Radio constraints:

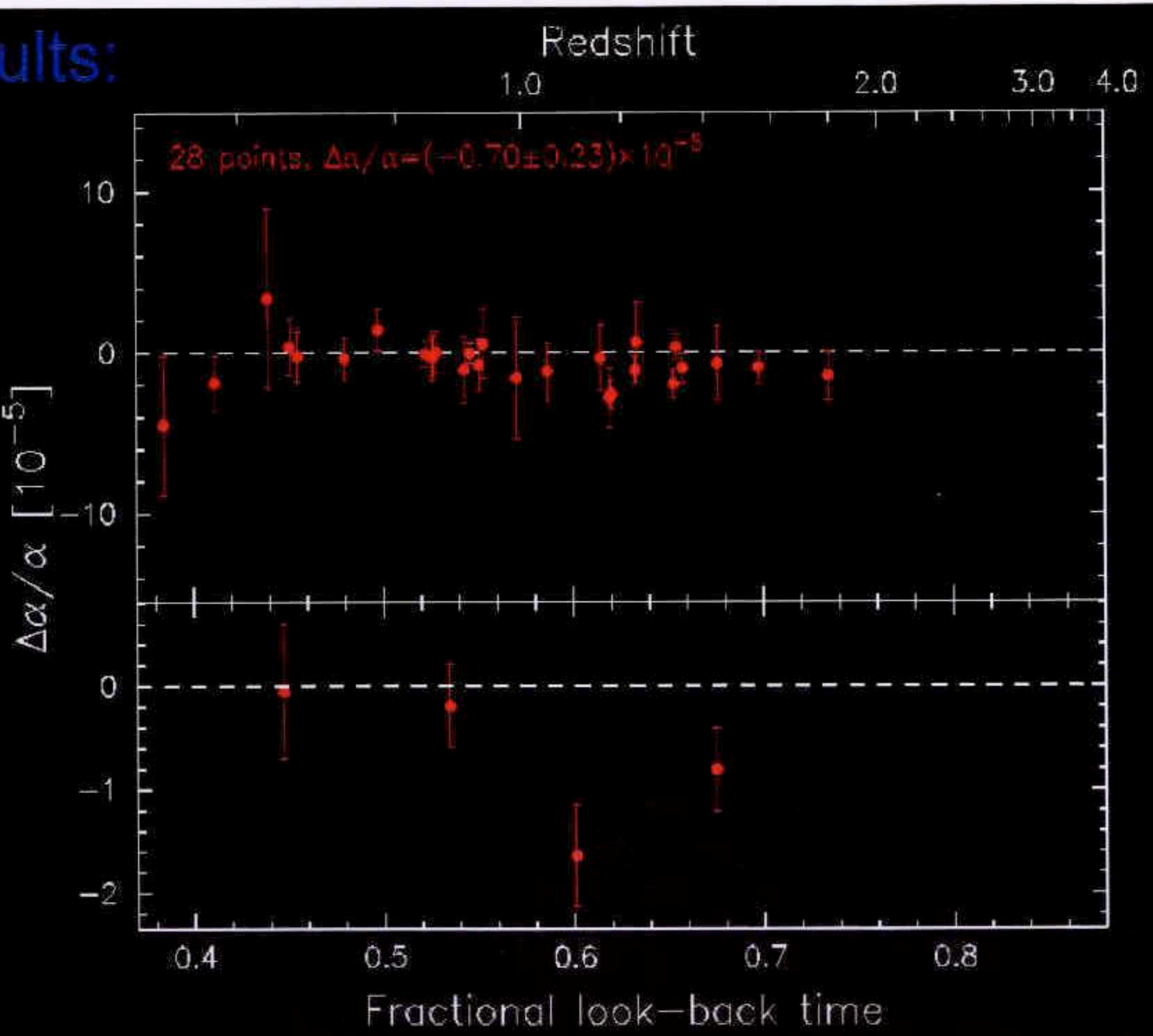
- Hydrogen hyperfine transition at $\lambda_H = 21$cm.
- Molecular rotational transitions CO, HCO^+, HCN, HNC, CN, CS …
- $\omega_H/\omega_M \propto \alpha^2 g_P$ where g_P is the proton magnetic g-factor.

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

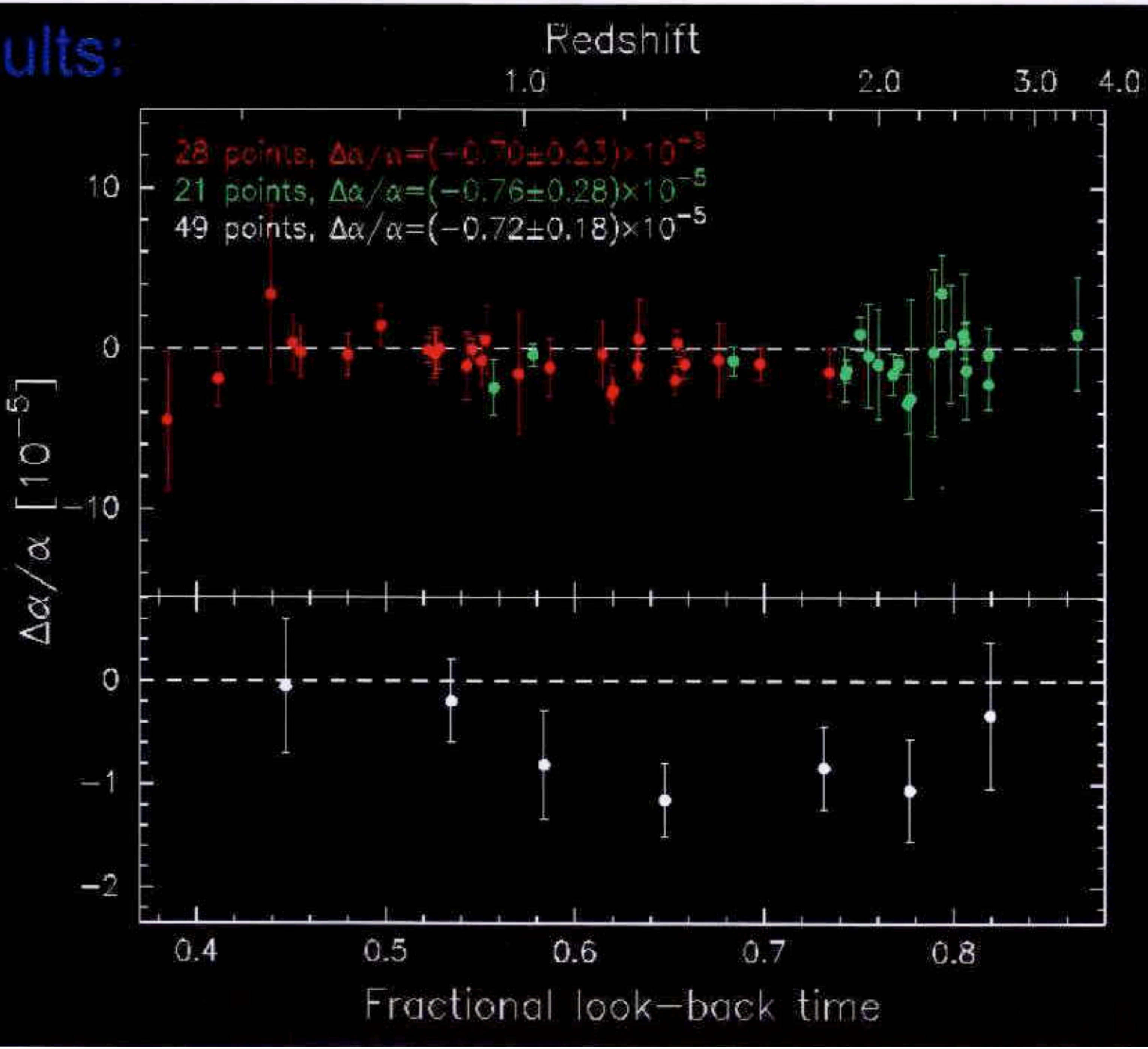
Low-redshift data (Mg II/Fe II systems):



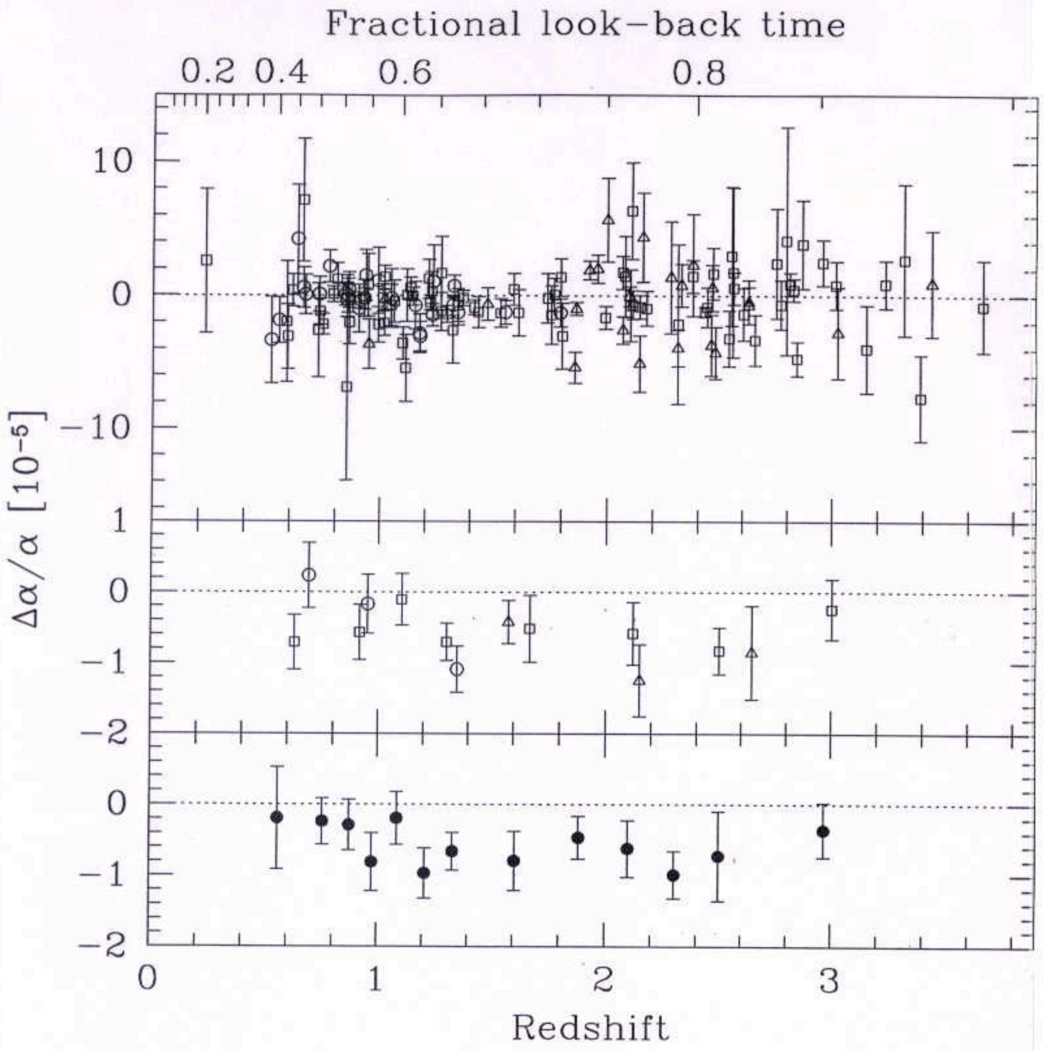
Results:


Redshift
1.0
2.0
3.0
4.0
28 points. Δα/α=(−0.70±0.23)×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

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

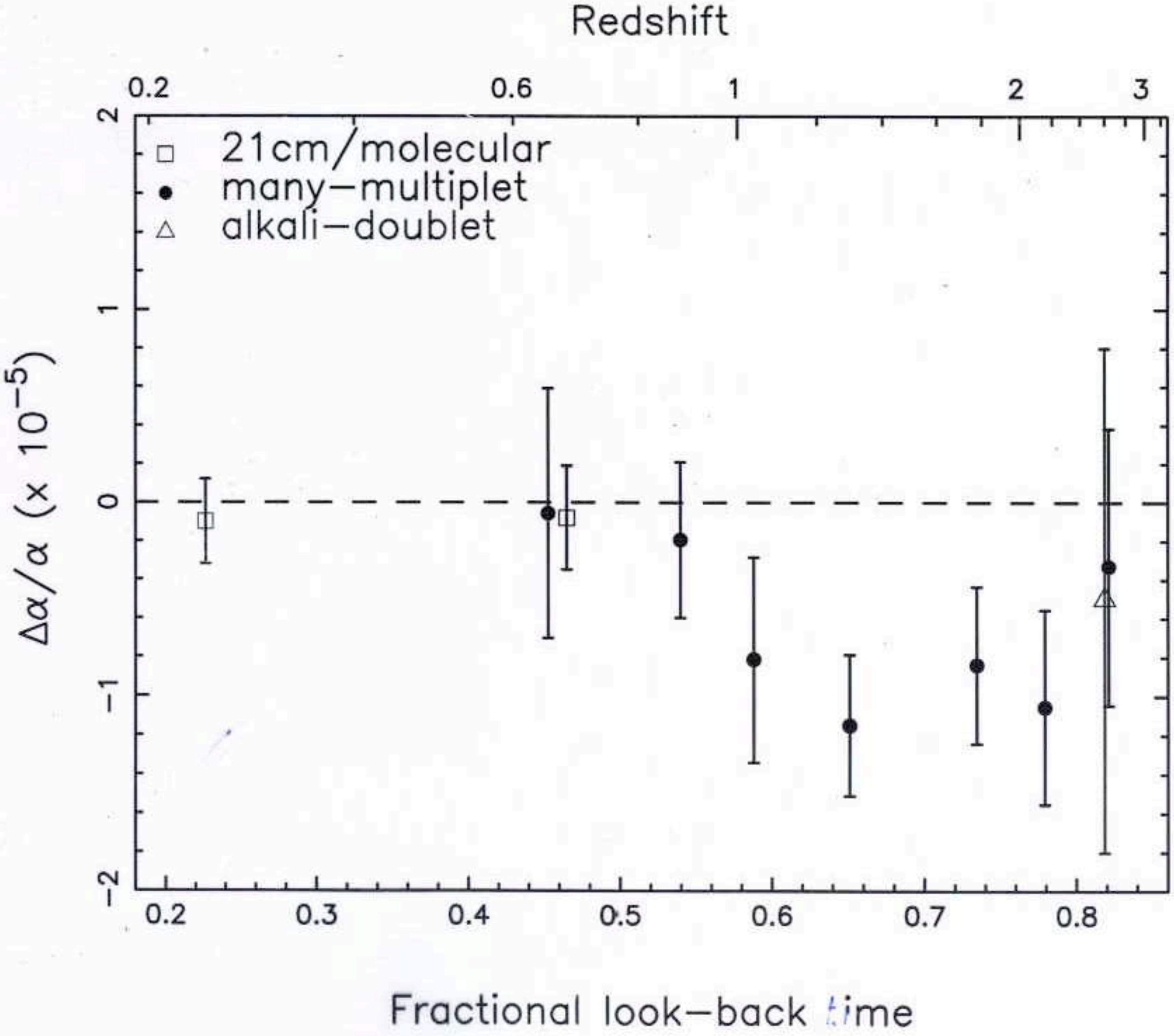
Murphy, Webb, Flambaum 2003



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

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

fudicial result $(-0.543 \pm 0.116)\cdot 10^{-5}$ $4.7\,\sigma$


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

- 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*, $z=1.15$

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

Molaro et al 2007 $-0.12(1.8)\times 10^{-6}$,$z=1.84$ $5.7(2.7)\times 10^{-6}$

- 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.

Probing the variability of α with QSO absorption lines

Potential systematic effects:

- **Laboratory wavelength errors:** New, mutually consistent laboratory spectra from Imperial College, Lund University and NIST
- **Data quality variations:** Can only produce systematic shifts if combined with laboratory wavelength errors
- **Heliocentric velocity variation:** Smearing in velocity space is degenerate with fitted redshift parameters
- **Isotopic ratio shifts:** Very small effect possible if evolution of isotopic ratios allowed
- **Hyperfine structure shifts:** same as for isotopic shifts
- **Magnetic fields:** Large scale fields could introduce correlations in $\Delta\alpha/\alpha$ for neighbouring QSO site lines (if QSO light is polarised) - extremely unlikely and huge fields required
- **Wavelength miscalibration:** mis-identification of ThAr lines or poor polynomial fits could lead to systematic miscalibration of wavelength scale
- **Temperature changes during observations:** Refractive index changes between ThAr and QSO exposures – random error
- **Line blending:** Are there ionic species in the clouds with transitions close to those we used to find $\Delta\alpha/\alpha$?
- **Atmospheric refraction effects:** Different angles through optics for blue and red light – can only produce positive $\Delta\alpha/\alpha$ at low redshift
- **Instrumental profile variations:** Intrinsic IP variations along spectral direction of CCD?

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 $\Delta\alpha/\alpha$.

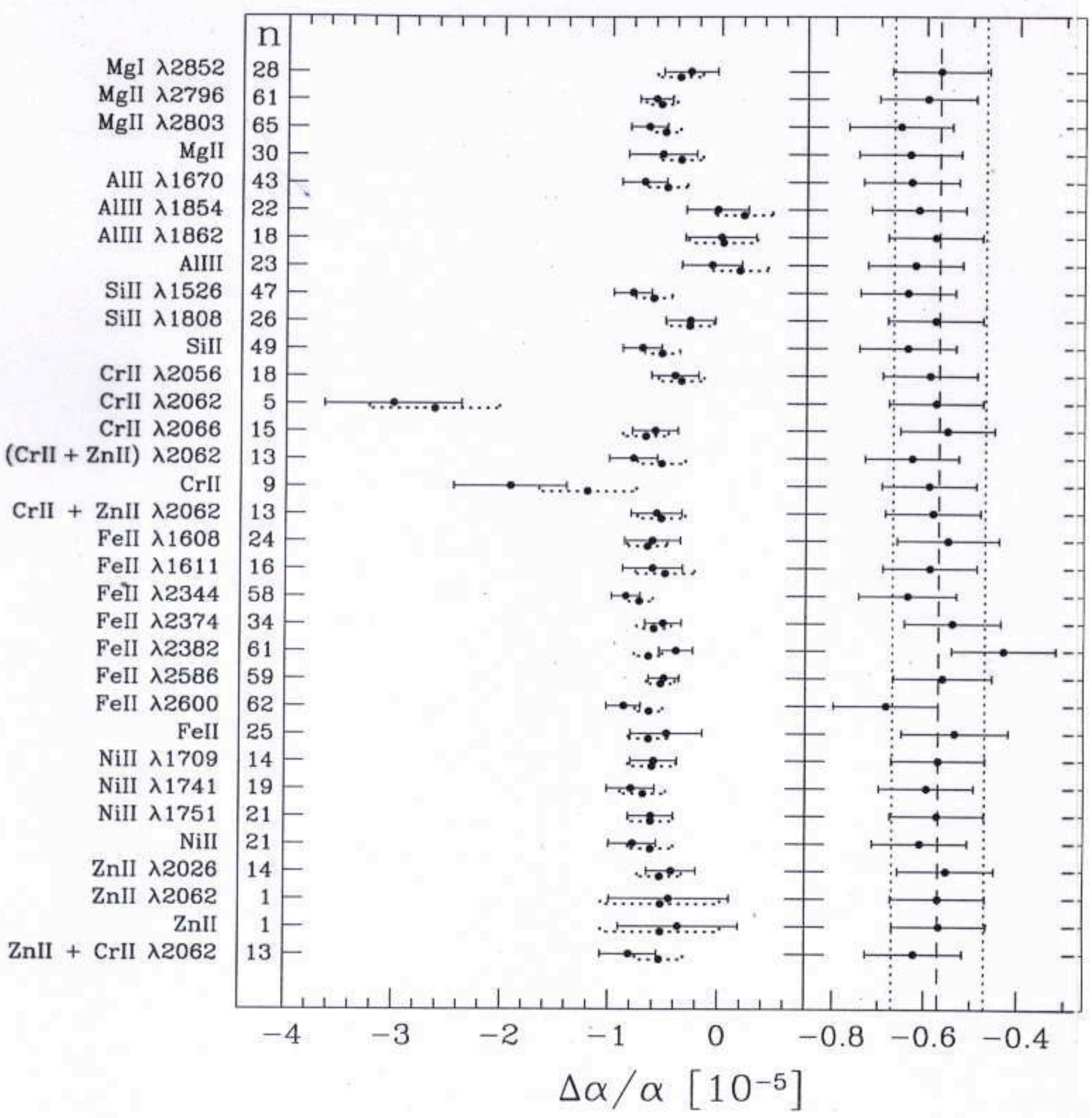
  Results: subset contains 12 systems (only in high z sample)

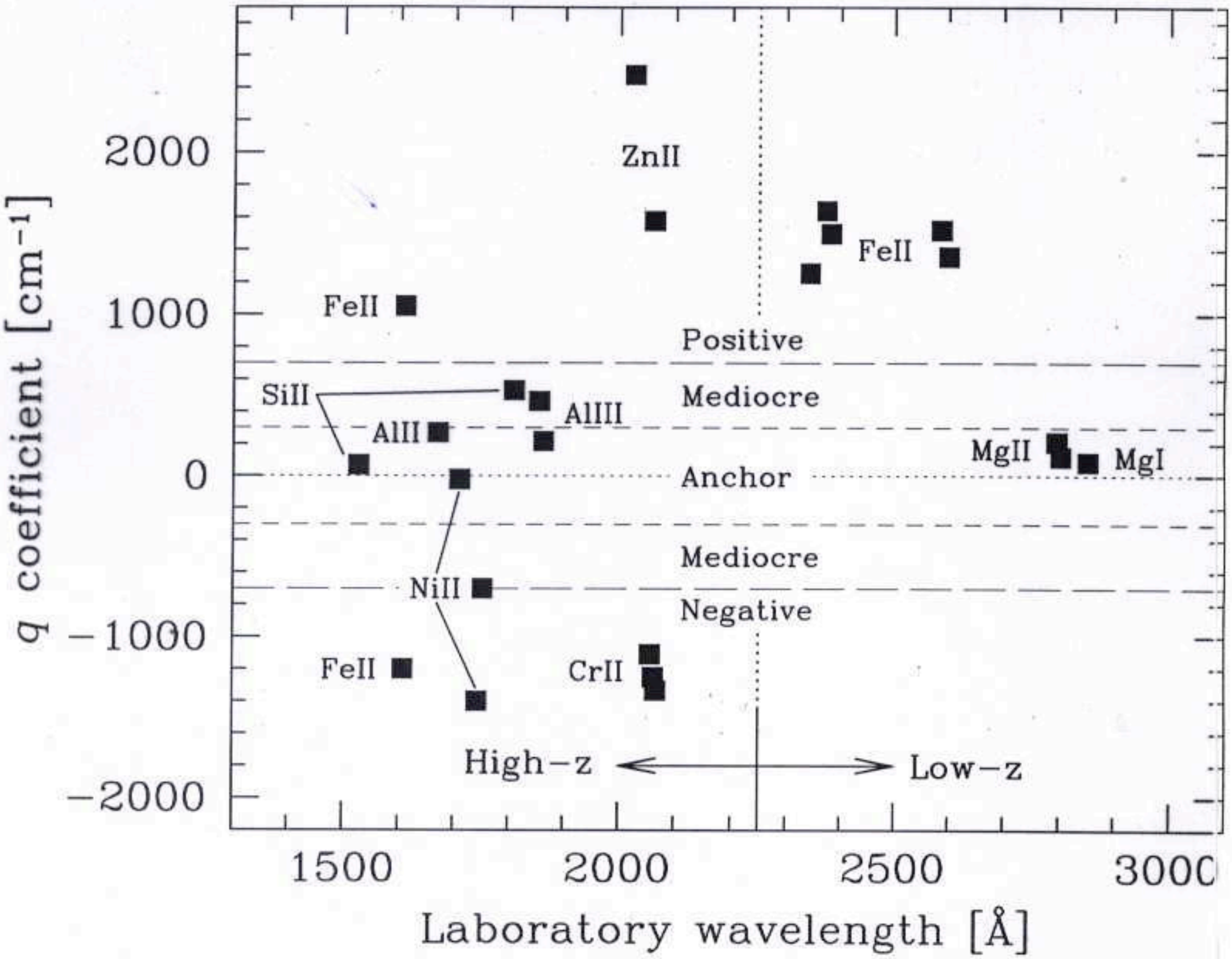
  No lines removed: $\Delta\alpha/\alpha = (-1.31 \pm 0.39) \times 10^{-5}$

  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
$\Delta\alpha/\alpha\ [10^{-5}]$


ZnII
FeII
FeII
Positive
SiII
Mediocre
AlIII
AlII
MgII
MgI
Anchor
Mediocre
NiII
Negative
FeII
CrII
High−z
Low−z
2000
1000
0
−1000
−2000
1500
2000
2500
3000
q coefficient [cm^{-1}]
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 $\delta\alpha<0$!

New interpretation: Spatial variation

Northern+(new)Southern hemisphere data: Linear variation with distance along some direction, $\alpha(x)=\alpha(0)+kx$,

$x=r\cos(\phi)$, $r=ct$ (Gly),

$\Delta\alpha/\alpha = 1.10(0.25)\ 10^{-6}\ r\cos(\phi)$

gradient direction 17.6(0.6) h, -58(6)°

$4.2\ \sigma$ deviation from zero. Data from two largest telescopes, Keck and VLT, give consistent results. 300 systems.

New interpretation: Spatial variation

Northern+(new)Southern hemisphere data: Linear variation with distance along some direction, $\alpha(x)=\alpha(0)+kx$,

$x=r\cos(\phi)$, $r=ct$ (Gly),

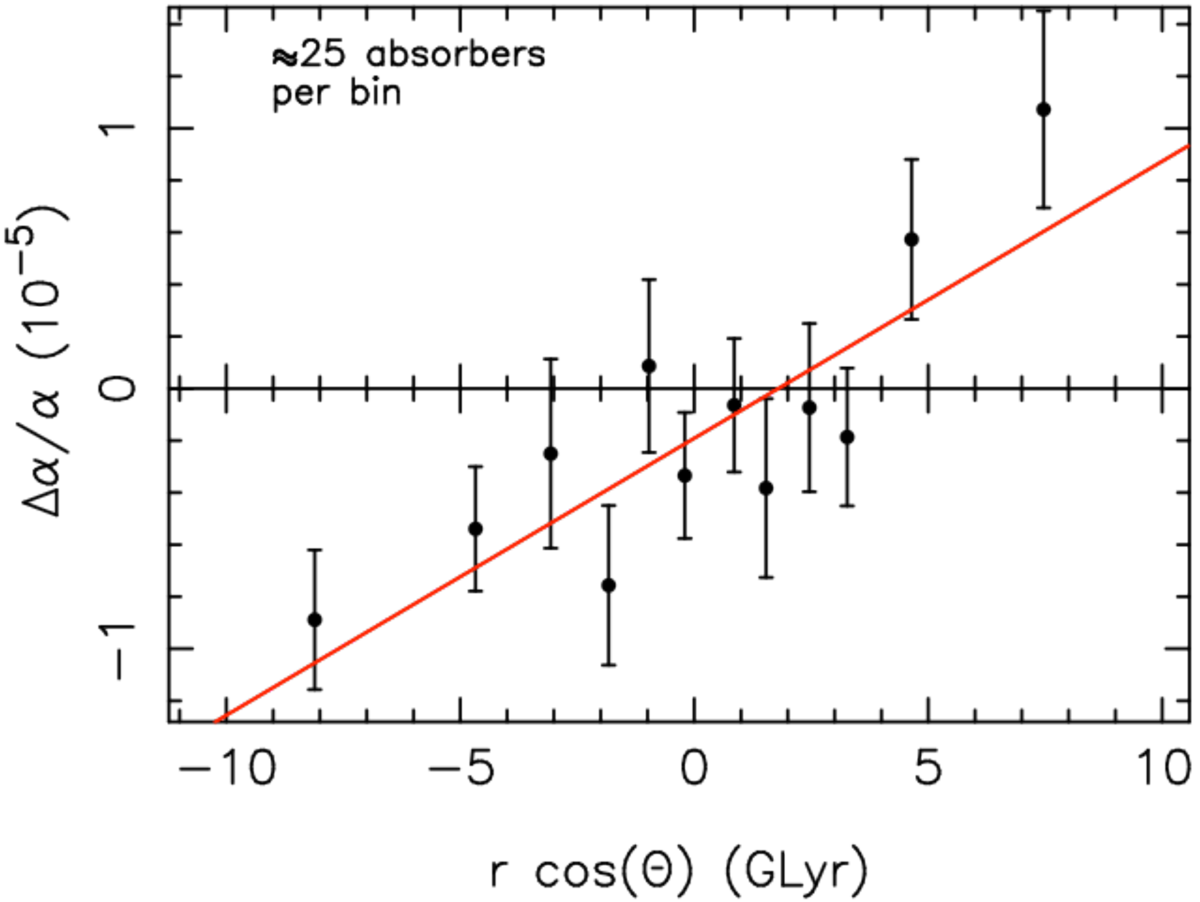
$\Delta\alpha/\alpha = 1.2\ 10^{-6}\ r\cos(\phi)$ dipole

$4.1\ \sigma$ deviation from zero. Data from two largest telescopes, Keck and VLT, give consistent results. 300 systems.

Results for m_q/Λ_{QCD} and m_e/m_p

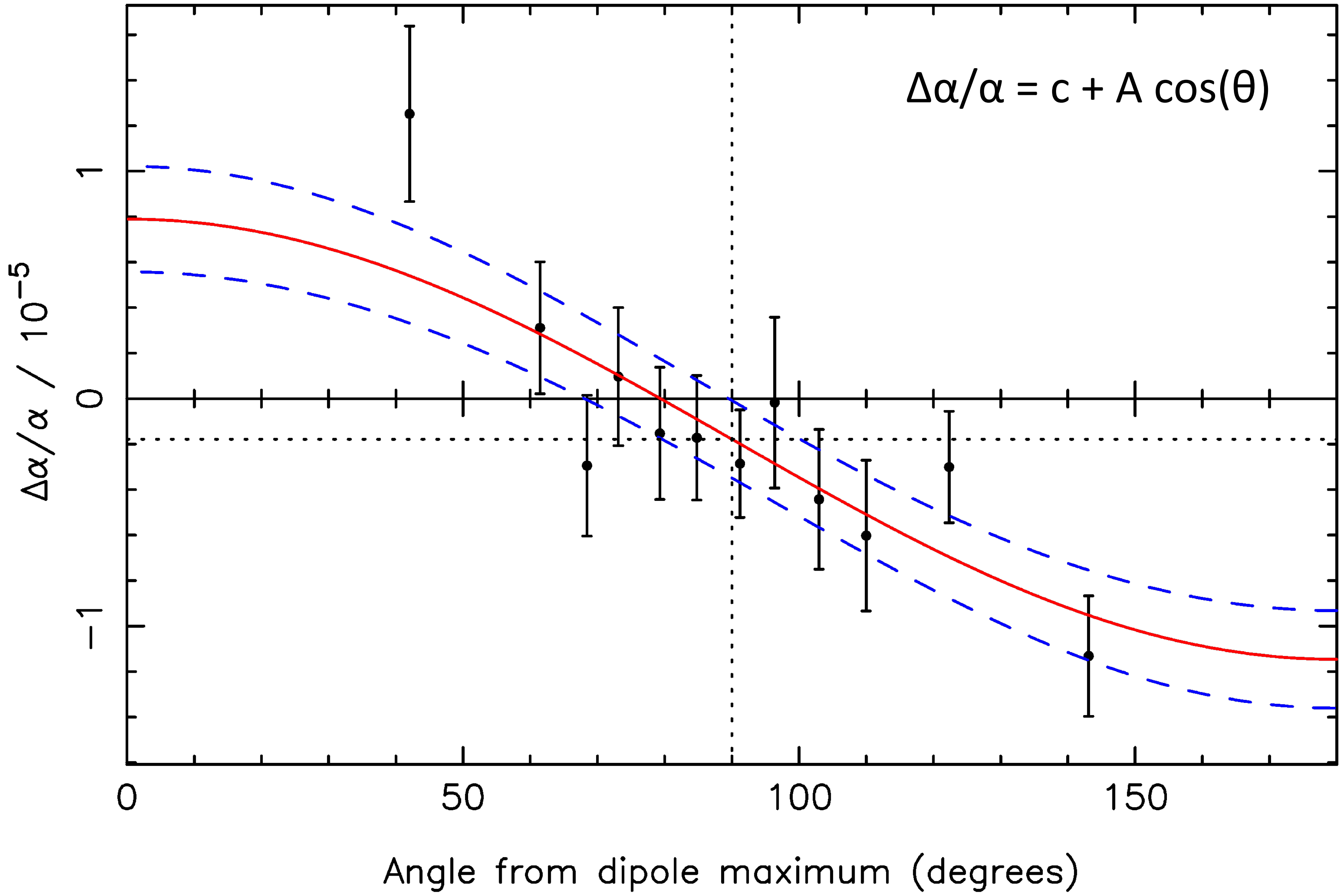
Big Bang Nucleosynthsis data and H_2 molecule data are consitent with the direction of the dipole.

Distance dependence



Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} GLyr^{-1} and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically preferred over a monopole-only model also at the 4.1σ level. A cosmology with parameters (H_0 , Ω_M , Ω_Λ) = (70.5, 0.2736, 0.726).

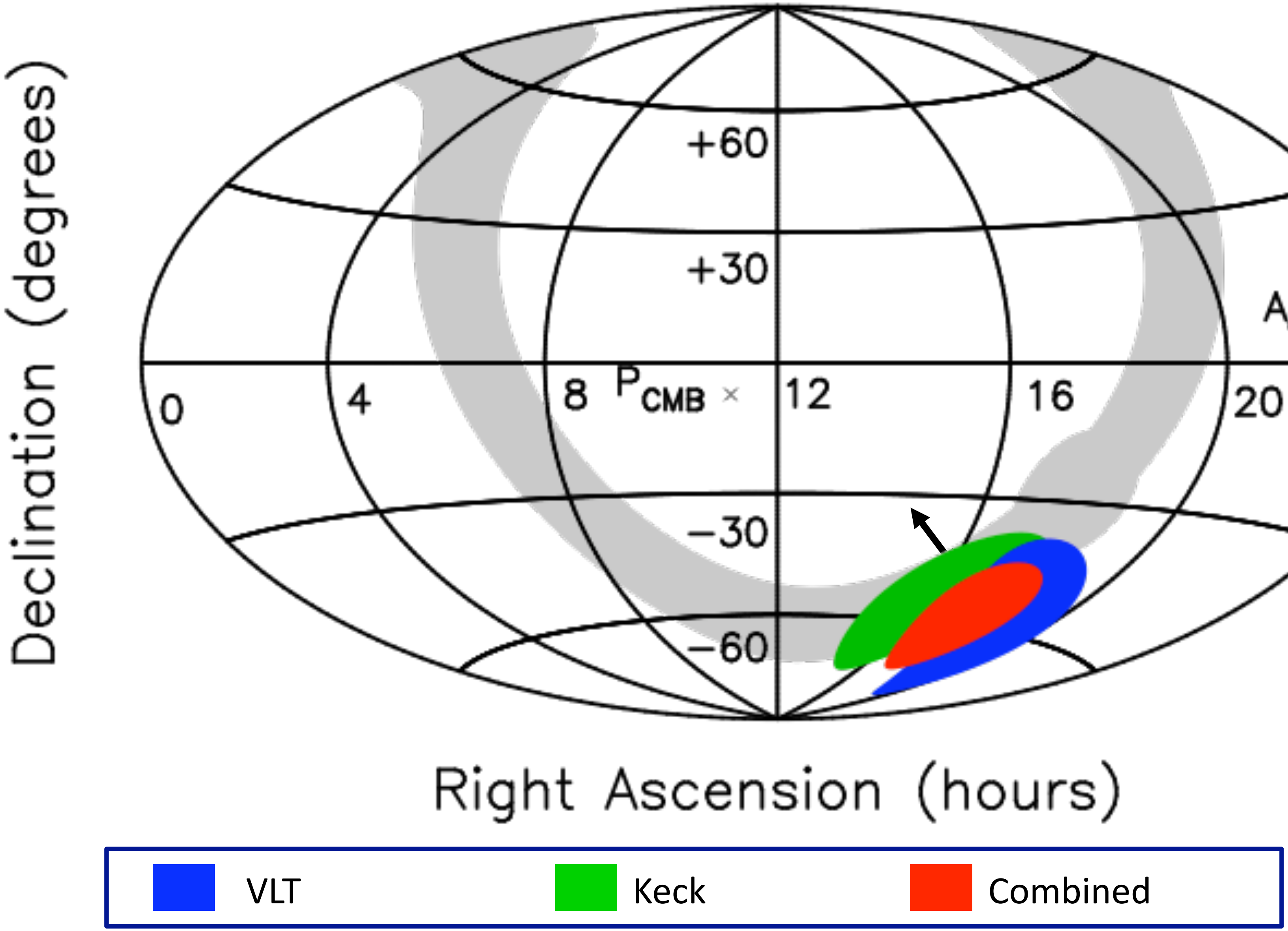
4.1σ evidence for a Δα/α dipole from VLT + Keck



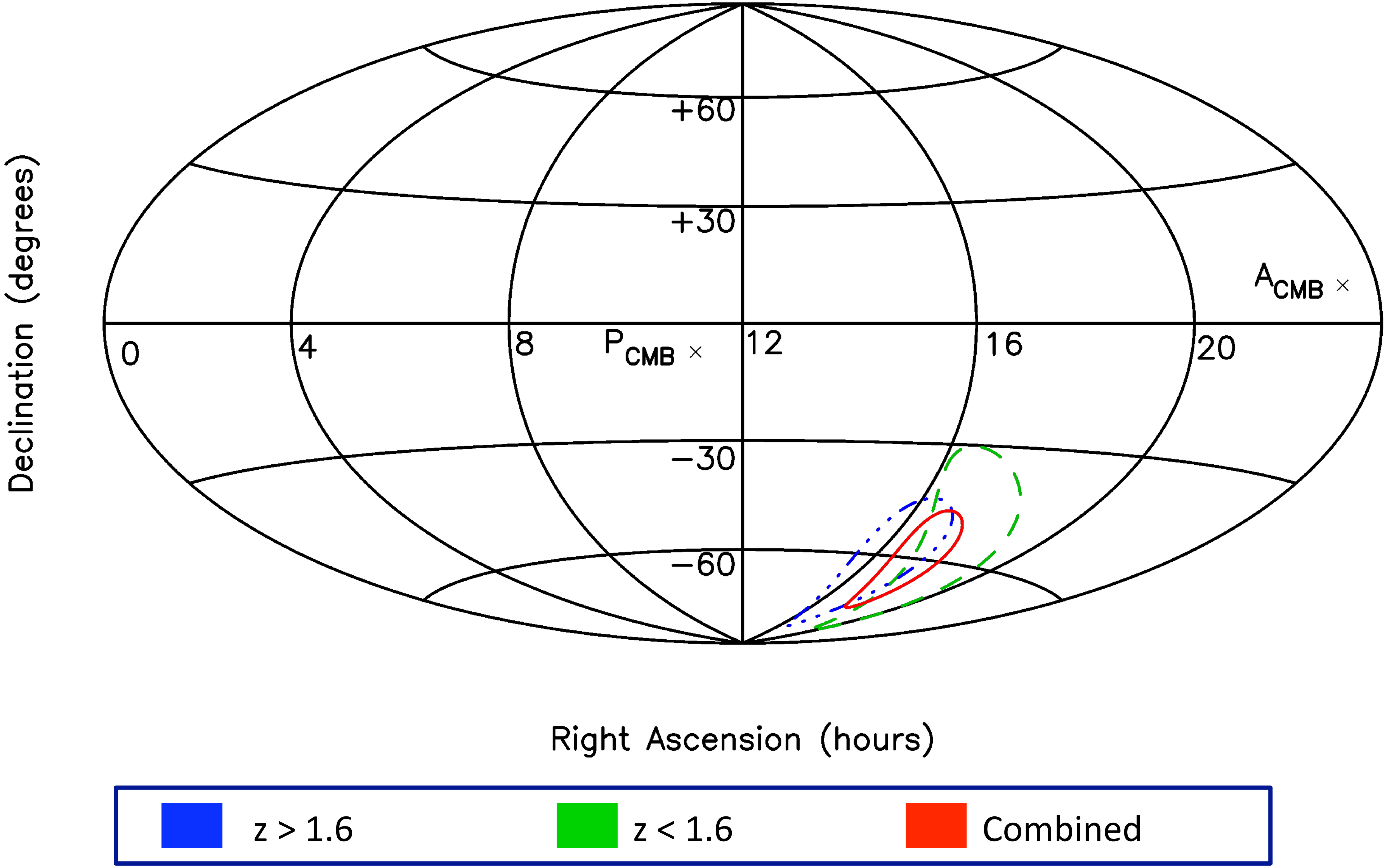
Julian King, UNSW

☺

Keck & VLT dipoles independently agree, p=4%

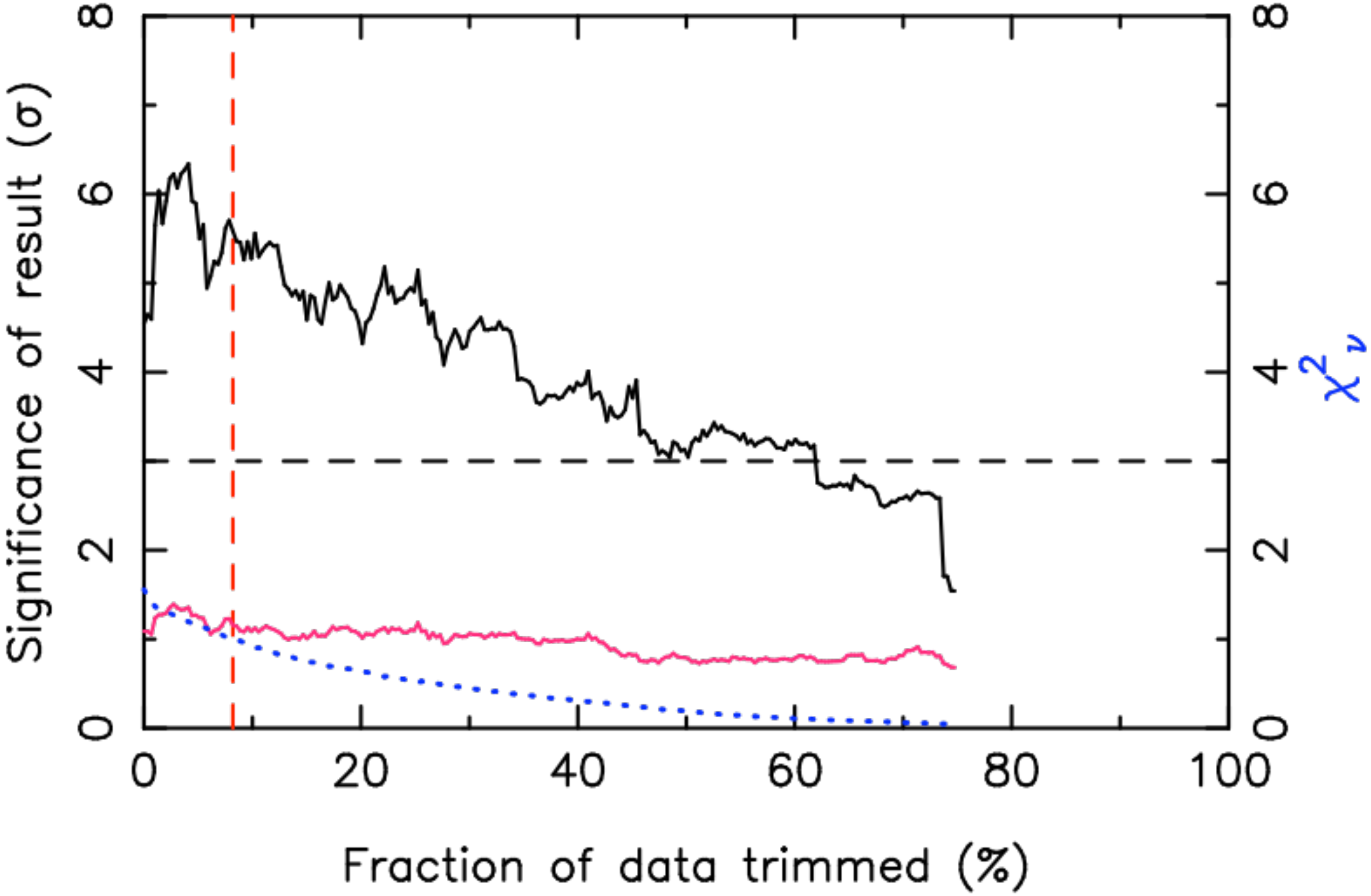


Low and high redshift cuts are consistent in direction. Effect is larger at high redshift.



Are a few high S/N outliers responsible for the signal, by chance?

- Alternative to growing error bars
- Robustness check – iterative trimming
- Adopt statistical-only errors and iteratively clip most deviant point
- How much data do we need to discard to remove the dipole?



- $\chi^2_\nu = 1$ reached when ~10% clipped
- Dipole significance ~5.5σ at $\chi^2_\nu = 1$
- Dipole significance stays above 3σ until ~60% of data discarded

Hints that this result might be real

Two internal consistencies:

1. Keck and VLT dipoles agree. Independent samples, different data reduction procedures, different instruments and telescopes.

2. High and low redshift dipoles also agree - different species used at low and high redshift – and different transitions respond differently to the same change in α.

Hints that this result might be real

Three internal consistencies:

1 Keck and VLT dipoles agree. Independent samples, different data reduction procedures, different instruments and telescopes.

2 High and low redshift dipoles also agree - different species used at low and high redshift – and different transitions respond differently to the same change in α.

3 Trimming increases significance and shows signal is present in the majority or all of the data.

Hints that this result might be real

Two internal consistencies:

1Keck and VLT dipoles agree. Independent samples, different data reduction procedures, different instruments and telescopes.

2High and low redshift dipoles also agree - different species used at low and high redshift – and different transitions respond differently to the same change in α.

Other suggestive points:

3Scatter in data exceeds statistical-only error bars (expected). Keeping all points and growing errors is conservative. Trimming increases significance and shows signal is present in the majority or all of the data.

4Monopole. Predominant in Keck. Mg isotopes? Early enrichment by very massive stars?

Evidence for spatial variation of α

- Webb, King, Murphy, Flambaum, Carswell, Bainbridge,arxiv:1008.3907, PRL, MNRAS

  $\alpha(x)= \alpha(0) + \alpha '(0) x + \ldots$

  $x=r \cos(\phi)$, $r=ct$ – distance (instead of time)

Reconciles all measurements of the variation

- Berengut, Flambaum, arxiv:1008.3957,PRL

Manifestations on atomic clocks, Oklo, meteorites and cosmological phenomena

- Berengut, Flambaum,King,Curran,Webb,

Further astronomical evidence, 1009.0591,PRD

Variation of strong interaction

Grand unification

$$\frac{\Delta\left(m / \Lambda_{QCD}\right)}{m / \Lambda_{QCD}} = R\frac{\Delta\alpha}{\alpha}$$

1. Proton mass $\mathrm{M}_{\mathrm{p}} = 3\Lambda_{QCD}$, measure m_e / M_p

2. Nuclear magnetic moments

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

3. 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 $m_q=0$. $\Delta m/m=K\,\Delta m_q/m_q$

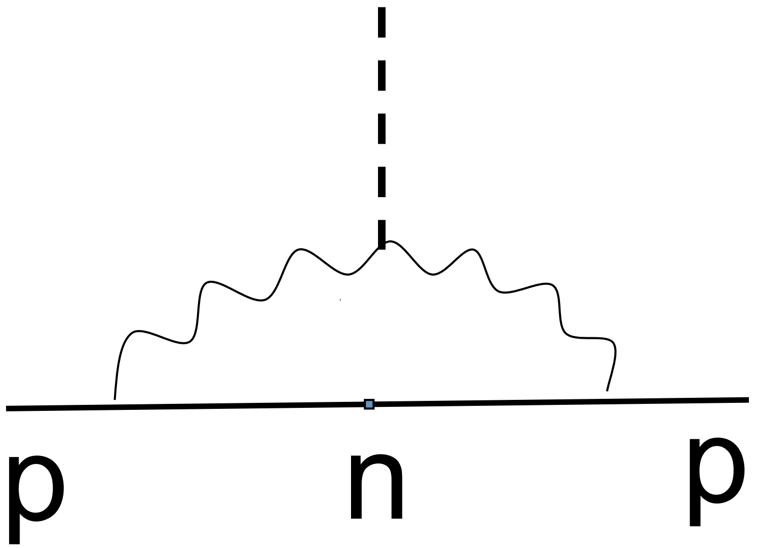
Argonne: K are calculated for p,n,ρ,ω,σ.

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

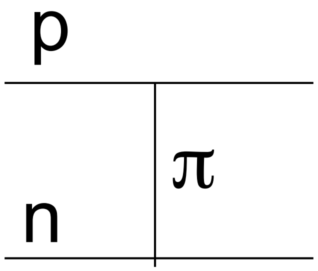
$$\text{Strange quark mass } m_s = 120\,MeV$$

Nuclear magnetic moments depends on π-meson mass m_π

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 $p^2/2M$

m_e / M_p limit from NH_3 -2 systems

Inversion spectrum: exponentially small“quantum tunneling” frequency ω_{inv}=W exp(-S(m_e / M_p))

ω_{inv} is exponentially sensitive to m_e / M_p

Laboratory measurements proposed (Veldhoven et al)

Flambaum,Kozlov PRL 2007

First enhanced effect in quasar spectra

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

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

More accurate measurements

Murphy, Flambaum, Henkel,Muller. Science 2008 $-0.74(0.47)(0.76)10^{-6}$

Henkel et al AA 2009 z=0.87 $<1.4\ 10^{-6}$ 3 σ

Levshakov,Molaro,Kozlov2008 our Galaxy $0.5(0.14)10^{-7}$

Evidence for spatial variation of α

- Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL, MNRAS

$$\alpha(x)= \alpha(0) + \alpha'(0)\, x + \ldots$$

$x=r\cos(\phi)$, $r=ct$ – distance (instead of time)

Reconciles all measurements of the variation

- Berengut, Flambaum, EPL

Manifestations on atomic clocks, Oklo, meteorites and cosmological phenomena

- Berengut, Flambaum,King,Curran,Webb,

Further astronomical evidence, PRD

Hydrogen molecule - 4 systems

$\Delta(m_e / M_p)/(m_e / M_p)=$

$3.3(1.5)\ 10^{-6}\ r\cos(\phi)$

gradient direction 16.7(1.5) h, -62(5)°

consistent with α gradient direction
17.6(0.6) h, -58(6)°

If we assume the same direction

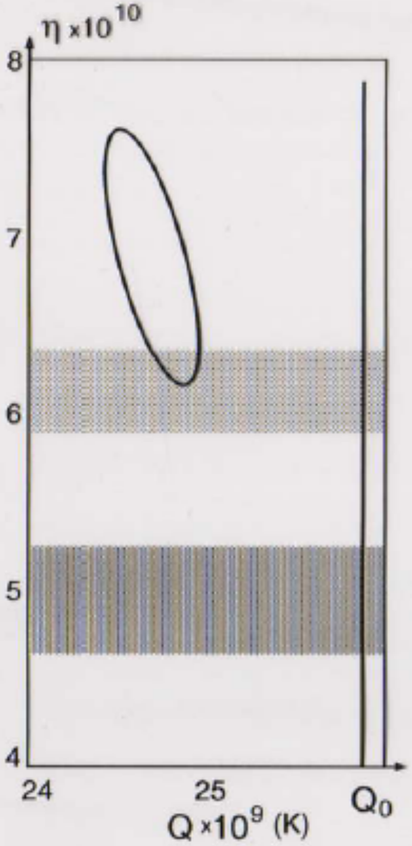
$2.6(1.3)\ 10^{-6}\ r\cos(\phi)$ 4% by chance

Big Bang nucleosynthesis: dependence on quark mass

- Flambaum, Shuryak 2002
- Flambaum, Shuryak 2003
- Dmitriev, Flambaum 2003
- Dmitriev, Flambaum, Webb 2004
- Coc, Nunes, Olive, Uzan,Vangioni 2007
- Dent, Stern, Wetterich 2007
- Flambaum, Wiringa 2007
- Berengut, Dmitriev, Flambaum 2010
- Bedaque, Luu, Platter 2011

Big Bang Nucleosynthesis

(Dmitriev, Flambaum, Webb)



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

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

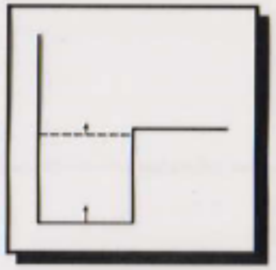
$$\boxed{\sim e^{-\frac{E_d}{T_f}}}$$

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

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

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.

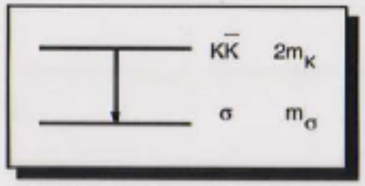


Virtual level in $n+p \to d+\gamma$ is even more sensitive to the variation of the potential.

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

Deutron binding energy is sensitive to the variation of the quark mass

- Shallow level : small variation of the potential leads to large variation of the binding energy.
- Virtual level in (n+p) is even more sensitive, and it influences the deuterium formation rate.
- BBN is exponentially sensitive to the deuteron binding energy E, exp(-E/T)

Deuterium abundance – 7 points

Big Bang Nucleosynthsis data give direction of the gradient in the deuterium abundance consitent with the direction of the α gradient. However, the amplitude of the relative spatial variation 0.0045(35) is not statistically significant. This would result in relative variation of $X=m_q/\Lambda_{QCD}$

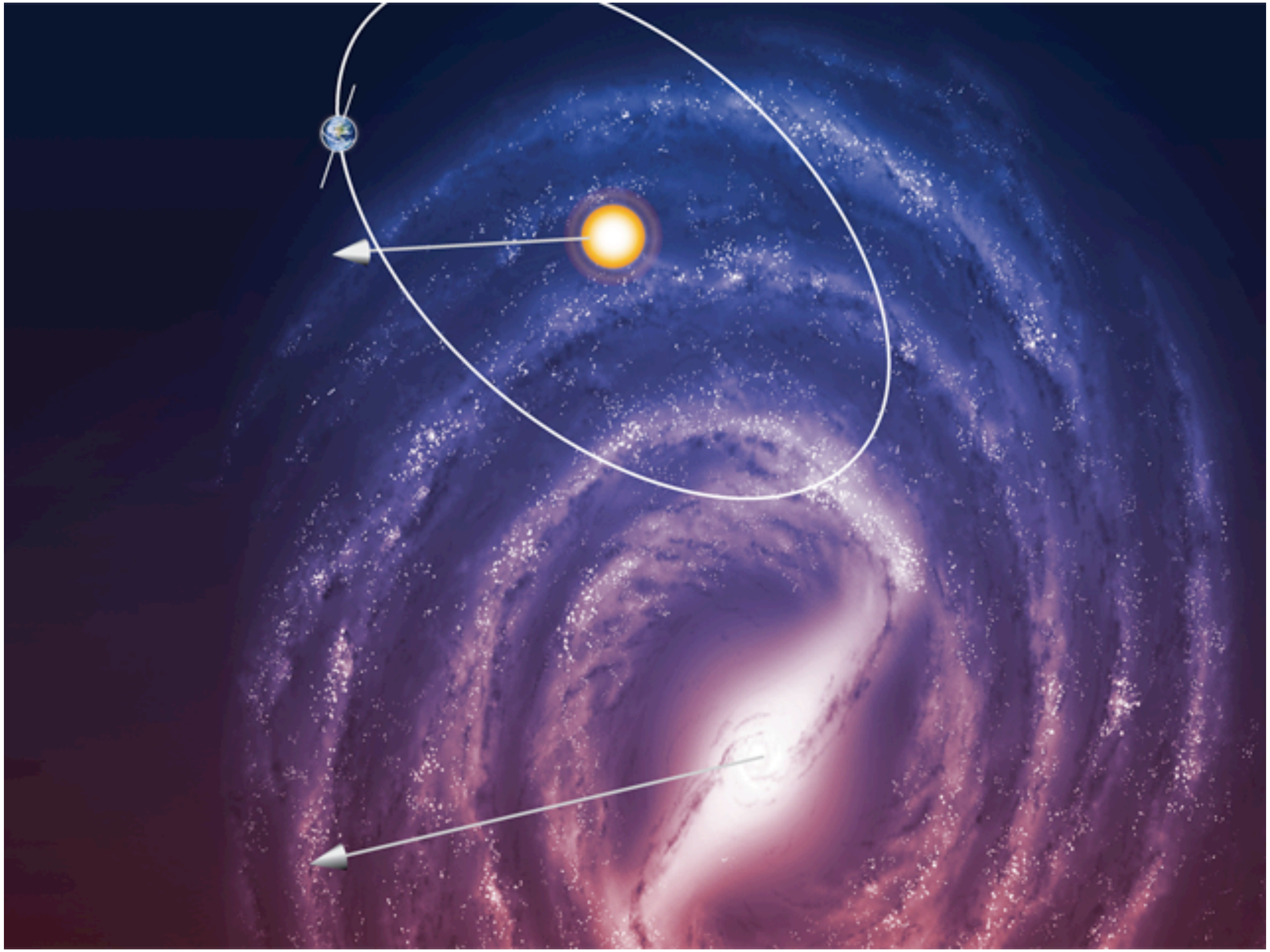
$\Delta X/X=0.0013(10)\ r\cos(\phi)$

$\Delta\alpha/\alpha= 0.003(3)\ r\cos(\phi)$

Compare with QSO

$\Delta\alpha/\alpha =1.10(0.25)\ 10^{-6}\ r\cos(\phi)$

Gradient α points down



Oklo natural nuclear reactor

n+^{149}Sm capture cross section is dominated by $E_r = 0.1$ eV resonance.
Shlyakhter-limit on $\Delta\alpha/\alpha$ two billion years ago

Our QCD/nuclear calculations
$\Delta E_r = 10$ Mev$\Delta X_q/X_q$ - 1 MeV $\Delta\alpha/\alpha$
$X_q = m_q / \Lambda_{QCD}$, enhancement 10 MeV/0.1 eV=10^8

Galaxy moves 552 km/s relative to CMB, $\cos(\phi)=0.23$
Dipole in space: $\Delta E_r = (10\ R\ -\ 1)$ meV

Fujii et al $|\Delta E_r| < 20$ MeV
Gould et al, $-12 < \Delta E_r < 26$ meV
Petrov et al $-73 < \Delta E_r < 62$ meV

Consequences for atomic clocks

- Sun moves 369 km/s relative to CMB

  $\cos(\phi)=0.1$

  This gives average laboratory variation

  $\Delta\alpha/\alpha = 1.5\ 10^{-18}\ \cos(\phi)$ per year

- Earth moves 30 km/s relative to Sun-

  $1.6\ 10^{-20}\cos(\omega t)$ annual modulation

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

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

If we fit spatial dipole, the direction is the same as in quasar data.

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

m_e / M_p limit from NH_3

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

Flambaum,Kozlov PRL 2007

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

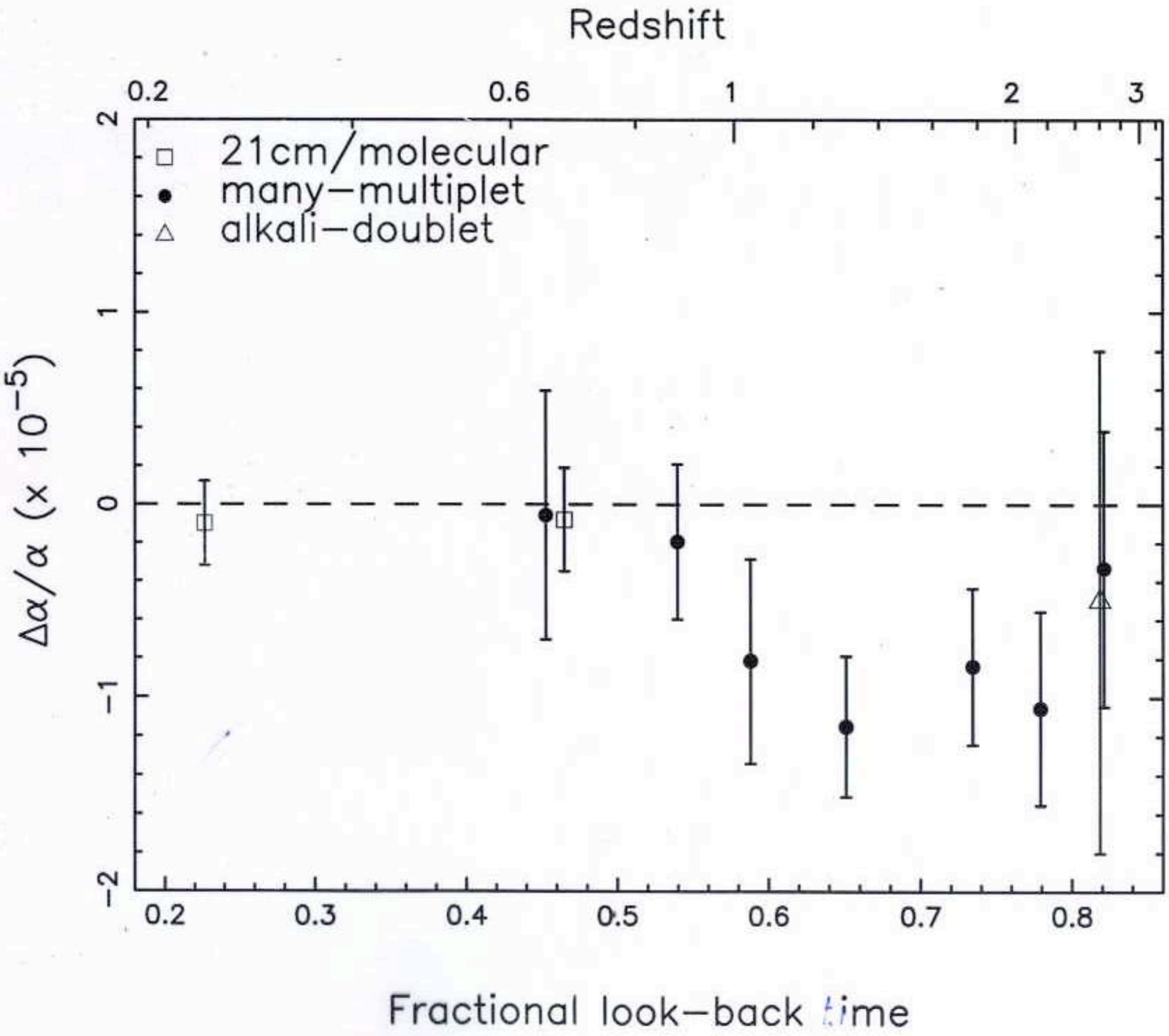
z=0.68, 6.5 billion years ago, $-1(3)10^{-16}$ /year

More accurate measurements

Murphy, Flambaum, Henkel,Muller. Science 2008 $-0.74(0.47)(0.76)10^{-6}$

Henkel et al AA 2009 z=0.87 $<1.4\ 10^{-6}$ 3 σ

Levshakov,Molaro,Kozlov2008 our Galaxy $0.5(0.14)10^{-7}$


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

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?

2008 Wendt,Reimers $<4.9\ 10^{-5}$

2008 Webb et al $0.26(0.30)10^{-5}$

Oklo natural nuclear reactor

n+^{149}Sm capture cross section is dominated by
E_r =0.1 eV resonance
Shlyakhter;Damour,Dyson;Fujii et al
Limits on variation of alpha

Flambaum,Shuryak 2002,2003 Dmitriev,Flambaum 2003
Flambaum,Wiringa 2008
$\Delta E_r = 10\ \mathrm{Mev}\Delta X_q/X_q - 1\ \mathrm{MeV}\ \Delta\alpha/\alpha$
$X_q=m_q/\Lambda_{QCD}$, enhancement 10 MeV/0.1 eV=10^8

2006 Gould et al, Petrov et al $|\Delta E_r|<0.1\mathrm{eV}$,
$|\Delta X/X| <10^{-8}$ two billion years ago, 10^{-17} /year

There are non-zero solutions

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

ΔE_r = 1 MeV $\Delta\alpha/\alpha$

Limits on variation of alpha

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

Flambaum,Shuryak 2002,2003 Dmitriev,Flambaum 2003

Flambaum,Wiringa 2008

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

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 $|x|<8.\ 10^{-9}$

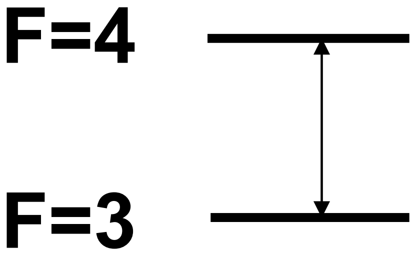
Gould et al $|\Delta E_r|<0.026$ eV $|x|<3.\ 10^{-9}$, $<1.6\ 10^{-18}$ y^{-1}

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

Atomic clocks

Cesium primary frequency standard:

HFS of 6s:



F=4

F=3

ν = 9 192 631 770 Hz

Also: Rb, Cd^+, Ba^+, Yb^+, Hg^+, etc.

E.g. $\nu(Hg^+)$ = 40 507 347 996.841 59(14)(41) Hz

(D. J. Berkeland *et al*, 1998).

Optical frequency standards:

Z	Atom	Transition	Frequency	Source
20	Ca	$^1S_0$-$^3P_1$	455 986 240 494 144(5.3) Hz	Degenhardt et al, 2005
38	Sr^+	$^1S_0$-$^3P_1$	434 829 121 311(10) kHz	Ferrari et al, 2003
49	In^+	$^1S_0$-$^3P_0$	1 267 402 452 899 920(230) Hz	von Zanthier et al, 2005
70	Yb^+	$^2S_{1/2}$-$^2F_{7/2}$	642 121 496 772 300(600) Hz	Hosaka et al, 2005

Also: **H, Al^+, Sr, Ba^+, Yb, Hg, Hg^+, Tl^+, Ra^+**, etc.

Accuracy about 10^{-15} can be further improved to 10^{-18}!

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, $(m_e, m_q)/\Lambda_{QCD}$

Advantages:

- Very narrow lines, high accuracy of measurements.
- Flexibility to choose lines with larger sensitivity to variation of fundamental constants.
- Simple interpretation (local time variation).

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 , ThIV

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

Hg II –negative shifter, Al II –anchor

Yb II - positive and negative shifters

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 , ThIV

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

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

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

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

Cs: β=0, m_e/M_p measurement! Not magnetic moment.
Rydberg contstant in SI units=Cs hyperfine=$(m_e/M_p)\alpha^{2.83}$

Comparison to Cs frequency standard: m_e/M_p measurement!

Cs hyperfine=…Rydberg $(m_e/M_p)\alpha^{2.83}$

1s-2s, and any ns-n's in Hydrogen

Transition frequency = … Rydberg

Measurement of the Cs/H variation gives variation of $(m_e/M_p)\alpha^{2.83}$

Measurement of the Cs/any optical transition gives variation of $(m_e/M_p)\alpha^k$

Measurement of optical/ optical transition gives variation of α^k

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

Optical transitions: <u>atomic calculations</u> (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 α , nuclear magnetic moments and nuclear radii.

We performed atomic, QCD and nuclear calculations.

Microwave transitions and absolute frequency measurements

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

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

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

Primary standard Cs: $\beta=0$, absolute optical frequency measurements (optical/Cs hyperfine) sensitive to m_e/M_p ! Not to proton magnetic moment.

Variation of 1/Rydberg constant in SI units=Cs hyperfine=$(m_e/M_p)\alpha^{2.83}$

Future optical standard: variation of Rydberg constant determined by relativistic corrections in the optical standard frequency

Atomic units: Ry=1/2

Measurements of Ry variation misleading!

We performed atomic, nuclear and QCD calculations

of powers κ ,β for H,D,He,Rb,Cd$^+$,Cs,Yb$^+$,Hg$^+$…

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

^{133}Cs: $\kappa=0.83$, $\beta=0.002$

Cs standard is insensitive to variation of m_q/Λ_{QCD}!

^{87}Rb: $\kappa=0.34$, $\beta=-0.02$

^{171}Yb+: $\kappa=1.5$, $\beta=-0.10$

^{199}Hg+: $\kappa=2.28$, $\beta=-0.11$

^{1}H: $\kappa=0$, $\beta=-0.10$

Complete Table in Phys.Rev.A79,054102(2009)

Results for variation of fundamental constants

Source	$\text{Clock}_1/\text{Clock}_2$	$d\alpha/dt/\alpha\,(10^{-16}\,\text{yr}^{-1})$
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)	$1(10)^{a}$

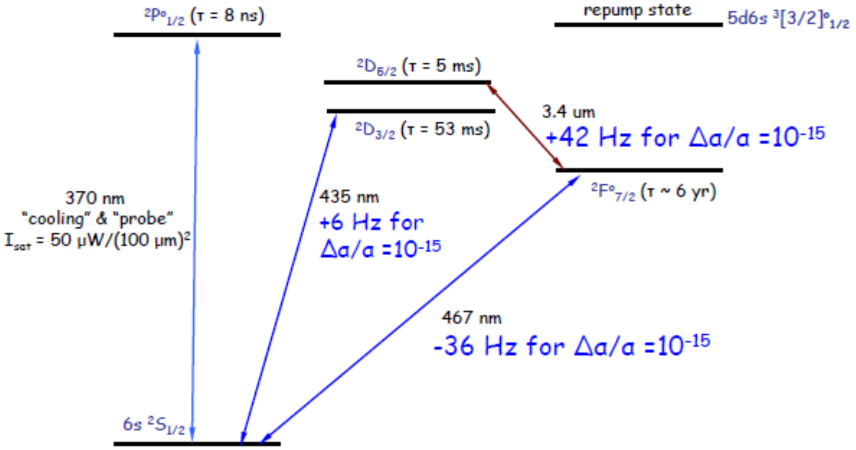
[a] assuming $m_{q,e}/\Lambda_{QCD} = Const$

Combined results: $d/dt\,\ln\alpha = -1.6(2.3) \times 10^{-17}\ \text{yr}^{-1}$

$d/dt\,\ln(m_q/\Lambda_{QCD}) = 3(25) \times 10^{-15}\ \text{yr}^{-1}$

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

Larger q in Yb II



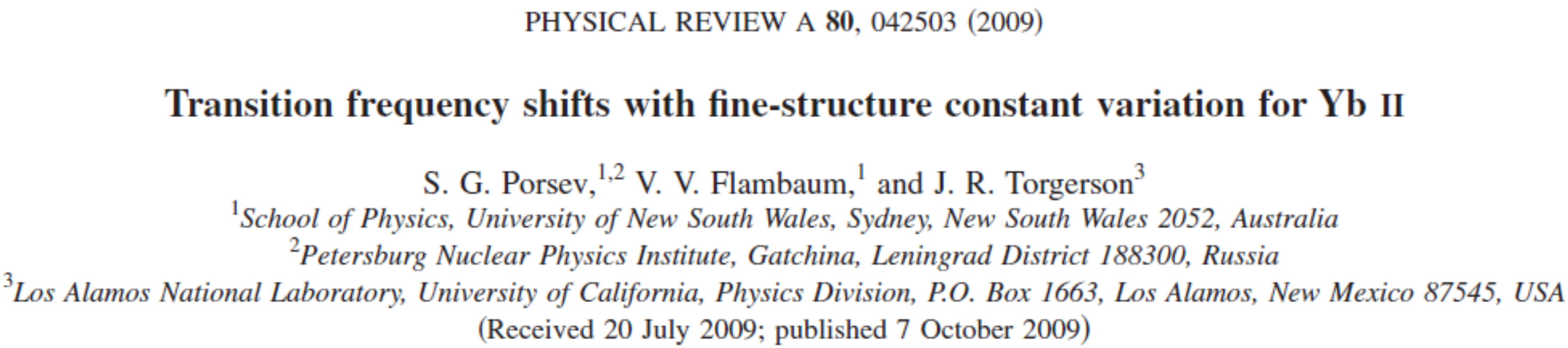
Ground state $f^{14}\ 6s\ ^2S_{1/2}$ → $f^{13}\ 6s^2\ ^2F_{7/2}$ q_1=-60 000

$f^{13}6s^2\ ^2F_{7/2}$ to higher metastable states q_2 up to 85 000

Difference $q=q_2 - q_1$ may exceed 140 000,

so the sensitivity to alpha variation using comparison of two transitions in Yb II exceeds that in HgII/AlI comparison (measurements at NIST) 2.7 times

Shift of frequency difference is 2.7 times larger



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Transition frequency shifts with fine-structure constant variation for Yb II

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Larger q in Yb II

Transition from ground state f^{14} 6s $^2S_{1/2}$ to metastable state f^{13} $6s^2$ $^2F_{7/2}$ q_1=-60 000

For transitions from metastable state $f^{13}6s^2$ $^2F_{7/2}$ to higher metastable states q_2 are positive and large, up to 85 000

Difference $q=q_2 - q_1$ may exceed 140 000,

so the sensitivity to alpha variation using comparison of two transitions in Yb II exceeds that in HgII/AlI comparison (measurements at NIST) 2.7 times.

Shift of frequency difference is 2.7 times larger

Dzuba,Flambaum; Porsev, Flambaum, Torgerson

Experiments: PTB, NPL,…

Largest q in multiply charged ions, narrow lines

q increases as $Z^2 (Z_i+1)^2$

To keep frequencies in optical range we use configuration crossing as a function of Z

Crossing of 5f and 7s

Th IV: q_1=-75 300

Crossing of 4f and 5s

Sm15+, Pm14+, Nd 13+

Difference $q=q_2 - q_1$ is 260 000

5 times larger than in Hg II/Al II

Relative enhancement up to 500

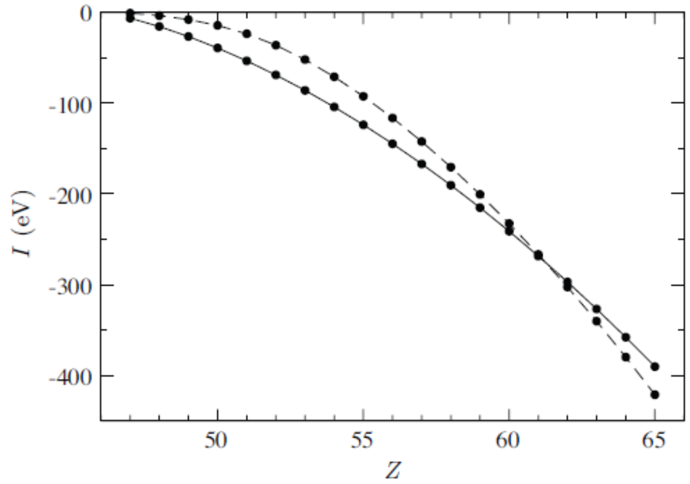

FIG. 2. Dirac-Fock ionisation energies of 5s (solid) and 4$f_{7/2}$ (dashed) levels for the Ag isoelectronic sequence.

In Sm+14 there are narrow transitions and E1 transitions in the laser range (for cooling)

Holes in filled shells: 13 times larger q than in Hg II/Al II

Largest q in multiply charged ions, holes in filled shells

q increases as Z^2 $I^{1.5}$

Ionization potential I is largest for filled shells.

To keep frequencies in optical range we use configuration crossing as a function of Z

Crossing of 4f and 5s in filled shells in Ir 17+

Difference $q=q_2 - q_1$ is 730 000

13 times larger than in Hg II/Al II

Transition frequency 35 000 in laser range, narrow line.

There is E1 transition 45 000 for trapping and cooling.

Crossing of 4s and 5p in W 7+

Cf: 23 times larger than in Hg II/Al II

Berengut, Dzuba, Flambaum, Ong

Atomic clocks with highly charged ions

Highly charged ions have small size, r = const /Z_{ion}

Narrow E2 transitions, r^2

Greatly reduced coupling to external perturbations:
Polarizability r^3
Small balck body radiation shift
Suppressed quadrupole shift, etc

Precision at the level 10^{-19}

Derevianko, Dzuba, Flambaum 2012; Berengut, Dzuba, Flambaum, Ong 2012

Plus enhanced sensitivity to α variation : potential for 2-3 order of magnitude improvement in laboratory measurements of α variation

Optical E1 transitions in highly charged ions

Normally E1 transitions in highly charged ions are in x-ray range.

Near the configuration crossing the electric dipole transitions may have laser range frequencies.

Sm 14+, Ir 17+, …

Important applications:

Ion cooling,

test of the calculations, improved prediction of the clock transitions,

astrophysical applications- search for very hot highly ionised gas (lost half of the matter),

plasma diagnostic,

search for alpha variation.

Quantum chaos in many-excited-electron states, statistical theory and enhancement of electron recombination in highly charged ions with open shells

Enhancement factor **$K = 10^3$**

V. Dzuba, V.V. Flambaum,G. Gribakin, C. Harabati

Excellent testing ground to study quantum mechanics of chaotic systems, matrix elements between chaotic states

Enhancement of relative effect

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

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

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

Relative enhancement $\Delta\omega/\omega_0 = 10^8\,\Delta\alpha/\alpha$

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

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

Dysprosium miracle

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 $\omega_0 = 10^{-4}\ \mathrm{cm}^{-1}$

Our proposal and calculations : Enhancement factor
K = 10^8 (!), i.e. $\Delta\omega/\omega_0 = 10^8\,\Delta\alpha/\alpha$

Measurements (Berkeley,Los Alamos)

$d\ln\alpha/dt = -2.7(2.6)\times 10^{-15}\ \mathrm{yr}^{-1}$

Problem: states are not narrow!
There are close narrow levels in molecules.

More suggestions …

Atom	**State$_1$**		**State$_2$**		**K**
Ce I	$^5H_3$	2369.068	$^1D_2$	2378.827	2000
	$^3H_4$	4762.718	$^3D_2$	4766.323	13000
Nd I	$^5K_6$	8411.900	$^7L_5$	8475.355	950
Nd I	$^7L_5$	11108.813	$^7K_6$	11109.167	10^5
Sm I	$^5D_1$	15914.55	$^7G_2$	12087.17	300
Gd II	$^8D_{11/2}$	4841. 106	$^{10}F_{9/2}$	4852.304	1800
Tb I	$^6H_{13/2}$	2771.675	$^8G_{9/2}$	2840.170	600

Enhancement in molecular clocks

DeMille et al 2008 – enhancement in Cs_2 **, cancellation between electron excitation and vibration energies**

Flambaum 2006 Cancellations between rotational and hyperfine intervals

$\Delta\omega/\omega_0 = K\,\Delta\alpha/\alpha$ Enhancement **K = 10^2 -10^3**

Flambaum, Kozlov 2007 Cancellations between fine structure and vibrations

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

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

Enhancement in molecular clocks

DeMille 2004, DeMille et al 2008 – enhancement in Cs_2 **, cancellation between electron excitation and vibration energies**

Flambaum 2006 Cancellations between rotational and hyperfine intervals in very narrow microwave transitions in LaS, LaO, LuS,LuO, YbF, etc.

$\omega_0 = E_{rotational} - E_{hyperfine} = E_{hyperfine}/100\text{-}1000$

$\Delta\omega/\omega_0 = K \Delta\alpha/\alpha$ Enhancement **$K = 10^2 - 10^3$**

Cancellation between fine structure and vibrations in molecules

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(μ,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

Cancellation between fine structure and rotation in light molecules

Bethlem,Bunning,Meijer,Ubach 2009

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,…

$\mu=m_e/M_p$

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

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 +6 new calculations

Nuclear/QCD estimate: Enhancement **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 10^5 Hz for $\Delta\alpha/\alpha = 10^{-15}$

Compare with atomic clock shift 1 Hz

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

Nuclear clocks ^{229} Th3+: 19 digits precision

In stretched states $F=F_z=I_{nucleus}+J_{electron}$ the ion wave function is a product of electron and nuclear wave functions. Electronic shifts produced by external perturbations in the ground and excited nuclear states are equal and cancel out.

Nuclear size is very small. Nuclear polarizability, black body radiation shift and other shifts are very small.

Campbell, Radnaev, Kuzmich, Dzuba, Flambaum, Derevianko PRL 2012

Potential to improve sensitivity to variation of the fundamental constants by 7 orders of magnitue

Enhancement of relative effect

Our proposal and calculations:

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}

ω_0 = 10^{-4} $cm^{-1.}$ Relative enhancement $\Delta\omega/\omega_0 = 10^8\,\Delta\alpha/\alpha$

Measurement Berkeley **$d\ln\alpha/dt$ =-2(3)x 10^{-16} yr^{-1}**

Different signs of ω_0 in different isotopes: cancellation of errors!

Close narrow levels in molecules

Enhancement in molecular clocks

DeMille et al 2004,2008 – enhancement in Cs_2 **, cancellation between electron excitation and vibration energies**

Flambaum 2006 Cancellations between rotational and hyperfine intervals

$\Delta\omega/\omega_0 = K\, \Delta\alpha/\alpha$ Enhancement **$K = 10^2$ -10^3**

Flambaum, Kozlov 2007 Cancellations between fine structure and vibrations

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

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

Neutrino speed and variation of the fundamental constants

- Limiting speed c may be different deep underground (neutrino experiments)
- Fine structure constant $\alpha = e^2/2\varepsilon_0 hc$ *contains c and may be different*
- *Accuracy of atomic clocks is 10 orders of magnitude better – compare ratio of clock frequencies deep underground*

Neutrino speed and variation of the fundamental constants

Flambaum, Pospelov 2012

QED Lagrangian with additional term describing modification of limiting speed c by depth-dependent tensor $h_{\iota\kappa}$ different from the general relativity metric tensor $g_{\iota\kappa}$

Relations between neutrino speed experiments and atomic clock experiments placed deep underground, e.g. Sudbury mine 2 km, Mariana Trench 11 km, deeper than neutrino

Evolution fundamental constants and their dependence on scalar and gravitational potential

Fundamental constants depend on scalar field ϕ – dark energy, Higgs, dilaton, distance between branes, size of extra dimensions.

Cosmological evolution of ϕ in space and time

Change of ϕ – change of $\alpha(\phi)$

Evolution fundamental constants and their dependence on scalar and gravitational potential

Fundamental constants depend on scalar field ϕ – dark energy, Higgs, dilaton, distance between branes, size of extra dimensions.

Cosmological evolution of ϕ in space and time is linked to evolution of matter.

Changes of Universe equation of state:

Radiation domination, cold matter domination, dark energy domination-

Change of ϕ – change of $\alpha(\phi)$

Scalar charge-source of ϕ

Massive bodies have scalar charge S proportional to the number of particles

Scalar field $\phi=S/r$, proportional to gravitational potential GM/r -

Variation of α proportional to gravitational potential

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

Neutron star, white/brown dwarfs, galaxy, Earth, Sun – compare spectra, $\omega(\alpha)$

Dependence of fundamental constants on gravitational or scalar potential

Projects –atomic clocks at satellites in space or close to Sun (JPL project)

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

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

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

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

New results from Dy, Sr/Cs

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

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

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

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

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

Measurements Ferrel et al 2007

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

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

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

New best limits

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

Nuclear clocks

Peik, Tamm 2003: UV transition between first excited and ground state in ^{229}Th nucleus Energy 7.6(5) eV, width 10^{-3} Hz. Perfect clock!

Flambaum 2006: Nuclear/QCD estimate- Enhancement **10^5**

He,Re; Flambaum,Wiringa; Flambaum,Auerbach,Dmitriev;

Hayes,Friar,Moller;

Litvinova,Feldmeier,Dobaczewski,Flambaum;

$\Delta\omega = \mathbf{10^{19}}$ Hz ($\Delta\alpha/\alpha + 10\ \Delta X_q/X_q$), $X_q = m_q/\Lambda_{QCD}$,

Shift 10-100 Hz for $\Delta\alpha/\alpha = 10^{-18}$

Compare with atomic clock shift 0.001 Hz

Berengut,Dzuba,Flambaum,Porsev: Sensitivity to $\Delta\alpha/\alpha$ is expressed via isomeric shifts of ^{229}Th atomic lines,

frequency in ^{229} Th - frequency in ^{229}Th * . Measure, please!

Enhancement of relative effect

Our proposal and calculations:

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}

$\omega_0 = 10^{-4}\ cm^{-1}$. Relative enhancement $\Delta\omega/\omega_0 = 10^8\,\Delta\alpha/\alpha$

Measurement Berkeley **$d\ln\alpha/dt$ =-2(3)x 10^{-16} yr^{-1}**

Different signs of ω_0 in different isotopes: cancellation of errors!

Close narrow levels in molecules

Enhancement in molecular clocks

DeMille et al 2008 – enhancement in Cs_2 **, cancellation between electron excitation and vibration energies**

Flambaum 2006 Cancellations between rotational and hyperfine intervals

$\Delta\omega/\omega_0 = K\,\Delta\alpha/\alpha$ Enhancement **$K = 10^2$ -10^3**

Flambaum, Kozlov 2007 Cancellations between fine structure and vibrations

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

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

Cancellation between fine structure and vibrations in molecules

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

Conclusions

- Spatial gradient of alpha from quasar data, 4.2 sigma, Keck and VLT data agree,low and high red shift data agree, no contradictions with other groups.
- It provides alpha variation for atomic clocks due to Earth motion at the level 10^{-18} and 1 meV shift in Oklo resonance. One-two orders of magnitude improvement in the measurement accuracy is needed.
- Very weak indications for the spatial variation in H_2 quasar spectra and BBN abundance of deuterium. The same direction of the gradient!

New systems with higher absolute sensitivity include:

- highly charged ions.
- ^{229}Th nucleus – highest absolute enhancement (10^5 times larger shift)
- Many systems with relative enhancement due to transition between close levels: Dy atom, a number of molecules with narrow close levels,…

- Search for anisotropy in CMB, expansion of the Universe, structure formation

Test of Grand Unification Theories. Origin of matter in the universe(Bariogensis)

- Grand Unification Theories combine electromagnetic, weak and strong interactions and all known elementary particles into one theory. One needs new experiments to select correct theory. Atomic and molecular experiments are used to test unification theories of elementary particles (by measuring effects of violation of the fundamental symmetries predicted by unification theories).
- This theory should also explain origin of matter in the universe. Equal amounts of matter and antimatter were produced after Big Bang. Why there was no complete annihilation? Very small excess of matter was generated by a weak interaction violating fundamental symmetries.

  Time reversal violation, parity (mirror symmetry) violation, charge symmetry violation.
- A new generation of experiments with enhanced effects is underway in atoms, diatomic molecules, and solids

Conclusions

- Spatial gradient of alpha from quasar data, 4.2 sigma, Keck and VLT data agree, low and high red shift data agree, no contradictions with other groups.
- It provides alpha variation for atomic clocks due to Earth motion at the level 10^{-18} and 1 meV shift in Oklo resonance. One-two orders of magnitude improvement in the measurement accuracy is needed. Three orders for meteorites.
- Very weak indications for the spatial variation in H_2 quasar spectra and BBN abundance of deuterium. The same direction of the gradient!

New systems with higher absolute sensitivity include:

- transitions between ground and metastable states in highly charged ions. Frequencies are kept in laser spectroscopy range due to the configuration crossing phenomenon. An order of magnitude gain.
- ^{229}Th nucleus – highest absolute enhancement (10^5 times larger shift), UV transition 7eV.
- Many systems with relative enhancement due to transition between close levels: Dy atom, a number of molecules with narrow close levels,…

- Search for anisotropy in CMB, expansion of the Universe, structure formation

Parity violation in Cs, calculations

Dzuba, Flambaum, Ginges 2002 (+radiative corrections in strong field 2005)

accuracy 0.5%, 1.1 sigma from Standard Model

Porsev,Derevianko 2010, 0.27%, 0 sigma

- Berengut,Dzuba,Flambaum,Roberts 2012

Many-body corrections to Porsev et al (tail,core)

Corrected result coinsides exactly with Dzuba et al. If we take Porsev et al error , 1.5 sigma

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1.1 sigma- more room for new physics

Two heavy fermions bound via Higgs exchange: new problem for QED community

- Heavy leptons and quarks of 4th generation- Higgs exchange dominates since the interaction is proportional to mass.
- New types of relativistic, retardation and radiative corrections

Flambaum, Kuchiev PRD 84, 114024 (2011)

Conclusions

- Spatial dipole in quasar data provides alpha variation for atomic clocks due to Earth motion at the level 10^{-18} per year.

New systems with higher absolute sensitivity include:

- transitions between metastable states in Yb II
- transitions between ground state and metastable state in Th 3+ and many highly charged ions. Frequencies are kept in laser spectroscopy range due to the configuration crossing phenomenon. An order of magnitude gain.
- ^{229}Th nucleus – highest absolute enhancement (10^5 times larger shift), UV transition 7eV.

- Many systems with relative enhancement due to transition between close levels: Dy atom, a number of molecules with narrow close levels,…

Nuclear clocks

Peik, Tamm 2003: UV transition between first excited and ground state in ^{229}Th nucleus. Energy 7.6(5) eV, width 10^{-4} Hz. Perfect clock!

Our nuclear/QCD calculations - Enhancement **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 2000 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, Beck et al

^{229}Th: why enhancement?

$\omega = Q + E_{pk} + E_{so} = 7.6$ eV **huge cancellations!**

Q=Coulomb=100 KeV **10^{-4} total Coulomb**

$E_{so} = \langle V_s\, L\, S \rangle$=spin-orbit=-1.0 MeV

E_{pk} =potential+kinetic=1 MeV

Extrapolation from light nuclei

$\Delta E_{pk}/E_{pk} = -1.4\, \Delta m_q/m_q$

$\Delta E_{so}/E_{so} = -0.24\, \Delta m_q/m_q$

$\Delta\omega/\omega_0 = 10^5\ (0.14\, \Delta\alpha/\alpha + 1.6\, \Delta X_q/X_q)$

Dependence on α

$\Delta\omega = Q\,\Delta\alpha/\alpha$

- Total Coulomb energy 10^3 MeV in ^{229}Th
- Difference of moments of inertia between ground and excited states is 4%
- If difference in the Coulomb energy would be 0.01%, Q=100 KeV, estimate for the enhancement factor

$Q/\omega_0 = 10^5\ \mathrm{eV} / 7\ \mathrm{eV} = 1.4\ 10^4$

Enhancement in ^{229}Th

	α	$X_q = m_q / \Lambda_{QCD}$	
Flambaum 2006	$\sim 10^5$	$0.5\ 10^5$	estimate
Hayes,Frier 2007	0	impossible	arguments
He,Ren 2007	$0.04\ 10^5$	$0.8\ 10^5$	rel.mean field

Main effect (dependence of deformation on α) missed, change of mean-field potential only

Dobaczewski

et al 2007 **$0.15\ 10^5$** **Hartree-Fock**

preliminary

^{229}Th: Flambaum,Wiringa 2007

$\omega = E_{pk} + E_{so} = 7.6$ eV huge cancellations!

$E_{so} = \langle V_s\, L\, S \rangle$=spin-orbit=$-1.04$ MeV

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$\Delta E_{pk}/E_{pk} = -1.4\, \Delta m_q/m_q$

$\Delta E_{so}/E_{so} = -0.24\, \Delta m_q/m_q$

$\Delta\omega/\omega_0 = 1.6$ **10^5** $\Delta X_q/X_q$

Difference of Coulomb energies

$\Delta\omega = Q\,\Delta\alpha/\alpha$

Hayes,Frier,Moller <30 Kev

He,Ren 30 KeV

Flambaum,Auerbach,Dmitriev

-500 Kev < Q < 1500 KeV

Litvinova,Feldmeier,Dobaczewski,

Flambaum

-300 Kev < Q < 450 KeV

Sensitivity to $\Delta\alpha$ may be obtained from measurements

$\Delta\omega = Q\ \Delta\alpha/\alpha$

Berengut,Dzuba,Flambaum,PorsevPRL2009

$Q/\text{Mev} = -506\ \Delta\langle r^2\rangle/\langle r^2\rangle + 23\Delta Q_2/Q_2$

Diffrence of squared charge radii $\Delta\langle r^2\rangle$ may be extracted from isomeric shifts of electronic transitions in Th atom or ions

Diffrence of electric quadrupole moments ΔQ_2 from hyperfine structure

Experimental progress in ^{229}Th

- Transition energy measured in Livermore

  7.6 (5) eV instead of 3.5(1.0) eV
- Intensive search for direct radiation

  Argonne

  Peik et al,

  Habs et al, …

Ultracold atomic and molecular collisions.

Cheng Chin, Flambaum PRL2006

Enhancement near Feshbach resonance.

Variation of scattering length

$\Delta a/a = K\, \Delta\mu/\mu$, $K = 10^2 - 10^{12}$

$\mu = m_e/M_p$

Hart,Xu,Legere,Gibble Nature 2007

Accuracy in scattering length 10^{-6}

Evolution fundamental constants and their dependence on scalar and gravitational potential

Fundamental constants depend on scalar field ϕ – dark energy, Higgs, dilaton, distance between branes, size of extra dimensions.

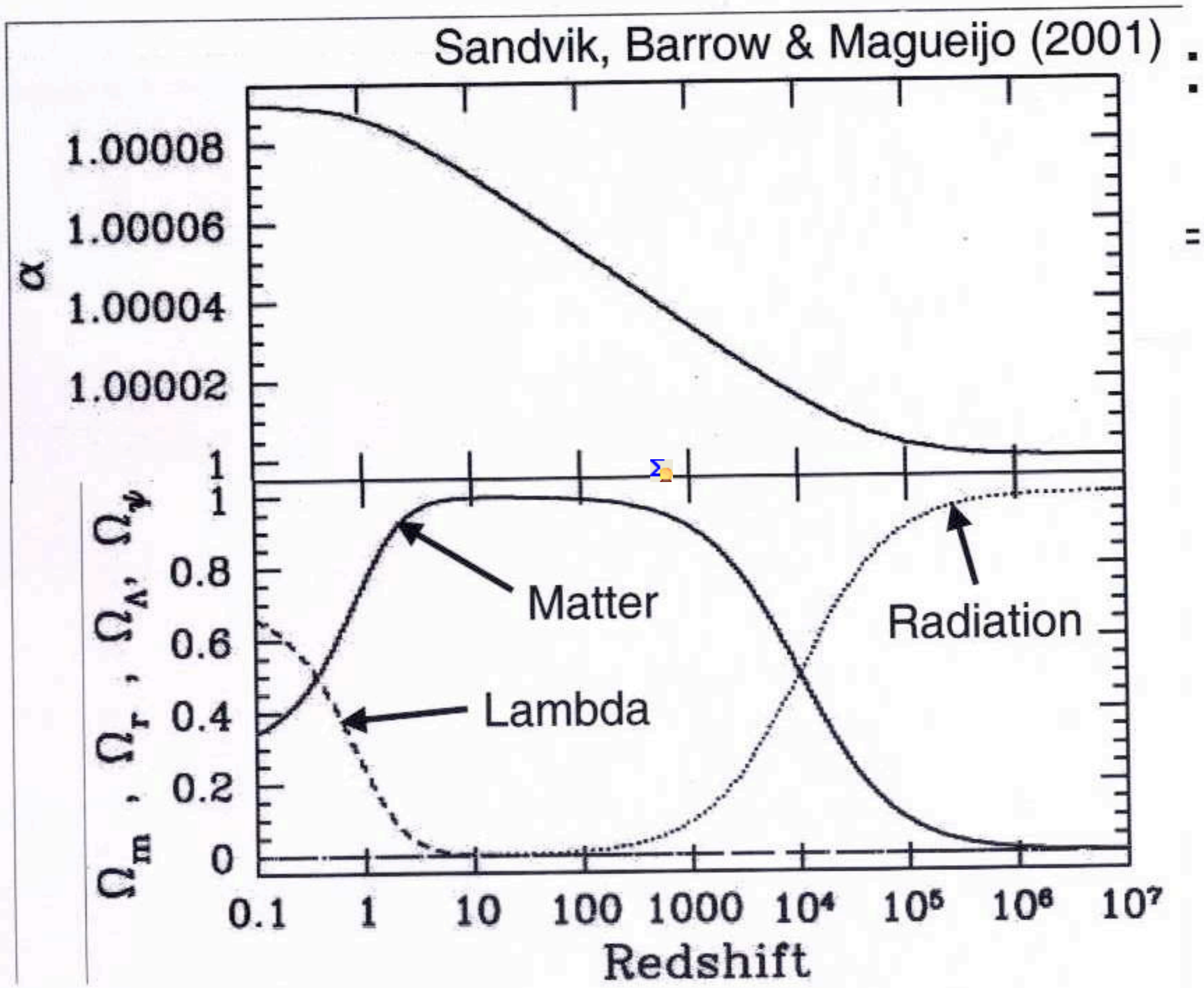
Cosmological evolution of ϕ in space and time is linked to evolution of matter.

Changes of Universe equation of state:

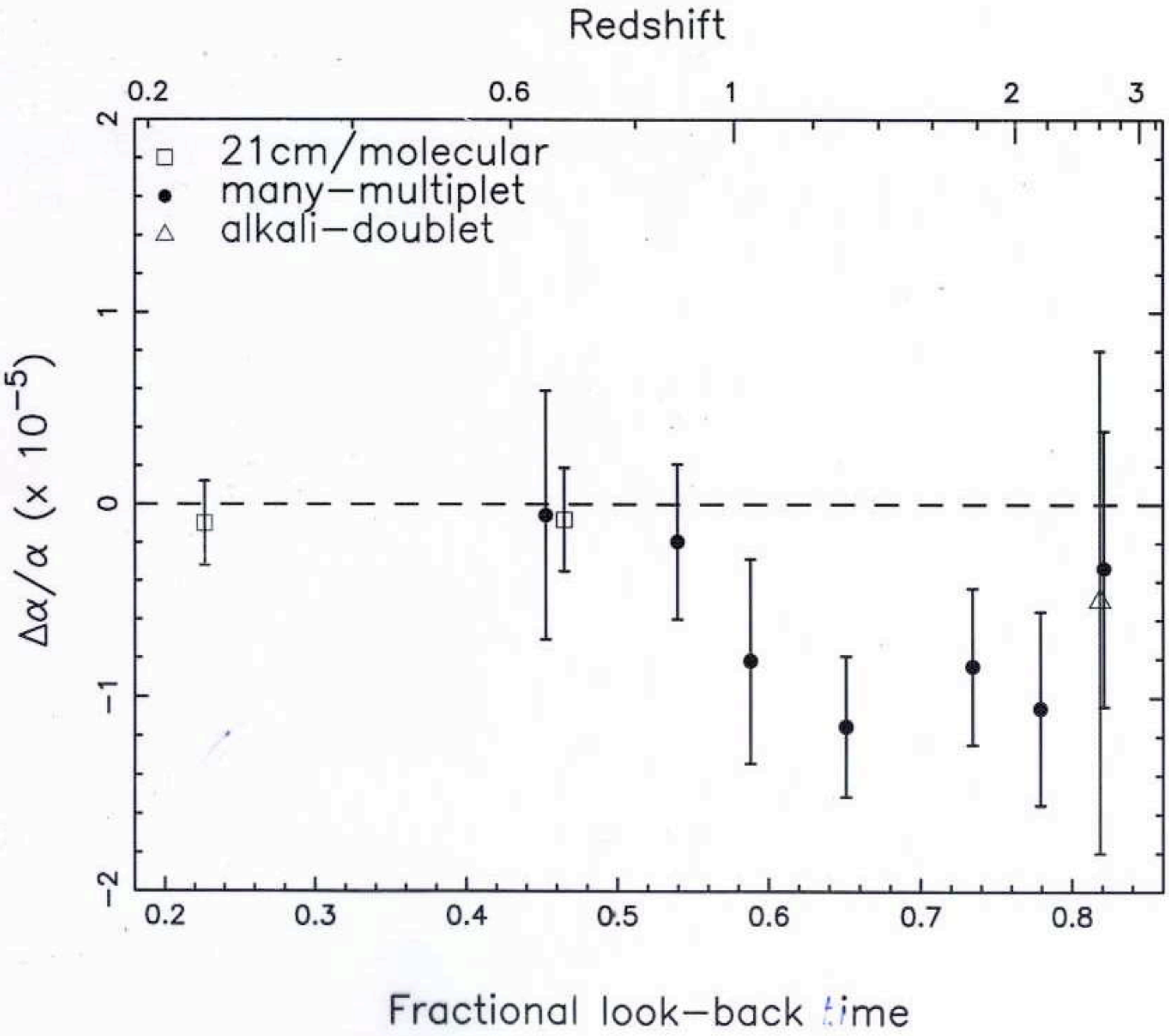
Radiation domination, cold matter domination, dark energy domination-

Change of ϕ – change of $\alpha(\phi)$

Bekenstein model.   Olive, Pospelov - driven by dark matter


Sandvik, Barrow & Magueijo (2001)

$=e^2/\hbar c$


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

Scalar charge-source of ϕ

Massive bodies have scalar charge S proportional to the number of particles

Scalar field $\phi=S/r$, proportional to gravitational potential GM/r -

Variation of α proportional to gravitational potential

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

Neutron star, white/brown dwarfs, galaxy, Earth, Sun – compare spectra, $\omega(\alpha)$

Dependence of fundamental constants on gravitational or scalar potential

Projects –atomic clocks at satellites in space or close to Sun (JPL project)

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

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

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

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

New results from Dy, Sr/Cs

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

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

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

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

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

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Microwave clocks in optical lattice

- Sr,Hg ,… in optical lattice. Optical clocks.

Magic wavelength-cancellation of dynamical Stark shifts, very accurate optical frequencies.

Katory, Kimble, Ye,…

- Hyperfine transitions, linear polarization - no magic wavelength in atoms with valence s-electron: Cs , Rb,…

There is magic wavelenght for atoms with $p_{1/2}$ electron- due to hyperfine mixing $p_{1/2}$-$p_{3/2}$ Al, Ga,…

Beloy,Derevinako,Dzuba, Flambaum PRL 2009

- Circular polarisation- all wavelengths are magic for a certain direction of magnetic field – “magic angle”

Cs (primary standard), Rb,… PRL 2008

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 : hyperfine H/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 $<10^{-8}$
- 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

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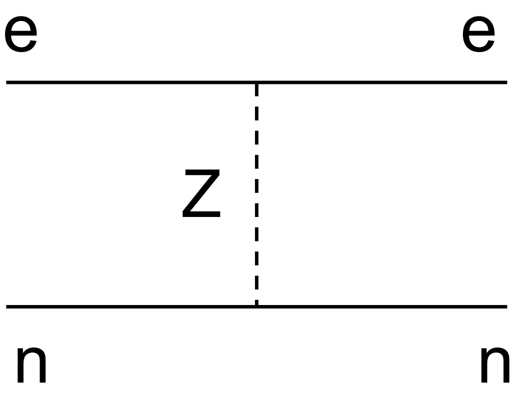
- Oklo: sensitive to m_q/Λ_{QCD} ,, effect $<10^{-8}$
- Atomic clocks: present time variation of α , m/Λ_{QCD}
- Highest sensitivity is in Yb II and Th IV, compare transitions from ground and metastable states
- Transitions between narrow close levels in atoms and molecules – huge enhancement of the 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

Atomic parity violation



- Dominated by Z-boson exchange between electrons and nucleons

$$H = \frac{G}{\sqrt{2}}\left[C_{1p}\bar{e}\gamma_\mu\gamma_5 e\bar{p}\gamma^\mu p + C_{1n}\bar{e}\gamma_\mu\gamma_5 e\bar{n}\gamma^\mu n\right]$$

Standard model tree-level couplings: $C_{1p} = \frac{1}{2}\left(1-4\sin^2\theta_W\right)$; $C_{1n} = -\frac{1}{2}$

- In atom with Z electrons and N neutrons obtain effective Hamiltonian parameterized by “nuclear weak charge” Q_W

$$h_{PV} = \frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

$$Q_W = 2(NC_{1n} + ZC_{1p}) \approx -N + Z(1-4\sin^2\theta_W) \approx -N$$

- APV amplitude $E_{PV} \propto Z^3$ [Bouchiat,Bouchiat]

Bi,Pb,Tl,Cs Test of standard model via atomic experiments!

Calculations [Dzuba,Flambaum,Ginges, 2002]

$E_{PV} = -0.897(1 \pm 0.5\%) \times 10^{-11}\ iea_B(-Q_W/N)$

Porsev,Beloy,Derevianko 2009 0.3%

Cs Boulder

➔ $Q_W - Q_W^{SM} = 1.1\ \sigma$

Tightly constrains possible new physics, e.g. mass of extra Z boson $M_{Z'} > 1$ TeV . New experiments: Ba+, 20 times enhancement in Ra+, Fr

$$E_{PV} = \sum_p \frac{W_{sp} E1_{ps}}{E_s - E_p}$$

E_{PV} includes -0.8% shift due to strong-field QED self-energy / vertex corrections to weak matrix elements W_{sp}

[Kuchiev,Flambaum; Milstein,Sushkov,Terekhov]

A complete calculation of QED corrections to PV *amplitude* includes also

- QED corrections to energy levels and E1 amplitudes

[Flambaum,Ginges; Shabaev,Pachuki,Tupitsyn,Yerokhin]

PV : Chain of isotopes

Dzuba, Flambaum, Khriplovich

Rare-earth atoms:

- close opposite parity levels-enhancement
- Many stable isotopes

Ratio of PV effects gives ratio of weak charges. Uncertainty in atomic calculations cancels out. Experiments:

Berkeley: Dy and Yb;

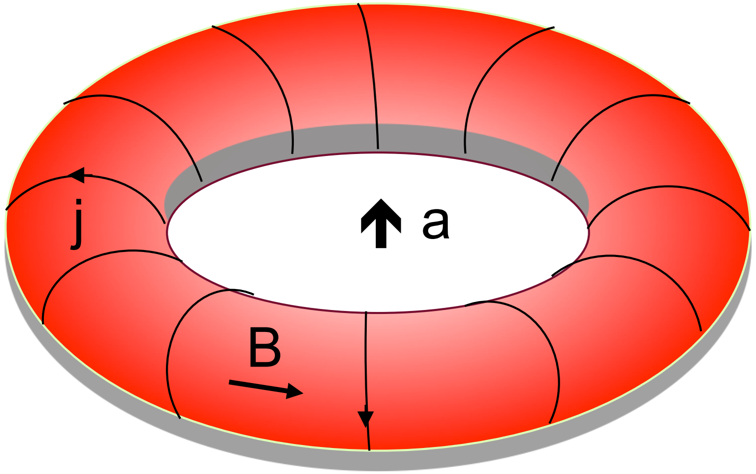
Ra, Ra^+, Fr Argonne, Groningen,TRIUMF?

Test of Standard model or neutron distribution.

Brown, Derevianko,Flambaum 2008. Uncertainties in neutron distributions cancel in differences of PNC effects in isotopes of the same element. Measurements of ratios of PNC effects in isotopic chain can compete with other tests of Standard model!

Nuclear anapole moment

- Source of nuclear spin-dependent PV effects in atoms
- Nuclear magnetic multipole violating parity
- Arises due to parity violation inside the nucleus



- Interacts with atomic electrons via usual magnetic interaction (PV hyperfine interaction):

$$h_a = e\vec{\alpha}\cdot\vec{A} \propto \kappa_a \vec{\alpha}\cdot\vec{I}\rho(r)\ , \quad \kappa_a \propto A^{2/3}$$

[Flambaum,Khriplovich,Sushkov]

$E_{PV} \propto Z^2 A^{2/3}$ measured as difference of PV effects for transitions between hyperfine components

Cs: |6s,F=3> – |7s,F‘=4> and |6s,F’=4> – |7s,F=3>

Probe of weak nuclear forces via atomic experiments!

Nuclear anapole moment is produced by PV nuclear forces. Measurements+our calculations give the strength constant g.

- Boulder Cs: g=6(1) in units of Fermi constant

Seattle Tl: g=-2(3)

New accurate calculations Haxton,Liu,Ramsey-Musolf; Auerbach, Brown; Dmitriev, Khriplovich,Telitsin: problem remains.

Our proposals:

10^3 enhancement in Ra atom due to close opposite parity state;

Dy,Yb,…(experiment in Berkeley)

Enhancement of nuclear anapole effects in molecules

10^5 enhancement of the nuclear anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity.

Theorem: only nuclerar-spin-dependent (anapole) contribution to PV is enhanced (Labzovsky; Sushkov, Flambaum).

Weak charge can not mix opposite parity rotational levels and Λ−doublet.

Molecular experiments : Yale, Groningen.

Enhancement of nuclear anapole effects in molecules

10^5 enhancement of the nuclear anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity. Theorem: only anapole contribution to PV is enhanced (Labzovsky;Sushkov,Flambaum 1978). Weak charge can not mix opposite parity rotational levels and Λ−doublet.

Ω=1/2 terms: $\Sigma_{1/2}$, $\Pi_{1/2}$. Heavy molecules, effect Z^2 $A^{2/3}$ $R(Z\alpha)$

YbF,BaF,SrF,PbF,LuS,LuO,LaS,LaO,HgF,Cl,Br,I;BiO,BiS,PbO+, YbO+,HgO+…

PV effects 10^{-3} , microwave or optical M1 transitions. For example, circular polarization of radiation or difference of absorption of right and left polarised radiation.

Cancellation between hyperfine and rotational intervals - enhancement.

Interval between the opposite parity levels may be reduced to zero by magnetic field – further enhancement.

Molecular experiments : Yale, Groningen

New calculations for many molecules and molecular ions: Borschevsky,Ilias,Beloy,Dzuba,Flambaum,Schwerdtfeger 2012

Atomic electric dipole moments

- Electric dipole moments violate parity (P) and time-reversal (T)

$$\vec{d} \equiv \vec{r} \propto \vec{J}$$

- T-violation ≡ CP-violation by CPT theorem

CP violation

- Observed in K^0, B^0
- Accommodated in SM as a single phase in the quark-mixing matrix (Kobayashi-Maskawa mechanism)

However, not enough CP-violation in SM to generate enough matter-antimatter asymmetry of Universe!

➔ Must be some non-SM CP-violation

- Excellent way to search for new sources of CP-violation is by measuring EDMs
  - SM EDMs are hugely suppressed

  → Theories that go beyond the SM predict EDMs that are many orders of magnitude larger!

e.g. electron EDM

Theory	d_e (e cm)
Std. Mdl.	$< 10^{-38}$
SUSY	$10^{-28} - 10^{-26}$
Multi-Higgs	$10^{-28} - 10^{-26}$
Left-right	$10^{-28} - 10^{-26}$

Best limit (90% c.l.): $|d_e| < 1.6 \times 10^{-27}\ e\ cm$ Berkeley (2002)

- Atomic EDMs $d_{atom} \propto Z^3$ [Sandars]

Sensitive probe of physics beyond the Standard Model!

Enhancement of electron EDM

- Atoms: Tl enhancement d(Tl)= -585 d_e

Experiment – Berkeley. New calculations for Tl,Fr,Cs,…Old results confirmed and improved.

- Molecules –close rotational levels,

Ω –doubling – huge enhancement of electron EDM (Sushkov,Flambaum 1978)

Ω =1/2	10^7	YbF	London
Ω=1	10^{10}	PbO,ThO	Yale,Harvard
Ω=2	10^{13}	HfF^+	Boulder

Weak electric field is enough to polarise the molecule. Molecular electric field is several orders of magnitude larger than external field (Sandars)

Nuclear EDM-screening: d_N E_N

- Schiff theorem: $E_N=0$, neutral systems
- Extension for ions:

Ion acceleration $a= Z_i\, eE/M$

Nucleus acceleration $a=Z\, eE_N/M$

$$E_N=E\, Z_i/Z$$

In molecules screening is stronger:

$a= Z_i\, eE/(M+m)$, $E_N= E\, (Z_i/Z)(M/(M+m))$

Schiff moment contribution dominates in heavy molecular ions!

Schiff: Incomplete sctreening in neutral atoms

- Hyperfine interaction: atomic EDM is proportional to nuclear EDM times nuclear magnetic moment
- Finite nuclear size.

Effect due to nuclear Schiff moment

We performed new calculations of both effects for all atoms of experimental interest

EDMs of atoms of experimental interest

Z	Atom	[S/(e fm3)]e cm	[$10^{-25}\eta$] e cm	Expt.
2	^{3}He	0.00008	0.0005	
54	^{129}Xe	0.38	0.7	Seattle, Ann Arbor, Princeton,Tokyo
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

S-nuclear Schiff moment; neutron $d_n = 5 \times 10^{-24}\, e\ \mathrm{cm}\ \eta$,

t,W,Z bags and bariogenesis, Flambaum,Shuryak PRD2010

The pressure of the walls collects over 100 of heavy particles t,W,Z into h=0 areas, compresses and heats the gas of t,W,Z until mechanical equilibirium is reached: pressure of hot gas compensates pressure of the walls P=v forming metastable bags.

Finite size h=0 sphaleron produces barion number violation inside the bags. The barrier is 2 TeV only (instead of 14 TeV for <h>=v).

Summary

- Atomic and molecular experiments are used to test unification theories of elementary particles

Parity violation

  - Weak charge: test of the standard model and search of new physics
  - Nuclear anapole, probe of weak PV nuclear forces

Time reversal

  - EDM, test of physics beyond the standard model.

1-3 orders improvement may be enough to reject or confirm all popular models of CP violation, e.g. supersymmetric models

- A new generation of experiments with enhanced effects is underway in atoms, diatomic molecules, and solids

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