Search for Variation of Fundamental Constants

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Nuclear and QCD calculations V.V.Flambaum,
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Quasar observations C.Churchill,J.Prochazka,A.Wolfe, thanks to W.Sargent,R.Simcoe

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 **$|\Delta c|>0$?**
- Cosmic Microwave Background Radiation
- ✓ Quasar Absorption Spectra [1] **$|\Delta c|>0$?**
- Oklo natural nuclear reactor
- Analysis of meteorite data
- ✓ Atomic clocks [1]

[1] *Based on analysis of atomic spectra*

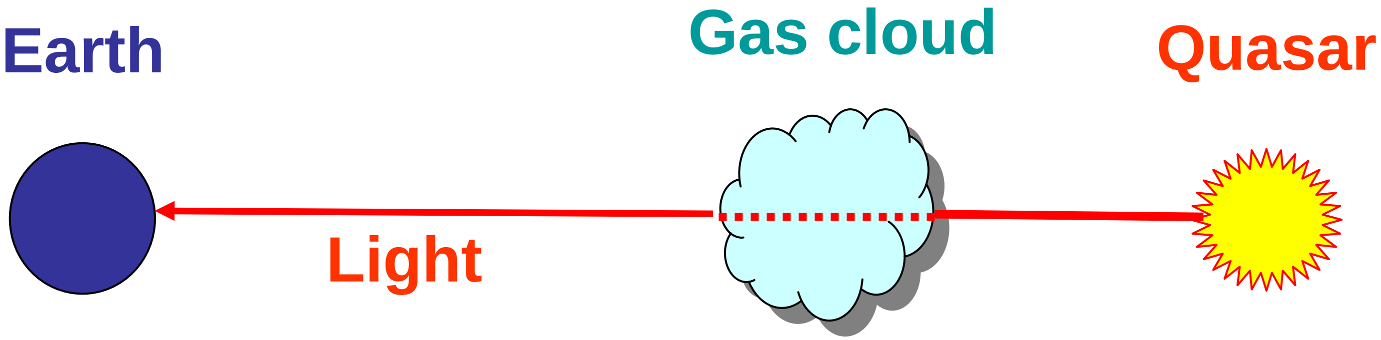
Which Constants?

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

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

$$\alpha_{strong}(r) = Const/\ln\left(r\Lambda_{\mathrm{QCD}}/\hbar \mathrm{c}\right)$$

Quasar absorption spectra

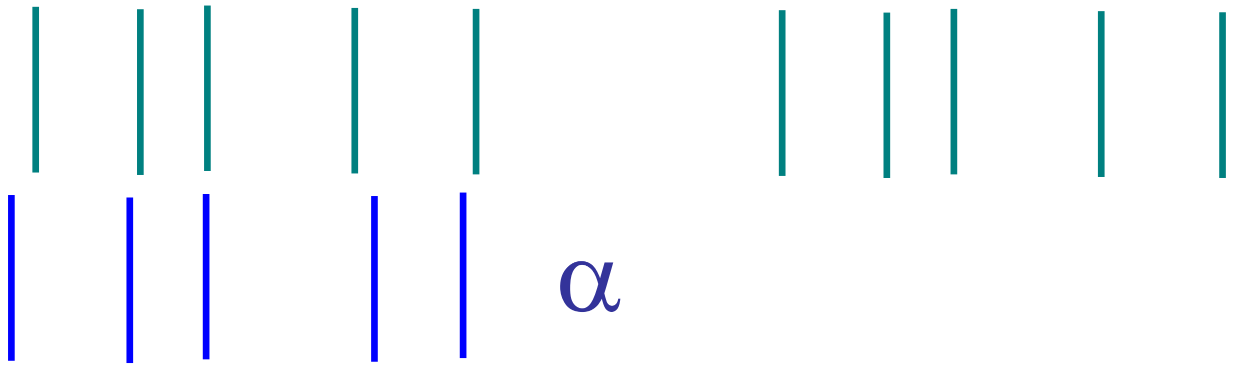


Earth

Gas cloud

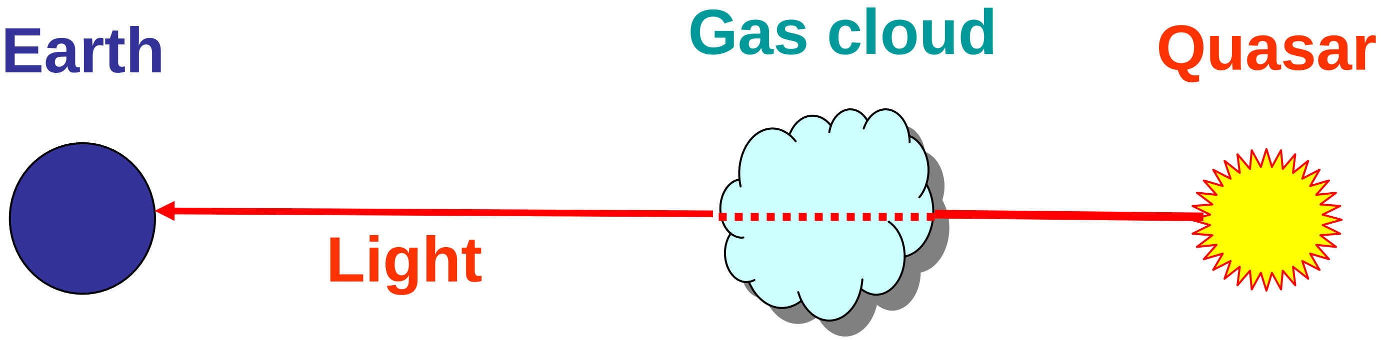
Quasar

Light



α

Quasar absorption spectra

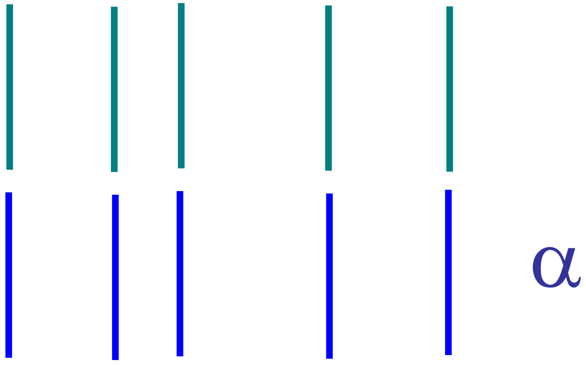


Earth

Gas cloud

Quasar

Light



One needs to know *E*(α^2) for each line to do the fitting

Alkali Doublet Method

(Varshalovich, Potekhin, Ivanchik, et al)

Fine structure interval

$$\Delta_{FS} = E(p_{3/2}) - E(p_{1/2}) = A(Z\alpha)^2$$

If Δ_Z is observed at red shift Z and Δ_0 is FS measured on Earth then

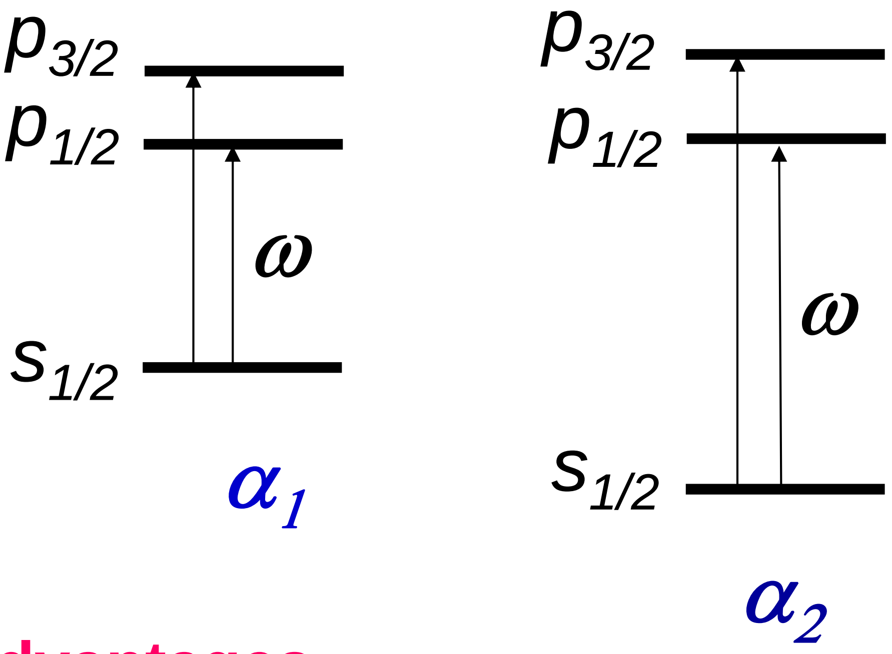
$$\frac{\Delta\alpha}{\alpha} = \frac{1}{2}\left(\frac{\Delta_Z}{\Delta_0} - 1\right)$$

Ivanchik *et al*, 1999: $\Delta\alpha/\alpha = -3.3(6.5)(8) \times 10^{-5}$.

Murphy *et al*, 2001: $\Delta\alpha/\alpha = -0.5(1.3) \times 10^{-5}$.

Many Multiplet Method

(Flambaum, Webb, Murphy, et al)



$$\delta\omega >> \delta\Delta_{FS}\,!$$

Advantages:

- **Order of magnitude gain in sensitivity**
- **Statistical: all lines are suitable for analysis**
- **Many opportunities to study systematic errors**

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 momemtum j.

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

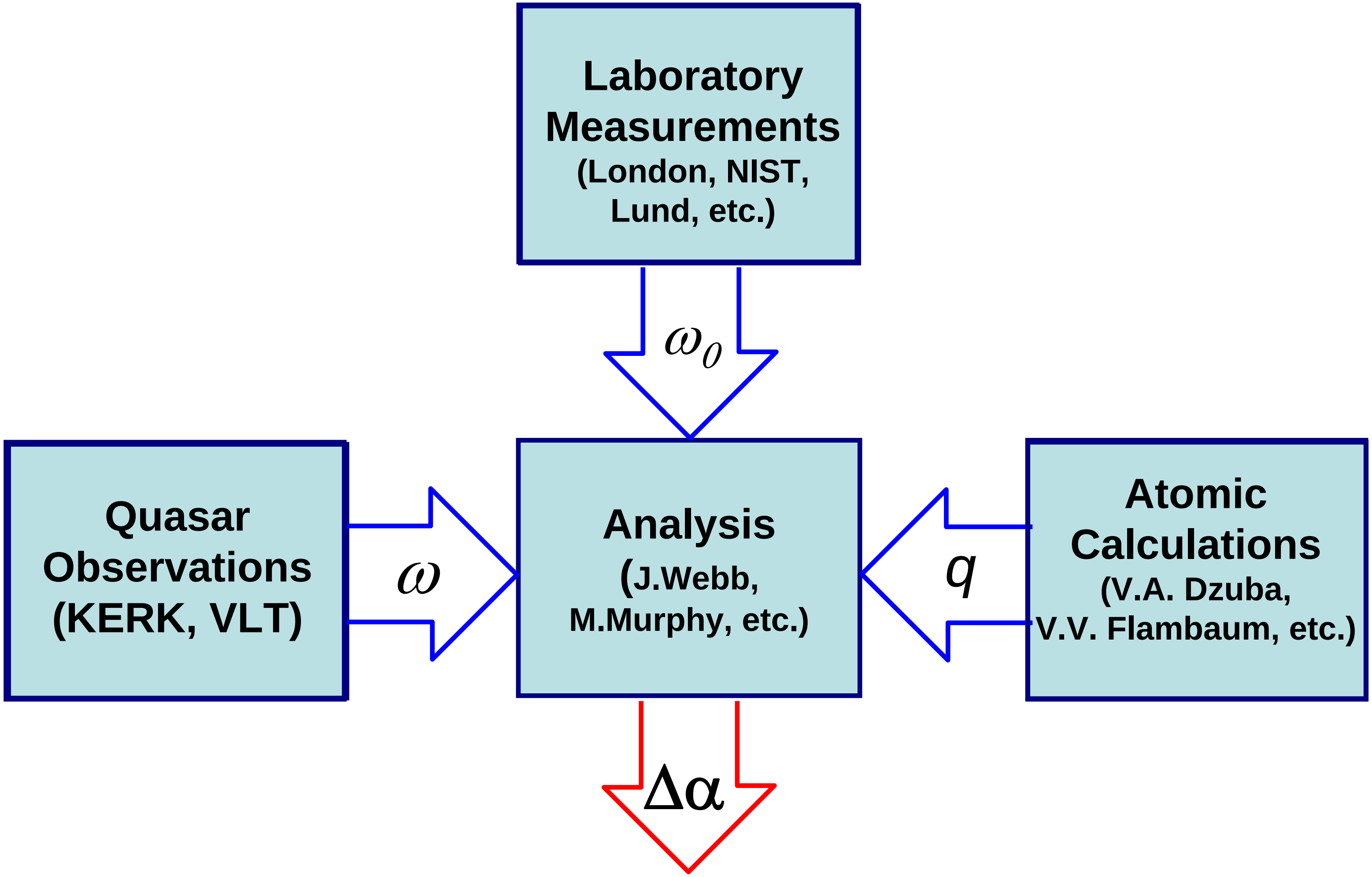
For α close to α_0 $\quad \omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$

q is found by varying α in computer codes:

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

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

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



Laboratory Measurements
(London, NIST, Lund, etc.)

ω_0

Quasar Observations (KERK, VLT)

ω

Analysis
(J.Webb, M.Murphy, etc.)

q

Atomic Calculations
(V.A. Dzuba, V.V. Flambaum, etc.)

$\Delta\alpha$

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}	Method	Accuracy
1	Correlation Potential Method	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%

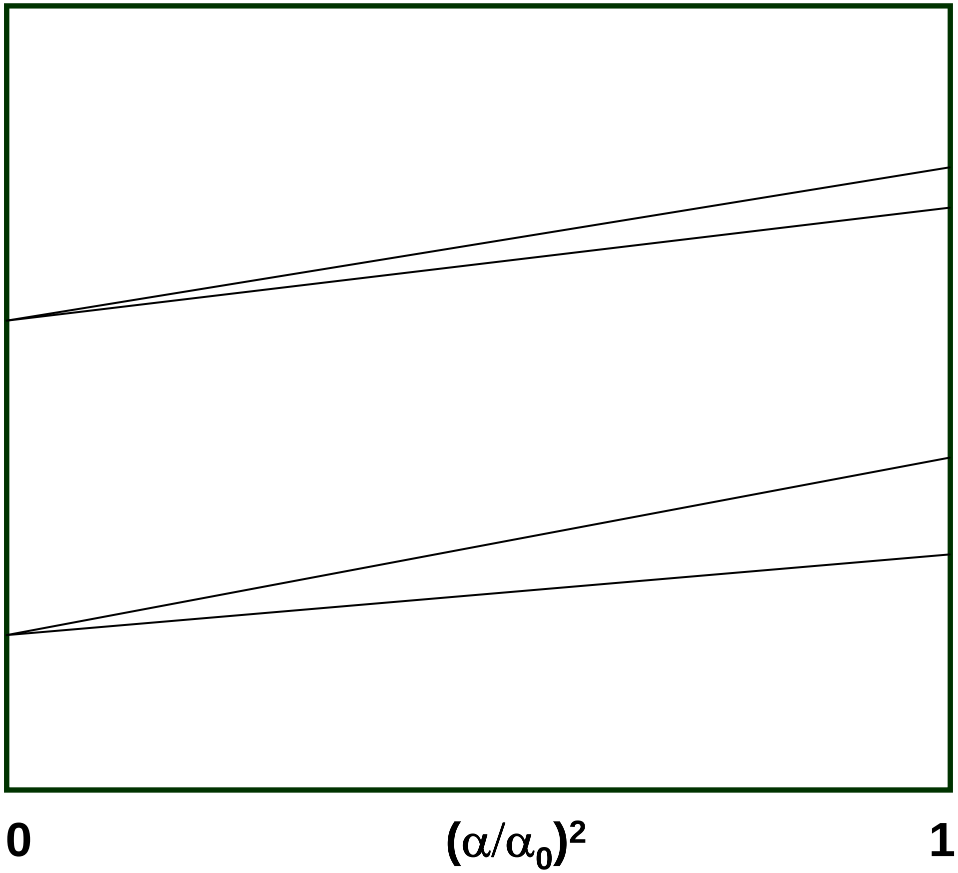
These methods cover all periodic system of elements

They were used for many important problems:

- Saving Standard Model from PNC in Cs.
- Predicting spectrum of **Fr**, etc., etc., etc.

Fine structure unomalies and level crossing

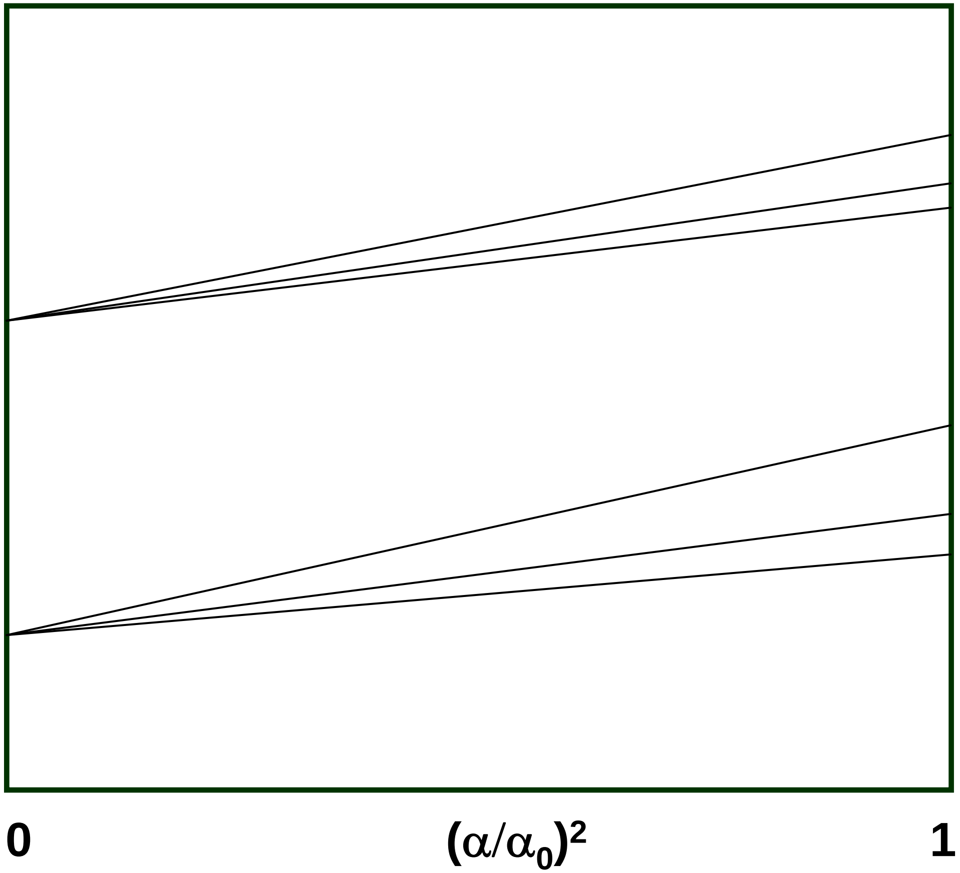
Energies of “normal” fine structure **doublets** as functions of α^2



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

Fine structure unomalies and level crossing

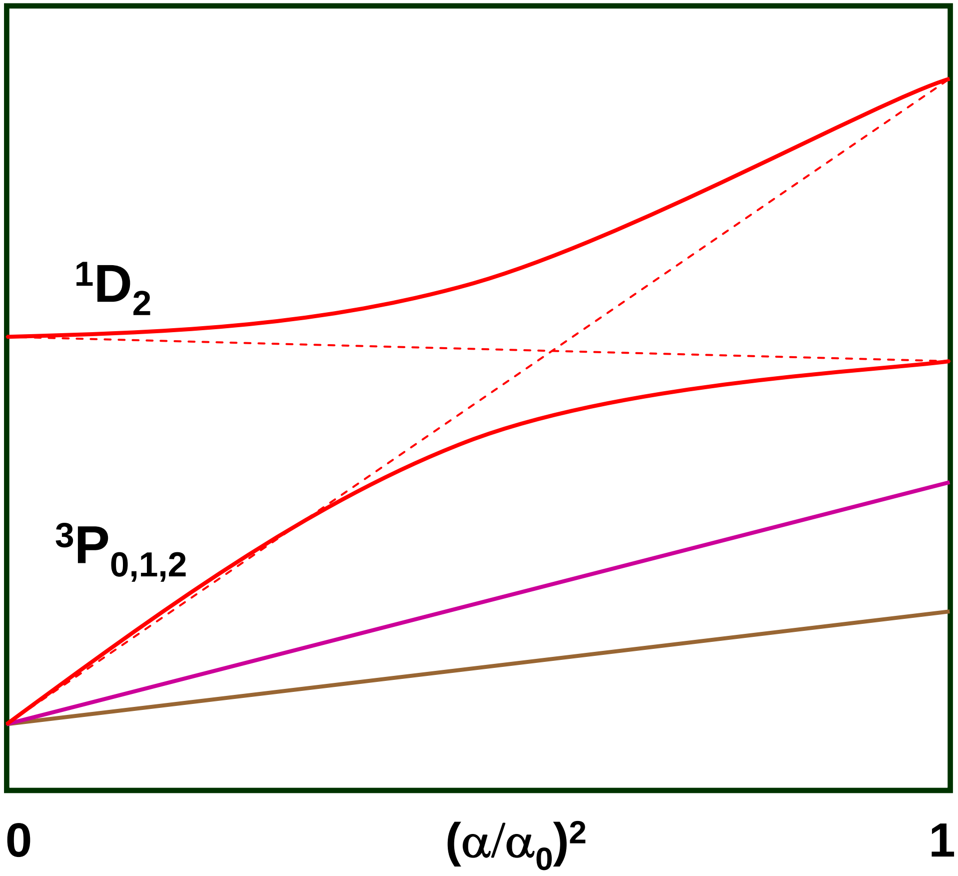
Energies of “normal” fine structure triplets as functions of α^2



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

Fine structure unomalies and level crossing

Energies of strongly interacting states as functions of α^2



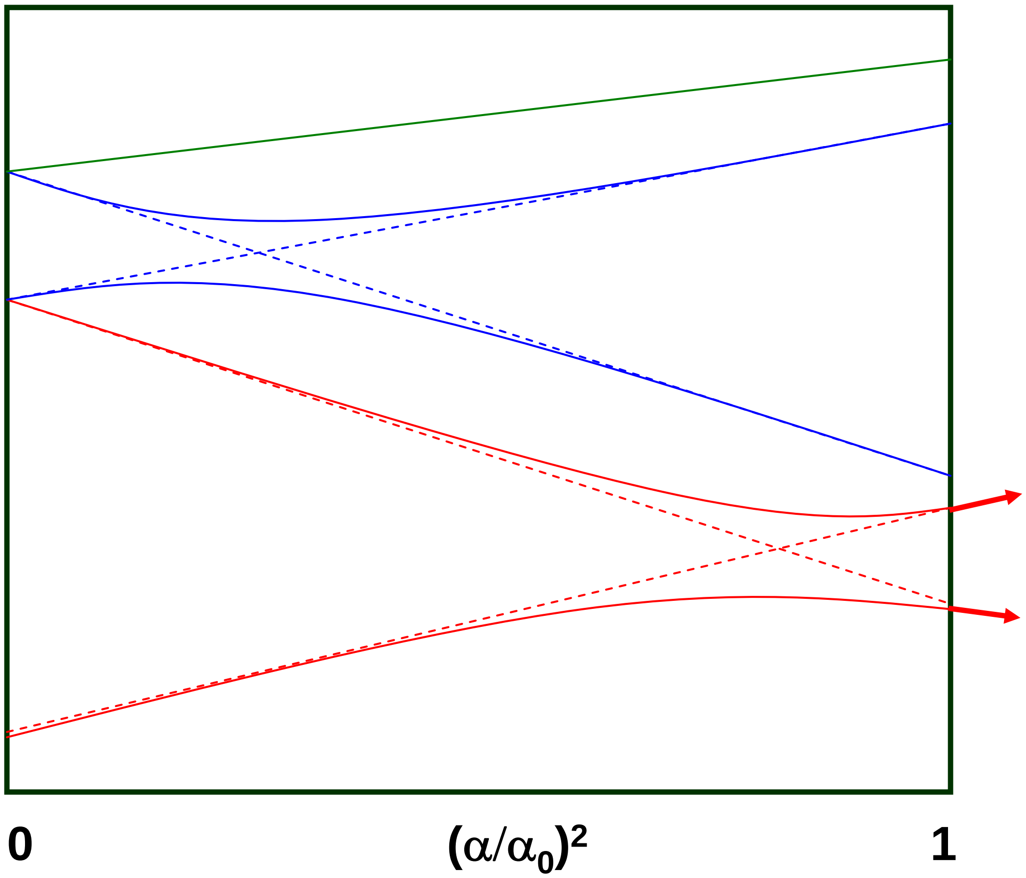
$$\xcancel{\Delta E = A(Z\alpha)^2}$$

Implications to study of α variation

- Not every fine structure interval can be used in the analysis based on formula $\Delta E=A(Z\alpha)^2$ (not good!).
- Strong enhancement is possible (good, but for atomic clocks only).
- Level crossing may lead to instability of calculations (bad!).

Problem: level pseudo crossing

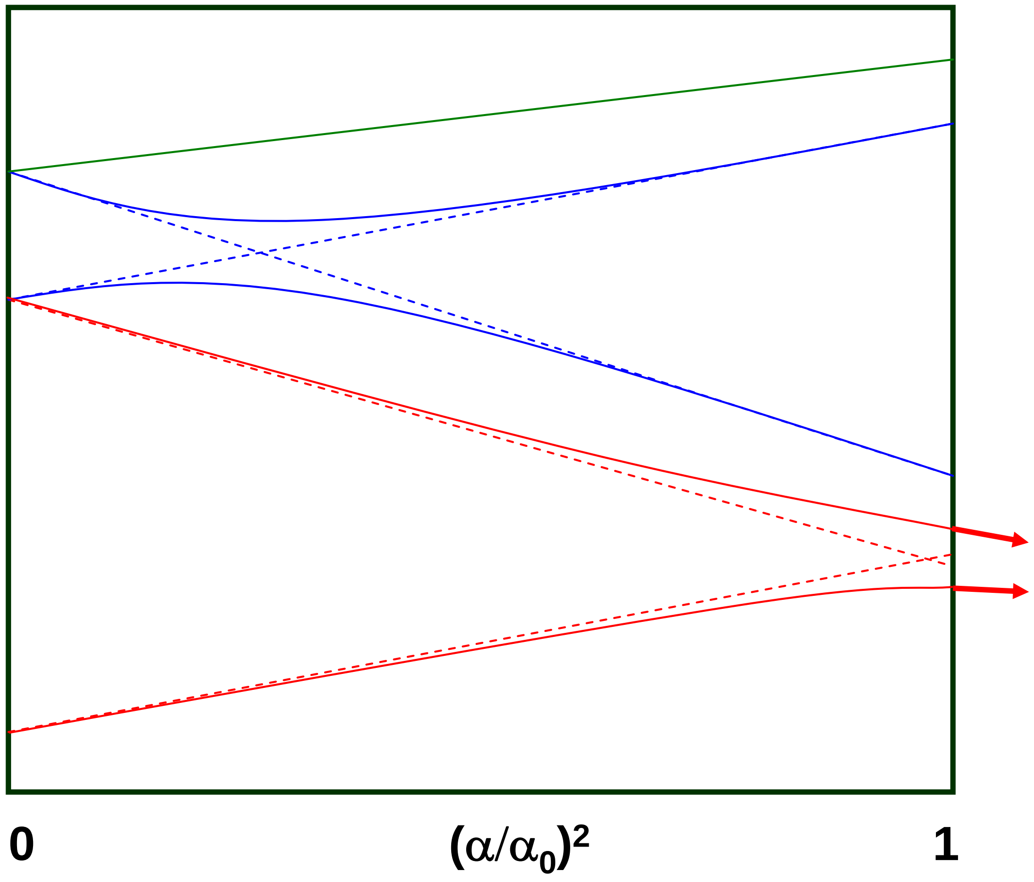
Energy levels of Ni II as functions of α^2



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

Results of calculations

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

Complicated behaviour of atomic spectra provides opportunity to study systematic errors!

Results of the analysis

(based on Keck/HIRES data)

- Webb et al, 1999: 0.5<z<1.6

  $\Delta\alpha/\alpha = -1.1(4) \times 10^{-5}$

- Webb et al, 2001: 0.5<z<3.5

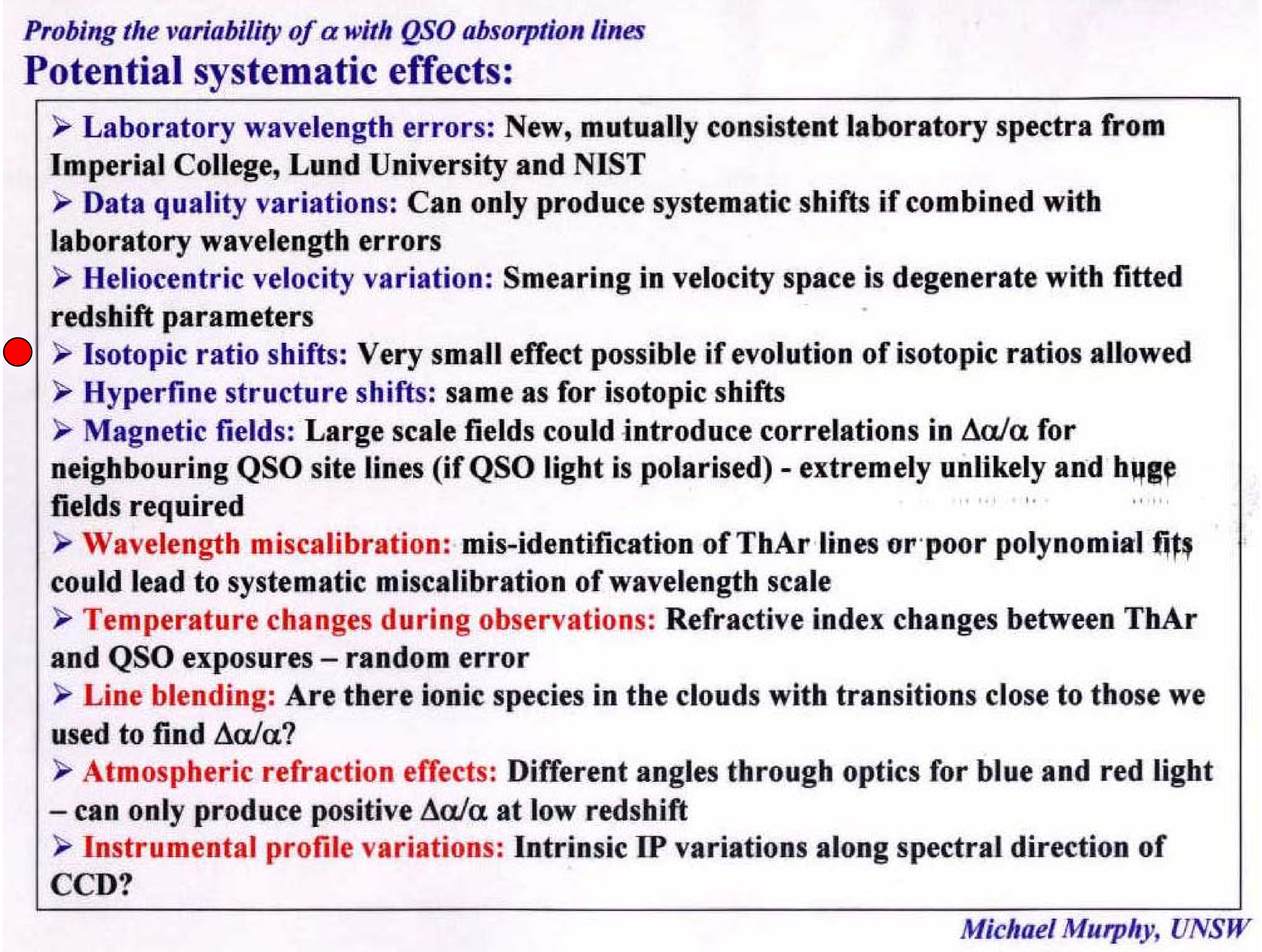
  $\Delta\alpha/\alpha = -0.72(18) \times 10^{-5}$

- Webb et al, 2003: 0.2<z<3.7

  $\Delta\alpha/\alpha = -0.57(10) \times 10^{-5}$

- Murphy et al, 2003: 0.2<z<4.2

  $\Delta\alpha/\alpha = -0.543(116) \times 10^{-5}$



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?

Michael Murphy, UNSW

No explanation by systematic effects have been found so far!

MM results from the VLT/UVES data

Source	$\Delta\alpha/\alpha$ [10^{-5}]	*z* (red shift)
Srianand et al, PRL 92, 121302, 2004 Chand et al, AA 417, 853, 2004	**-0.06(0.06)**	0.4<z<2.3
Chand et al, AA 430, 47, 2005	**0.15(43)**	1.59<z<2.92
Chand et al, AA 451, 45, 2006	**0.05(24)**	1.1508
Quast et al, AA 415, L7, 2004	**-0.04(19)(27)**	1.15
Levshakov et al, AA 434, 827, 2005	**0.24(38)** **0.04(15)**	1.839 1.15
Levshakov et al, AA 449, 879, 2006	**-0.07(84)**	1.15

The same MM method, same atomic calculations, different telescope.
The results are consistent with zero and disagree with the Keck/HIRES data.

Spatial variation

(C.L. Steinhardt, PRD, **71**, 043509 (2005))

	$\Delta\alpha/\alpha\ [10^{-5}]$
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, 2003: No evidence for spatial variation

Different explanation

- Murphy, Webb, Flambaum, astro-ph/0611080

  Proposed a simple model to calculate $\Delta\alpha/\alpha_{\mathrm{lim}}$ from LSR fitting of the data.
  Then it must be $\Delta\alpha/\alpha > \Delta\alpha/\alpha_{\mathrm{lim}}$ for all systems
  In reality: Murphy et al, 2004, 143 systems: **all okay**
  Chand et al, 2004, 11 out of 23 systems: **failed**
  Levshakov et al, 2006, single system: **failed**

- Murphy, Webb, Flambaum, astro-ph/0612407

  Redone the analysis of Chand et al which lead to $\Delta\alpha/\alpha = -0.06(06)\ 10^{-5}$
  MWF's result is $\Delta\alpha/\alpha = -0.44(16)\ 10^{-5}$

- Murphy, et al, astro-ph/073623

  Problems in line calibration of the VLT data
  Induced systematic errors ~ 4 times quoted statistical errors

- MWF's results for VLT/UVES to follow

Search for variation of strong interaction

In Grand unification models (Marciano;Calmet,Fritzch; Langecker,Segre, Strasser; Dent)

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

It might be easier to find $\Delta(m/\Lambda_{QCD})$ than $\Delta\alpha/\alpha$

- **Tsanavaris,Webb,Murphy,Flambaum, Curran** PRL 2005; MNRAS, 2007

Hyperfine H/optical , 8 quasar absorption systems with Mg,Ca,Mn,C,Si,Zn,Cr,Fe,Ni
$0.24 < z < 2.04$

$$\Delta x/x = (0.63 \pm 0.99)\times 10^{-5}$$

- No variation

$$x = \alpha^2 g_p m_e/m_p$$

$$\mu = m_e/m_p$$

$$\Delta\mu/\mu = (0.63 \pm 0.99)\times 10^{-5}$$

$$\Delta\mu/\mu = (0.58 \pm 1.95)\times 10^{-5}$$

(high z)

- **Reinhold,Bunnin,Hollenstein,Ivanchik, Petitjean** PRL 2006 ,

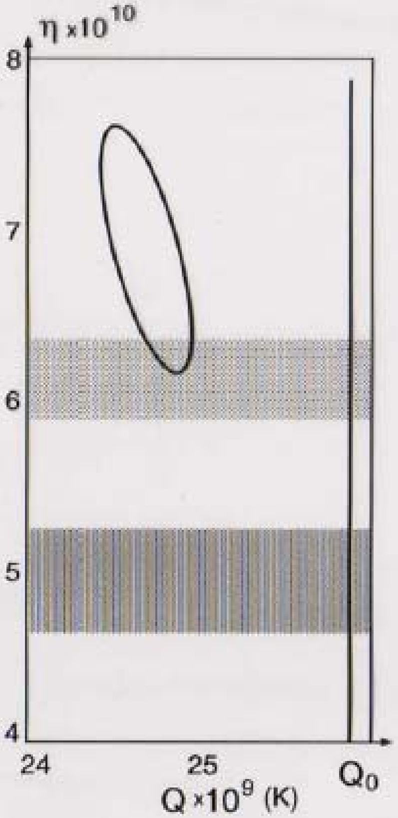
  H_2 molecule, 2 systems

$$\Delta\mu/\mu = (-2.4 \pm 0.6)\times 10^{-5}$$

- 4σ variation ! (z=2.6 and 3.0)

Big Bang Nucleosynthesis

(Dmitriev, Flambaum, Webb)



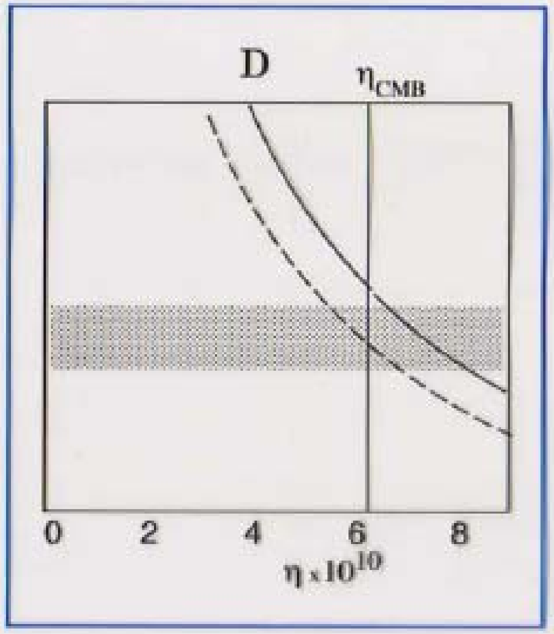
$p + n \rightarrow d + \gamma, \;\; 3\ \mathrm{sec} \le \mathrm{t} \le 6\ \mathrm{min}$

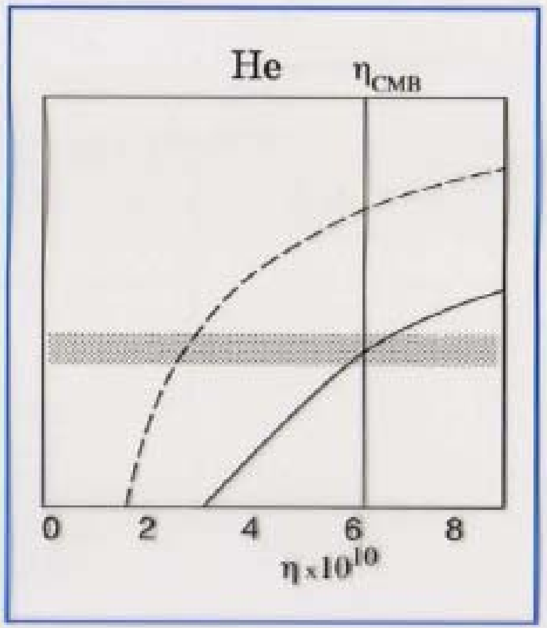
Productions of D, ^{4}He, ^{7}Li are exponentially sensitive to deuteron binding energy E_d

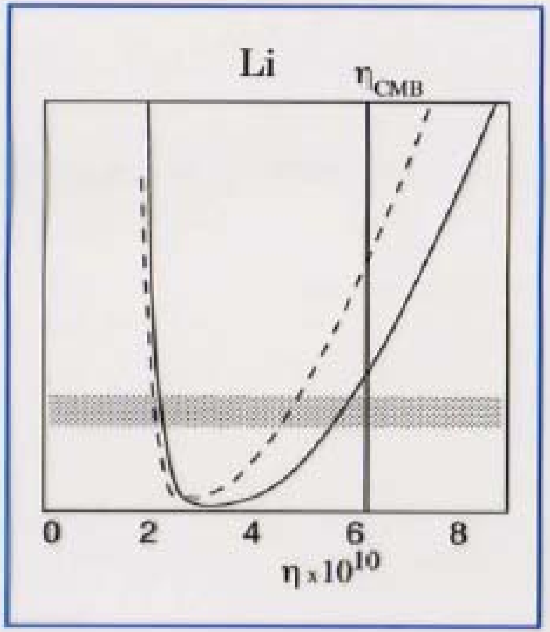
$$\boxed{\sim e^{-\frac{E_d}{T_f}}}$$

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

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







Comparison with observations gives

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

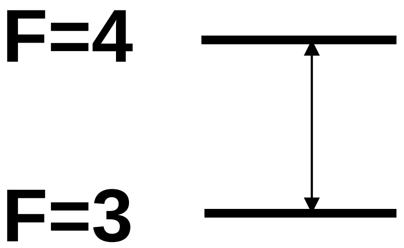
This also leads to agreement

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

Atomic clocks

Cesium primary frequency standard:

HFS of 6s:



$\nu = 9\,192\,631\,770$ Hz

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

E.g. $\nu(\mathrm{Hg}^+) = 40\,507\,347\,996.841\,59(14)(41)$ 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: Al^+, Sr, Ba^+, Yb, Hg, Hg^+, Tl^+, Ra^+, etc.

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

Opportunities:

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/Λ_{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 .

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

Microwave transitions: hyperfine frequency is sensitive to α (Prestage,Tjoelker,Maleki, Hg/H) and to nuclear magnetic moments (Karshenboim)

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

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

Results for variation of fundamental constants

Source	**$\mathrm{Clock}_1/\mathrm{Clock}_2$**	**$(d\alpha/dt)/\alpha\,(10^{-15}\,\mathrm{yr}^{-1})$**
Marion *et al*, 2003	Rb(hfs)/Cs(hfs)	0.05(1.3)[a]
Bize *et al*, 2003	Hg^+(opt)/Cs(hfs)	-0.03(1.2)[a]
Fisher *et al*, 2004	H(opt)/Cs(hfs)	-1.1(2.3)[a]
Peik *et al*, 2004	Yb^+(opt)/Cs(hfs)	-0.2(2.0)
Bize *et al*, 2004	Rb(hfs)/Cs(hfs)	0.1(1)[a]
Peik *et al*, 2006	Hg^+(opt)/Rb(hfs)	-0.26(0.39)

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

Peik *et al*, 2006	Hg^+(opt)/Rb(hfs)	$(d\mu/dt)/\mu = -1.2(2.2)\ 10^{-15}\,\mathrm{yr}^{-1}$

Search for enhancement

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

$K = 2q/\omega_0$ is an enhancement factor.

For a transition between excited states:

$$K = 2\Delta q/\Delta\omega$$

We should look for sufficiently different states (large Δq) separated by small energy interval!

For atomic clocks $K = 1 - 2$ (no enhancement!).

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

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

Measurements (Berkeley, Los Alamos):

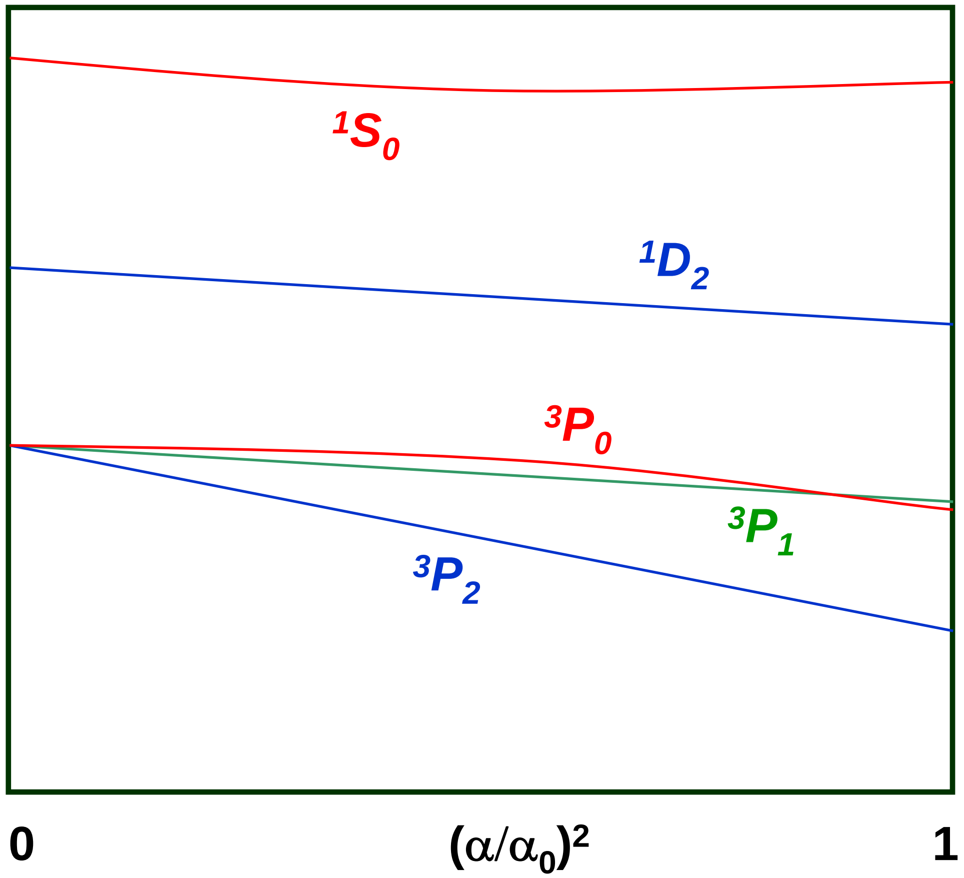
$d\ln\alpha/dt$ =-2.7(2.6)x 10^{-15} yr^{-1}

(Cingos *et al*, PRL **98**, 040801, 2007)

Problem: states are not narrow!

Fine structure anomaly in Te I

Real energy levels of the p^4 ground state configuration of Te I as functions of α^2



$E(^3P_1) - E(^3P_0) = 5\ \text{cm}^{-1}$!

Enhancement factor

K = 100

i.e. $\Delta\omega/\omega_0 = 100\ \Delta\alpha/\alpha$

Also, all states are metastable!

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

E. J. Angstmann *et al*, J. Phys. B 39, 1937 (2006)

Other ideas

- Enhanced effect of temporal variation of α in diatomic molecules, **V. Flambaum**, PRA 2006

$$\frac{\Delta\omega}{\omega} \propto \left(10^2 \div 10^3\right)\frac{\Delta\alpha}{\alpha}$$

for LaS, LaO, LuS, LuO, YbF, etc. due to cancelation between hfs and rotational intervals (small ω).

- Enhanced sensitivity to fundamental constants in ultracold atomic and molecular systems near Feshbach resonance, **Cheng Chin**, **V. Flambaum**, PRL 2006

Variation of m_e/m_p on the level 10^{-11} - 10^{-14} can be detected by monitoring scattering length on the 1% level.

- Enhanced effect of temporal variation of α and strong interaction in **^{229}Th**, **V. Flambaum**, PRL 2006

$$\frac{\Delta\omega}{\omega} \propto \left(10^5 \div 10^6\right)\frac{\Delta\alpha}{\alpha}$$

or

$$\frac{\Delta\omega}{\omega} \propto \left(10^5 \div 10^6\right)\frac{\Delta\left(m_q/\Lambda_{QCD}\right)}{m_q/\Lambda_{QCD}}$$

nuclear clock!

for the transition between the ground and first excited states of **^{229}Th** nucleus

Summary

Quasar data (α):

- **MM** method provides sensitivity increase up to 100 times.
- Anchors, positive and negative shifters - control of systematics.
- **Keck** - variation of α (4.5σ), **VLT** - no variation.
- MWF: problems in the analysis of the **VLT** data?

Quasar data (m_e/m_p):

- hyperfine H/optical – no variation, H_2 - variation (4σ) .
- Undiscovered systematics or space-time variation

Big Bang Nucleosynthesis:

may be interpreted as variation of m_s/Λ_{QCD} (4σ)

Atomic clocks provide strong constrains on present day time variation of fundamental constants (α, m_e/m_p, etc.)

Transitions between narrow close levels in atoms, molecules and nuclei – huge enhancement!